Impacts of changing rainfall patterns on the hydrology of the Mt Lofty Ranges

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the state's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provide the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

Ben Bruce
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

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Summary

The water allocation plans (WAPs) for the Eastern and Western Mount Lofty Ranges (MLR) Prescribed Water Resources Areas (PWRAs) are currently under review. Hydro-ecological investigations were undertaken by the Department for Environment and Water (DEW) to inform the review being led by the Hills and Fleurieu Landscape Board. A component of the investigations includes the assessment of long-term rainfall and streamflow trends across the two PWRAs. This technical report presents the methodology and results of analyses of rainfall data across the PWRAs and streamflow observations in 5 representative surface water catchments in the MLR.

The scope of this investigation is to inform the review of the WAPs by:

- identifying if rainfall, streamflow and their relationship ('rainfall-runoff response') patterns changed during the Millennium drought (drought) (1997 to 2008) and if they have recovered to pre-drought conditions (pre-1996) during the post-drought (2009 to 2022) period
- identifying if streamflow volumes and overall flow patterns during the post-WAP development period (2007 to 2022) were different from those used to develop the WAP (1974 to 2006).

The investigation includes analyses of historical rainfall and streamflow records: (a) for different climate periods (pre-drought, drought and post-drought) and different planning periods (WAP development and post-WAP development); and (b) at different time scales (decadal, annual, seasonal, monthly and daily (for streamflow).

Rainfall: Rainfall records from 24 Bureau of Meteorology (BoM) stations across the MLR were analysed using different statistical methods to investigate long-term trends, periodic shifts within long-term data and the impacts of the drought on rainfall totals and seasonality. Some of the key results of the analyses are summarised below:

- Long-term trend (*Mann-Kendall test*): Statistically significant declining trends were observed in long-term (1900 to 2022) data in annual rainfall at half of the stations investigated, spring season rainfall (predominantly in October) at more than half (58%) of the stations, and autumn rainfall (predominantly in April) at 25% of the stations. Increasing trends were observed in summer season rainfall at 3 (13%) stations and January rainfall at 5 (20%) stations, with all of these stations located either in the lower elevation sections of the Bremer catchment or across the Fleurieu region.
- 'Step change' (or 'Shift') in rainfall (*Wilcoxon Rank Sum and Welch's t-tests, and CUSUM plot deviations*): Comparison between the pre-drought and post-1996 (drought and post-drought) periods showed evidence of statistically significant negative shifts (step changes) in post-1996 annual rainfall, predominantly during spring (in October, at 60% of stations) and to a lesser degree in autumn (in April). Comparison between the two WAP development-related periods showed no evidence of a shift in rainfall between the periods.
- Rainfall recovery[1]: Comparison of the 3 drought-related-period medians provides an insight into rainfall 'recovery' during the post-drought period (since 2009).The results showed: (a) Annually, 91% of stations had either 'Fully' or 'Partially' recovered, primarily due to winter season recovery when 83% of stations had either 'Fully' or 'Partially' recovered, (b) Spring is the most impacted season with 80% of stations 'Yet to Recover', and (c) Autumn being next highly impacted, with 50% of stations Yet to Recover.

In summary, while the long-term trends in annual rainfall and the observed shifts in seasonal rainfall (since onset of the Millennium drought) vary spatially across the MLR, the combined results of the analyses provide evidence of a declining trend in long-term annual rainfall in large parts of the MLR, particularly during the last 3 decades. This could be attributed primarily to a possible step change (or negative shift) in spring season rainfall (predominantly in October) and to a lesser degree to autumn rainfall (in April) since the onset of the drought.

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1 Recovery status: 'Fully' recovered = Post-drought median ≥ Pre-drought and Drought medians; 'Partially' recovered = Post-drought median > Drought median and < Pre-drought median; 'Yet to recover' = Post-drought median < Pre-drought and Drought period medians.

Winter season rainfall has generally recovered to pre-drought conditions across most of the stations investigated. Stations where a long-term decline and/or negative shift in seasonal rainfall (since onset of the drought) was not observed are predominantly located in the lower elevation sections of the Bremer catchment and across the Fleurieu region.

Streamflow: Streamflow records for the period 1974 to 2022 from 5 streamflow gauging stations were analysed, representing flow from 5 representative sub-catchments in the EMLR PWRA (Finniss River and Bremer River catchments) and WMLR PWRA (Torrens River, Onkaparinga River and Myponga River catchments). Key results of the analyses are summarised below.

Streamflow recovery (*Comparison of drought and WAP-development related period medians*): In the case of the 4 non-Myponga sub-catchments investigated, comparison of flows between the 3 drought-related periods provides insight into the extent of streamflow recovery, given the changes to rainfall experienced since onset of the drought. During the post-drought period (since 2009): (a) Annual streamflow volumes increased in all 4 sub-catchments but were still lower than in the pre-drought period (Partial recovery). This increase is consistent with the increase, either Partial or Full recovery, in winter flows in all sub-catchments. (b) Autumn experienced the lowest seasonal flows in all the sub-catchments (Yet to Recover). (c) Spring season flows had Partially Recovered in the Finniss and Bremer sub-catchments and were Yet to Recover in the Torrens and Onkaparinga sub-catchments. When comparing the 2 WAP development periods, a common statistic for the 4 sub-catchments was that autumn and spring season median flows were lower in the post-WAP development period.

Flow regime (*Comparison of daily flow percentiles and flow duration curves*): Since onset of the drought (since 1997), daily flow patterns have been altered to varying extents in the 4 sub-catchments. The average number of flowing days per year has reduced in all sub-catchments except in the Finniss. These changes in daily flow behaviour were also observed between the WAP development and post-WAP development periods. Seasonality, average number of flowing days per year, and the low, medium, and high flow ranges are some of the key metrics that characterise the flow regime of a catchment. These are also some of the key hydrological metrics used in defining and evaluating environmental water requirements (EWR) metrics in the MLR WAPs. The results presented in this report provide evidence of alteration of flow regimes since the onset of the Millennium drought and during the post-WAP development period in the sub-catchments investigated (excluding Myponga).

Myponga sub-catchment is hydro-climatically different to the other 4 sub-catchments investigated, as reflected in its rainfall and streamflow patterns. This is also reflected in the context of drought-related impacts, for example, median seasonal flows in summer progressively increased through the 3 drought-related periods, and the highest median seasonal flows (excluding winter) were observed in the post-drought period in this sub-catchment.

Rainfall-runoff response: Annual rainfall-runoff relationships developed for the 5 sub-catchments investigated show that the underlying catchment rainfall-runoff response of Meadows Creek sub-catchment (Finniss River) and Mt Pleasant sub-catchment (Torrens River) have potentially shifted (downward) in the period since the onset of the drought. In the case of the Bremer River (sub-catchment upstream of the gauging station at Hartley), while there are indications of a downward trend in the relationship during the drought period, results for the post-drought period are inconclusive due to incomplete streamflow records. There is little evidence to suggest the rainfall-runoff response has shifted in the Onkaparinga (Scott Creek sub-catchment) or Myponga (sub-catchment upstream of the reservoir) since the onset of the drought. It is uncertain, at this time, if this observed downward shift in rainfall and in rainfall-runoff response (in some sub-catchments) is permanent or temporary and prolonged. It is also to be noted that this observed potential shift in rainfall-runoff response may be caused by multiple drivers, not all of which are the result of changing climate.

In summary, the data shows evidence of change in seasonal rainfall and flow patterns since the onset of the drought (which includes the post-WAP development period) in the catchments investigated, except in the Fleurieu region (including the Myponga catchment). A potential shift in catchment rainfall-runoff response was also observed in some of the sub-catchments. These changes in rainfall and rainfall-runoff response are recommended to be considered when the WAPs are amended. Some of key investigations recommended, as the next steps, include: (i) Recalibration of the models (that were developed when the WAPs were developed and used in quantifying resource capacities and environmental water requirements in the WAPs) with recent rainfall and streamflow data, to account for the recently observed rainfall-runoff response shifts, (ii) Undertake scenario modelling with climate projections data, to verify if the recently observed shifts are likely to continue into the future and have potential impacts on future rainfall-runoff responses, and (iii) For the Fleurieu region, undertake investigations to better understand the weather systems that influence long-term rainfall patterns and the drought interface with those weather systems, and additional streamflow monitoring in more catchments across the region to gain better understanding of the region's hydro-climate and rainfall-runoff response.

1 Introduction

Background

The water allocation plans (WAPs) for the Eastern and Western Mount Lofty Ranges (MLR) Prescribed Water Resources Areas (PWRAs) are currently under review. Hydro-ecological investigations were undertaken by the Department for Environment and Water (DEW) to inform the review, being led by the Hills and Fleurieu Landscape Board. This technical report presents a review of rainfall and streamflow observations in 5 surface water catchments in the MLR.

As part of the review, a series of scientific investigations were undertaken to improve understanding of the behaviour of the water resources in the PWRAs. Of particular importance is selecting an appropriate climate period, as the two fundamental metrics in establishing environmentally sustainable extraction limits – the resource capacity and the environmentally critical flow regime – vary based on climate period. Historically, such selections were generally based on the longest period of rainfall and streamflow data available, with rainfall records spanning from the early 1900s and streamflow records from the late 1960s. The WAPs were developed using streamflow data from 1974 to 2006. Resource capacity was then quantified to be the average annual flow for the period, with the impacts of development removed through modelling.

The 2013 WAPs included an assessment of the surface water resources capacity to meet the various current and future demands, as well as inform policies and principles for allocation and transfer of water. The WAPs also identified the needs of water-dependent ecosystems and the impacts of development on these needs by establishing environmental water requirements (EWRs) and Environmentally Sustainable Extraction Limits (ESEL).

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 (that is, 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 – with climate projections indicating a drying climate into the future – choosing an appropriate climate period becomes more critical when reviewing and amending plans that were developed using climate data from many decades ago.

The recent Millennium Drought, spanning from 1997 to 2008, 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 rainfall-runoff responses of catchments pre- and post-drought (Chiew et al. 2014; Peterson et al. 2021; Fowler et al. 2022; Saft et al. 2015). Results of the studies showed that in some areas, the ability of a catchment to generate runoff from a given amount of rainfall post-drought had recovered to pre-drought conditions, while in others it either didn’t recover, or the generation of runoff was suppressed (Victorian Department of Environment, Land, Water and Planning (DELWP) 2020).

The practice of using historical 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 responses, including non-stationarity. Recent investigations of historical water resources in the Barossa PWRA that informed the review of the Barossa WAP (Savadamuthu et al. 2023) showed evidence of a possible shift in rainfall patterns since the beginning of the Millennium drought, and its impacts on the area’s rainfall-runoff response and environmentally significant flow regimes.

The purpose of this body of work is to support the review of the Eastern Mount Lofty Ranges (EMLR) and Western Mount Lofty Ranges (WMLR) WAPs by:

- identifying if rainfall, streamflow, and their relationship patterns (rainfall-runoff response) have changed during the Millennium drought (1997 to 2008), and if they have recovered to pre-drought conditions (pre-1996) during the post-drought period (2009 to 2022)
- identifying if rainfall and streamflow patterns, and the relationship between the two for the post-WAP development period (2007 to 2022), are different from those used to develop the WAP (1974 to 2006).

The resource capacity (considered to represent the long-term average annual runoff in the absence of water resource development) and overall flow pattern are major inputs for determining WAP policy. If resource capacity and flow patterns have substantially changed in response to different climate through the drought and post-drought periods, then the assumptions and rules of the WAPs may not have been effective in meeting the objectives of the WAPs during the implementation period. If this is the case, and such changes to climate and runoff are expected to continue in the future, then the WAP should be amended to allow it to be effective in meeting its objectives.

The selection of an appropriate climate period that accounts for a potentially changing climate is essential to establish surface water resource capacity and environmental water requirement flow regimes for these areas, if WAPs are to be amended. This technical report investigates changes in rainfall and streamflow in MLR catchments, which will support the selection of an appropriate climate period(s) to underpin WAP policy, if amendment is needed.

2 Methodology

2.1 Catchments

Rainfall and streamflow records were analysed within 5 surface water catchments in the Eastern and Western Mount Lofty Ranges PWRAs. The catchments selected for analysis were:

- Finniss River in EMLR PWRA
- Bremer River in EMLR PWRA
- Onkaparinga River in WMLR PWRA
- Torrens River in WMLR PWRA
- Myponga River in WMLR PWRA.

This small subset of catchments was chosen to represent (a) the larger and high yielding catchments in both PWRAs, with high spatial variability of rainfall and runoff, and (b) catchments that have long-term and good quality rainfall and streamflow observations. It should be noted that the subset of catchments chosen for this investigation do not necessarily represent the hydrological variability of all catchments in MLR PWRAs.

2.2 Rainfall site selection

Daily rainfall observations across the selected MLR catchments were retrieved from the SILO database (Queensland Government 2024), which is managed by the Queensland Government. These climate data, which include daily rainfall, are based on historical climate data provided by the Bureau of Meteorology (BoM). The long-term climate period chosen for this investigation was 1900 to 2022. There are numerous BoM rainfall monitoring stations across the PWRAs, but only a small subset has data that were recorded at the BoM stations from 1900 onwards and not infilled (that is, estimated).

The SILO Patched Point Dataset is a collection of daily climate data sets for BoM observation stations that extends original BoM measurements back to 1889, with missing data infilled using interpolated values (Jeffrey et al. 2001). There are many stations with daily rainfall data in the SILO database, with a wide range of stations showing varying proportions of data having been interpolated.

A data quality code is assigned to each daily climate variable in a SILO series, indicating the source of the data. A quality code of 0 represents station-recorded data, as provided to the SILO database by BoM. Among other codes used by SILO, a quality code of 15 represents de-accumulated values from interpolated data and 25 represents interpolated daily observations.

To investigate the spatial and temporal variability in historic rainfall across the MLR, BoM stations having rainfall recorded for more than approximately 85% of days since the station opened were assumed to provide the most reliable data and useful description of long-term variability. As such, rainfall data for SILO sites across the selected catchments were analysed to identify operational sites that have the least infilled rainfall data (that is a quality code of 0 for more than 85% of days) for the period 1900 to 2022. Where such sites were not available, sites from neighbouring catchments with similar rainfall characteristics were chosen for analysis.

2.3 Streamflow data selection

Daily streamflow records were obtained from the South Australian Government's water database for key surface water monitoring stations to represent the surface water responses in these chosen catchments for analysis for the period 1974 to 2022. Stations were selected based on availability of good-quality long-term records. The stations used in this analysis were the following:

- Finniss River at Yundi (A4260504), daily streamflow data available for 1974 to 2022
- Bremer River near Hartley (A460533), daily streamflow data available for 1974 to 2022
- Scott Creek at Scott Bottom, Onkaparinga River (A5030502), daily streamflow data available for 1974 to 2022
- Torrens River at Mt Pleasant (A5040512), daily streamflow data available for 1974 to 2022
- Myponga River upstream (u/s) of reservoir (A5020502), daily streamflow data available for 1978 to 2022.

2.4 Hydrological analyses

Daily rainfall and streamflow records for the selected catchments were analysed in various forms, including annual, seasonal, and monthly totals; long-term medians; long-term trends; and the extent of deviation of each year's observed total from the long-term median.

The annual streamflow for each gauging station can be expressed as a percentile (or decile), with applicable descriptive category as shown in Table 1. These categories are consistent with categories used by the Bureau of Meteorology (BoM) to define surface water resources.

Table 1. Streamflow percentile/decile categories as defined by the BoM

Decile	Percentile	Description
N/A	100	Highest on record
10	90 to 100	Very much above average
8 and 9	70 to 90	Above average
4, 5, 6 and 7	30 to 70	Average
2 and 3	10 to 30	Below average
1	0 to 10	Very much below average
N/A	0	Lowest on record

In addition to reviewing annual streamflow, a further approach to investigating recent changes in the flow response and flow regime is through an analysis of the distribution of daily flow. Flow duration curves present the range of daily flow observations (generally on a logarithmic scale) as probability of exceedance curves.

Rainfall observations were analysed within two sets of key periods to investigate the likelihood of significant change in recorded rainfall during recent years, and subsequent change in the volume of streamflow recorded. The 2 key periods were defined by the periods used in the development of the WAPs and the Millennium drought. More specifically, hydrological data were analysed across the following sub-periods, in addition to all years on record (1900 to 2022):

- WAP development (1974 to 2006)
- Post-WAP development (2007 to 2022)

- Pre-drought (1900 to 1996)
- Millennium drought (1997 to 2008)
- Post-drought (2009 to 2022)
- Drought and post-drought (1997 to 2022).

It should be noted that the WAP development and post-WAP development periods are planning periods that overlap climatic periods. The relevance for the WAP review is the analysis of hydrological data that were used to develop the WAPs, what has been observed in the period since the development of the WAPs, and what may happen in the future. This analysis has investigated hydrological responses at both climate and planning periods, compared across the climate periods to establish whether there is evidence for a climate-driven difference, and then compared across the planning periods to see if those different climate periods have resulted in changes in resource capacity and flow patterns in the planning periods.

Through analysing hydrological data over these periods, particular years were chosen as points of potential climatic deviation. First, 1997 was representative of the start of the Millennium drought and may represent the start of a period of altered climate conditions in the MLR. Similarly, 2008 represents the end of the Millennium drought, with 2009 representing the start of a further period of altered climate conditions (Post-drought). 2006 represents the conclusion of the period used for the development of the WAP, and the period since then was chosen to assess whether the climate and rainfall-runoff responses were altered during the post-WAP development period.

In addition to these analyses, box and whisker plots were used to assess the distribution of these data and their skewness by displaying the data quartiles (or percentiles) and averages. Box plots generally show the 5-number summary of a set of data, including the minimum value, first (lower) quartile, median, third (upper) quartile, and maximum value. The distance between the upper and lower quartile (also the size of the box) is known as the Interquartile Range (IQR). Outliers may also be shown, which have large or small values relative to the rest of the data set (that are more than 1.5 times the IQR from the quartile values).

Figure 1 (from Massart et al., 2005) shows representative box plots for 6 datasets that exhibit (a) small dispersion, (b) large dispersion, (c) middle clustering (with long tails), (d) middle clustering based on a bimodal distribution, (e) upward skewness and (f) downward (negative) skewness. An example of upward or positive skewness is shown in Figure 1(e) where the median is shifted toward the lower portion of the box, with a wider range of observations in the upper quartile as compared to the lower quartile. The opposite is true in Figure 1(f), which is an example of downward or negative skewness. Knowledge of skewness tells the user whether deviations from the median are more likely to be positive or negative.

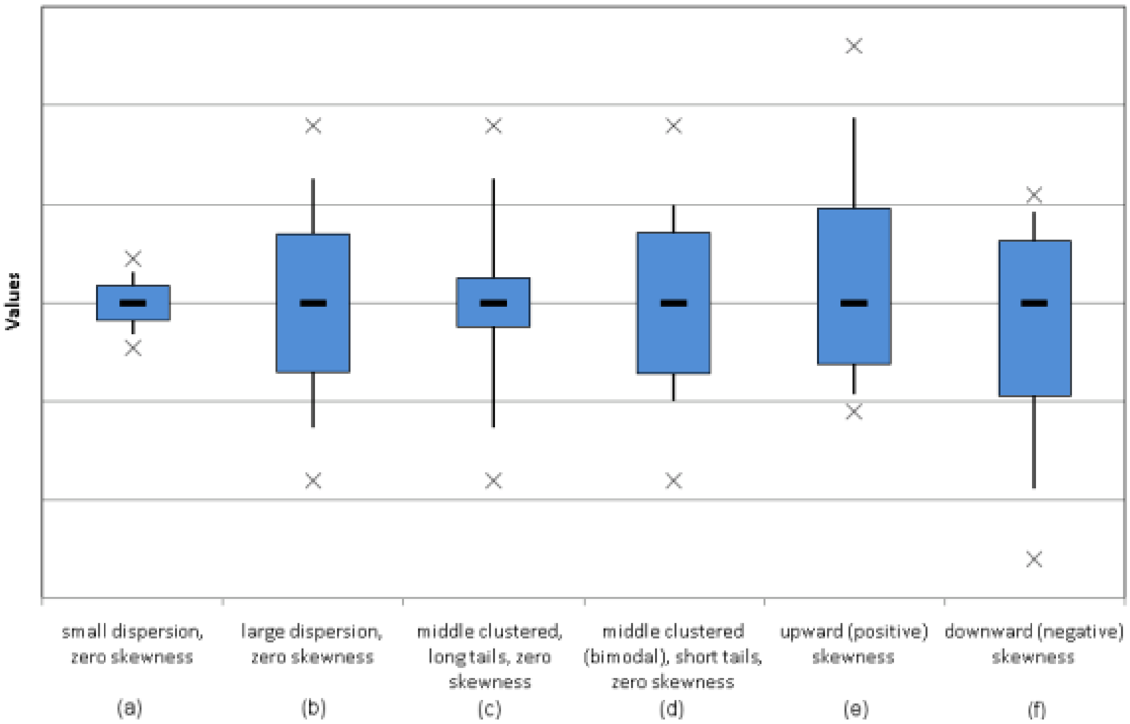


Figure 1. Examples of box plots (after Massart et al. 2005)

2.5 Recovery status categories

To obtain a PWRAs-scale picture of the 'recovery' status of rainfall and streamflow during the post-drought period (2009 to 2022), the stations were grouped into the following categories by comparing the post-drought median to drought and pre-drought period medians:

- Fully Recovered: Rainfall/streamflow was considered to have 'Fully Recovered' at a station where the post-drought median was greater than both the drought and pre-drought period medians. This also implies that the post-drought period was the wettest amongst the three comparison periods.
- Yet to Recover: Rainfall/streamflow was considered 'Yet to Recover' at a station where the post-drought median was less than both the drought and pre-drought period medians. This also implies that the post-drought period was the driest amongst the three comparison periods.
- Partially Recovered: Rainfall/streamflow was considered to have 'Partially Recovered' at a station where the post-drought median was greater than the drought period median but lower than the pre-drought period median.

2.6 Rainfall-runoff response

The runoff generated from a catchment is dependent on a combination of the quantity (and intensity) of rainfall and characteristics of the catchment, including topography, soil type and depth, land use and interception. The relationship between rainfall on a catchment area and the runoff generated from it (that is, the 'rainfall-runoff response') can be described with various methods. For the purposes of this report a visual inspection of annual rainfall and streamflow is used.

Rainfall-runoff relationships, once developed from historic data, can be a useful tool to estimate and/or predict runoff that could be expected for a specific quantity of rainfall. Streamflow recorded at a monitoring gauge (and measured in volumetric terms, such as megalitres, ML) can also be expressed as runoff depth (measured in millimetres, mm), by dividing flow by the catchment area upstream of a monitoring gauge. The ratio of runoff depth to rainfall provides an indication of the proportion of rainfall that enters the watercourse as surface flow. The ratio of runoff depth to total rainfall is termed the 'runoff coefficient'. Larger runoff coefficients are observed in areas with low infiltration and high runoff (urbanised areas, for example) and lower values for high infiltration and low runoff areas (forests, for example). Runoff coefficients are generally a good indicator of catchment yields and they describe the efficiency of a catchment in generating runoff from rainfall.

The generalised relationship between annual rainfall and runoff depth can also be explored through the calculation of a relationship using the hyperbolic tangent function known as a TanH curve. Boughton (1966) first described the use of the TanH curve to model the relationship between measured rainfall and runoff, and this was later modified by Grayson et al. (1996) to be:

$$Q = (P - L) - F \times tanh\left(\frac{P - L}{F}\right)$$

Where Q is runoff (in mm), P is annual rainfall (mm), and L and F are variables that determine the shape of the TanH curve. L sets the threshold below which there is little or no runoff (also termed the 'initial loss'), and F sets the gradient of the curve (also referred to as the 'continuing loss').

The hyperbolic shape of the TanH function implies that rainfall and runoff are not directly proportional, but that a threshold in annual rainfall must be reached before runoff occurs. Below this threshold (L), any rainfall is either lost as evaporation, stored in the ground, or infiltrates through to the groundwater.

When fitting this relationship, values for the 2 loss parameters are estimated by minimising the sum of squared errors, such that the TanH curve represents a line of best fit through the rainfall-runoff pairs and can therefore be used to estimate runoff depth for a selected annual rainfall total.

2.7 Statistical analyses

A suite of statistical tests was used to test the statistical significance of trends in the rainfall data series, or differences in the sample means for two subsets (indicating different periods) in the observed series. These tests included CUSUM analysis, Welch's *t*-test, the Wilcoxon Rank Sum Test, and the Mann-Kendall Test, and are described as follows:

- The CUSUM chart plots deviations of the cumulative sums (CUSUMs) of each sample value from a target value (e.g., Bissell 1969). In this context, CUSUM charts are used to monitor small shifts in the mean value of samples. The CUSUM chart is cumulative, and even minor drifting in the sample mean will cause steadily increasing (or decreasing) cumulative deviation values. Given the general use of CUSUM analysis is for monitoring processes that have a desired tolerance that is considered acceptable (for example in manufacturing processes), CUSUM charts usually include upper and lower *control* or *action* limits to highlight shifts outside an acceptable range. In the case of this analysis, these bounds are set as 4 standard deviations from the mean. In the context of assessing rainfall behaviour, the temporal progress of cumulative deviations relative to the mean is a primary factor to consider. Even if cumulative deviations do not exceed these control limits, a continuous downward trend can be indicative of a declining trend in the sample mean.
- Welch's *t*-test is a 2-sample location test that is used to test a null hypothesis that 2 populations have equal means, a variation on Student's *t*-test and more applicable when 2 samples have unequal variances and/or unequal sample sizes. As with Student's t-*t*est, Welch's *t*-test maintains an assumption of 2 populations being normally distributed (Zimmermann et al. 1993).
- The Wilcoxon Rank Sum Test represents a non-parametric version of the two-sample *t*-test, with a null hypothesis usually assuming that the 2 samples taken from one series will have equal medians (that is 2 populations with the same distribution and the same median). For this null hypothesis to be rejected, there must be evidence that the sample median value has changed, such that one distribution is shifted to the left or

right of the other. By assuming the distributions of the 2 samples remain equal, rejecting a null hypothesis means that there is evidence that the medians of the two samples are different.

- The Mann-Kendall Test is used to determine whether a time series has a monotonic upward or downward trend, which will occur when values consistently increase (or decrease) over time, but not always in a linear manner. The Mann-Kendall Test, which is non-parametric, can be used in place of a parametric linear regression analysis, which can be used to test if the slope of the estimated linear regression line is different from zero (Wang et al. 2020).

3 Rainfall analysis

Overview

The long-term annual rainfall distribution across the two PWRAs is shown in Figure 2. The distribution is shown to follow the elevation of the landscape. The two PWRAs are divided primarily by the Mt Lofty ranges that runs in a north–south direction, with the Fleurieu Peninsula being a distinct hydro-geological area that forms part of the Western MLR PWRA for administrative reasons. Annual rainfall varies across the MLR, generally following the MLR ridgeline, with the eastern side (EMLR PWRA) being on the 'rain shadow' side of the ridge and generally receiving lower annual rainfall than the western side (WMLR PWRA). Across both PWRAs, there is also a general south–north downward rainfall gradient, becoming much drier further north and beyond the PWRA boundaries. As shown in Figure 2, higher rainfall areas are located along the ridgeline boundary between the two PWRAs, ranging between 900 mm to 1000 mm per annum and dropping down quickly through the valleys and the plains to a low of ≈400 mm per annum on the east and ≈500 mm per annum on the west. Further catchment scale information is provided in the WAPs for the two PWRAs (Adelaide and Mount Lofty Ranges Natural Resources Management Board 2013 and South Australian Murray–Darling Natural Resources Management Board 2013).

For the purposes of this investigation, 24 rainfall sites were selected:

- to generally cover the spatial distribution of rainfall across the two PWRAs
- to meet the data quality criteria mentioned in Section 2.2
- with higher priority given to stations located in the headwater sections of the catchments considered in the streamflow and rainfall-runoff investigations.

A list of the of rainfall sites, and the catchment and PWRA in which they are located, are provided in Appendix 7.1 and displayed in Figure 2, respectively.

Analyses of rainfall records were undertaken using various measures, primarily to:

- identify long-term annual, seasonal, and monthly rainfall trends
- identify changes to long-term annual, seasonal, and monthly rainfall for 3 drought-related (pre-, during and post-drought) and 2 WAP development (WAP development and post-WAP development) periods
- identify, using standard statistical technical analysis tools, statistically significant trends and shifts in annual, seasonal, and monthly rainfall since the beginning of the Millennium drought.

Detailed analyses and results of rainfall records for one station per catchment is provided in the following sections. Results for the remaining reporting stations are provided as tables and charts in the Appendices.

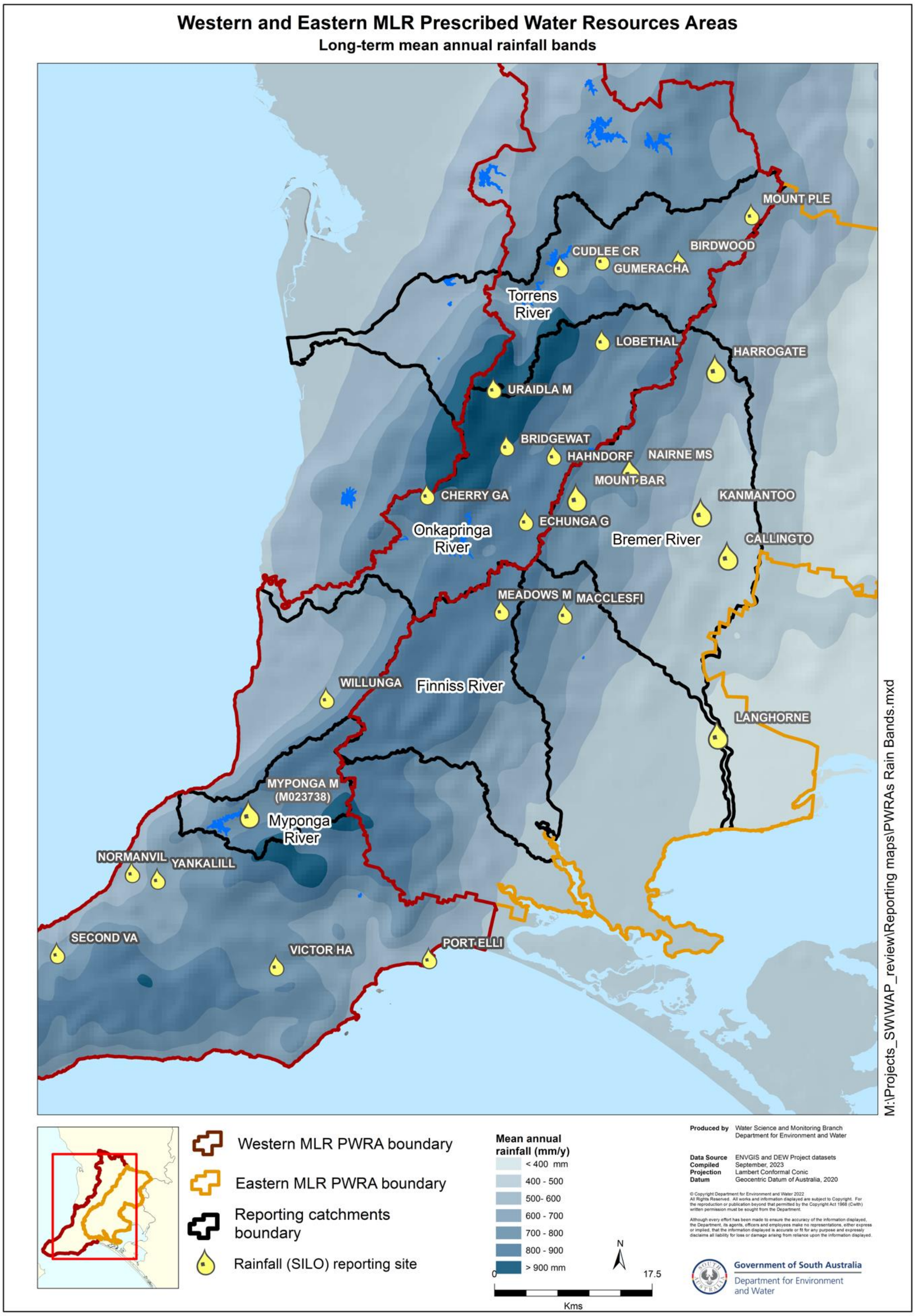


Figure 2. Boundaries of surface water catchments and PWRAs with locations of reporting rainfall stations

3.1 Finniss River catchment

3.1.1 Overview of rainfall stations

There are 5 currently operational rainfall observation stations in the Finniss River catchment. The overall quality of data within the SILO records for these series across 1900 to 2022 are summarised in Table 2. This demonstrates that only one operational site (Meadows, BoM site no. 23730) within the Finniss catchment had over 90% of its daily data recorded by the BoM throughout the period.

Table 2. Proportion of daily SILO rainfall series (1900 to 2022) in the Finniss catchment with various quality codes

Site ID	Site name	Catchment	SILO Data Quality Codes		
			0	15	25
23730	Meadows	Finniss	92%	6%	2%
23701	Ashbourne	Finniss	64%	3%	33%
23799	Meadows (Oakland Hills)	Finniss	43%	1%	56%
23818	Kuitpo Forest HQ	Finniss	19%	2%	79%
23887	Kuitpo Forest Reserve	Finniss	19%	0%	81%
23728	Macclesfield	Angas	91%	7%	2%

Given that the Meadows (23730) site is located in the wettest part of the Finniss catchment, sites located in drier parts of neigbouring catchments were also investigated. The Macclesfield (23728) site in the neighbouring Angas River catchment had BoM-recorded data for over 90% of its days, and was chosen as a comparison site for Meadows (23730).

3.1.2 Annual rainfall – all sites

Table 3 summarises main statistics for annual rainfall data from these two sites. The data shows average and median annual rainfall is over 130 mm and greater at Meadows compared to Macclesfield.

Table 3. Summary statistics for selected annual rainfall data (mm) for Finniss River catchment (1900 to 2022)

Statistics	Meadows (23730)	Macclesfield (23728)
Annual average	860	724
Annual median	837	705
Annual maximum	1517	1114
Annual minimum	454	391
Standard deviation	173	153

Figure 3 shows the behaviour of annual rainfall across different drought-related time periods in the form of boxplots, while Table 4 shows the absolute median values and relative changes across the various drought-related periods. Both the median annual rainfall, and the variation of annual rainfall (indicated by the IQR and range between minimum and maximum values of the boxplot whiskers), is shown to be reduced during the drought at both sites. The reduction in median rainfall from pre-drought to drought periods was approximately 8% at Meadows (23730) and 13% at Macclesfield (23728). Rainfall has not returned to pre-drought conditions at Meadows (23730) in the period since 2008, with median rainfall in the post-drought period remaining at 8% below the pre-drought median. In contrast, at Macclesfield (23728) the median annual rainfall for the post-drought period has returned to a similar value to the pre-drought median (3% difference). At each station, however, the post-drought period shows a negative skewness (Figure 3) indicating a wider range of rainfall observations in the lower quartile. This compares to a normalised distribution (that is, even distribution above and below the median) of rainfall in the pre-drought period for both stations, which may in part be related to the differences in sample sizes between the pre-drought and drought/post-drought periods, and is not expected to invalidate the assumptions of normal distributions of the Welch's t-test (refer to Section 3.1.4).

Figure 3. Distribution of annual rainfall at Meadows and Macclesfield for different periods (median (—), average (X), and outliers (O) shown)

Table 4. Median annual rainfall (mm) for different periods for the Finniss River catchment (1900-2022)

Period	Meadows (23730)	Macclesfield (23728)
All years (1900 to 2022)	837	705
Pre-drought (1900 to 1996)	874	721
Drought (1997 to 2008)	800	627
Post-drought (2009 to 2022)	800	739
Change compared to pre-drought		
Drought (%)	-74 (-8 %)	-94 (-13 %)
Post-drought (%)	-73 (-8 %)	18 (3 %)

Similar behaviour in rainfall is observed when considering WAP development-related periods (Figure 4 and Table 5). Median rainfall for Meadows (23730) over the last 15 years (Post-WAP development) is similar to that of the WAP development period (3% reduction in median), while for Macclesfield (23728) the median has increased (by

8%). At both stations, however, the distribution of annual rainfall over the post-WAP development period shows significant negative skewness, indicating a greater number of observations in the lower quartile.

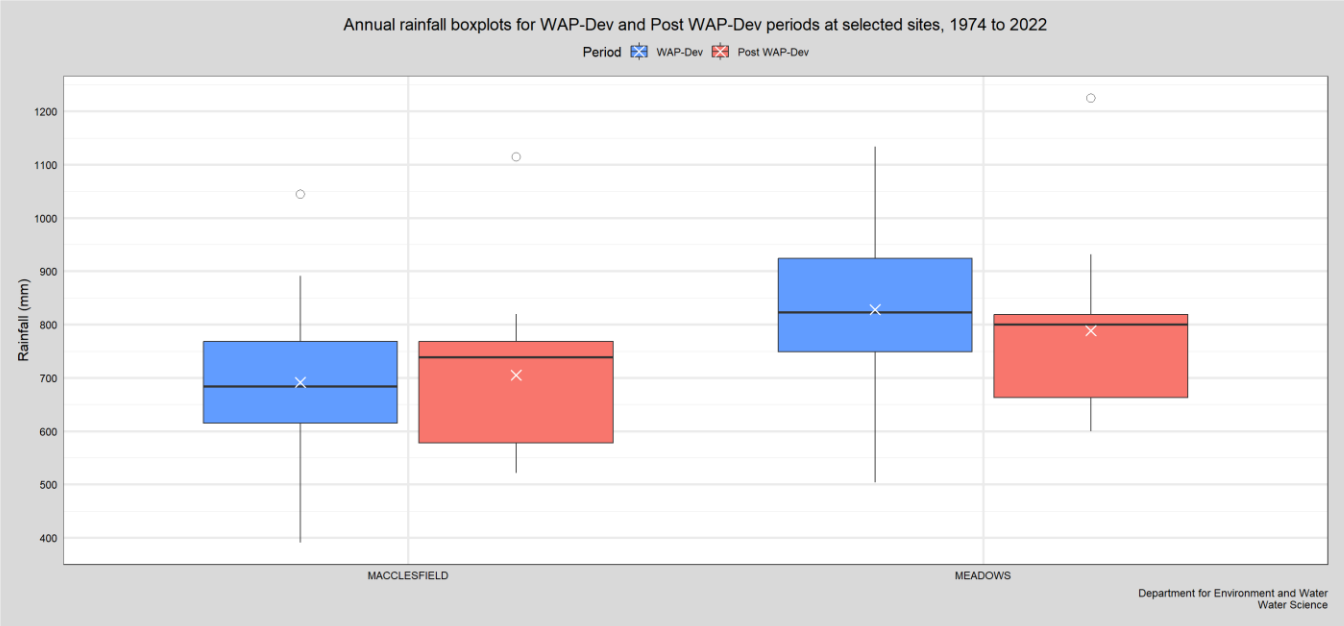


Figure 4. Distribution of annual rainfall at Meadows and Macclesfield during WAP development periods (median (—), average (X), and outliers (O) shown)

Table 5. Median annual rainfall (mm) for different WAP periods across the Finniss River catchment (1900 to 2022)

Period	Meadows (23730)	Macclesfield (23728)
All years (1900 to 2022)	837	705
Pre-WAP (1900 to 2006)	864	696
WAP development (1974 to 2006)	823	684
Post-WAP development (2007 to 2022)	800	739
Change (WAP development to Post-WAP-development) (%)	-23 (-3%)	55 (8%)

3.1.3 Detailed rainfall analysis – Meadows

Detailed rainfall analysis for Meadows (23730) at various timescales is presented below, given it is the only active station located within the Finniss River catchment currently available.

Annual rainfall analysis

Rainfall totals for Meadows (23730) at annual and decadal levels, with various period medians and trends included, are plotted in Figure 5(a) to (f). The trends of annual rainfall and decadal medians suggest gradually drying conditions over the period of record from 1900 to 2022 (refer to Figure 5(a) and (b)), with the latest decade showing the second lowest median on record (refer to Figure 5(e) and (f)). Annual deviations from the long-term median rainfall for Meadows (23730), shown in Figure 5(b), indicate that only one in the past 10 years was considered an ‘above median’ year, as per the classification in Table 1.

Periodic medians for pre-drought, drought, and post-drought periods (Figure 5(c)) show the median rainfall of periods since the commencement of the drought (1997) are below both the pre-drought and long-term medians. For WAP development and post-WAP development periods (Figure 5(d)) the data suggest that the post-WAP development period has occurred under similar (but marginally lower) rainfall conditions at this station to that of the period used for WAP development.

Figure 5. **Rainfall plots at Meadows (BOM site 23730) for 1900 to 2022 showing (a) long-term median, 10-year rolling median and linear trend, (b) deviation of annual rainfall from long-term median with linear trend, (c) annual rainfall showing median values of drought-related periods, (d) annual rainfall showing median values during the WAP development and Post WAP-development periods, (e) median annual rainfall per decade, (f) boxplots of distribution of annual median rainfall per decade**

Seasonal rainfall analysis

The previous section outlined evidence of trends towards drier conditions at Meadows in recent decades when rainfall was analysed at an annual timescale. To further investigate these drier conditions, and to determine whether reductions in rainfall are consistent across the year, historical rainfall at Meadows (23730) was aggregated at a finer scale to seasonal totals.

Table 6 summarises median seasonal rainfall related to the 3 climate periods used, together with the difference in annual and seasonal medians during the drought and post-drought periods in comparison to the pre-drought medians. This shows:

- Autumn, winter and spring seasons were drier in the post-drought period in comparison to drought and pre-drought period medians (Yet to Recover).
- Summer showed little change in median rainfall during the drought, while the post-drought period median was the wettest amongst the three comparison periods (Fully Recovered).

Table 6. Median seasonal rainfall (mm) at Meadows (BOM site 23730) for different drought related periods

Season	All years	Pre-drought	Drought	Post-drought	Change from pre-drought	
					Drought	Post-drought
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	mm (%)	mm (%)
Summer	80	81	78	90	-3 (-3%)	9 (12%)
Autumn	195	199	171	178	-27 (-14%)	-21 (-10%)
Winter	337	334	352	304	18 (6%)	-29 (-9%)
Spring	205	211	201	178	-10 (-5%)	-33 (-16%)
Annual	**837**	**874**	**800**	**800**	**-74 (-8%)**	**-73 (-8%)**

Table 7 summarises seasonal medians for the WAP development and post-WAP development periods. These values demonstrate that the post-WAP development phase (2007 onwards) was drier in all seasons ('driest') except summer, when compared to the WAP development period.

Table 7. Median seasonal rainfall (mm) at Meadows (BOM site 23730) for WAP development and Post-WAP development periods

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Summer	80	75	77	1	2%
Autumn	195	187	178	-9	-5%
Winter	337	349	326	-23	-7%
Spring	205	206	156	-50	-24%
Annual	**837**	**823**	**800**	**-23**	**-3**

Monthly rainfall analysis

Table 8 summarises median rainfall for each calendar month for the 3 drought-related periods and the relative change from pre-drought to drought and post-drought medians.

- During the drought period, all months except May, June, July and November experienced a reduction in median monthly rainfall ('drier').
- The post-drought period data indicates all months except January, February and July were drier than the pre-drought period (Yet to Recover).
- October, April and March rainfall has been the most impacted since the commencement of the drought. April showed the largest decrease in median rainfall during the drought, although it recovered slightly in the post-drought period. In contrast, October and March show monthly medians decreasing progressively through the 3 comparison periods (driest).
- July has been on the other end of the spectrum, with the monthly median increasing progressively through the 3 comparison periods ("wettest")

Table 8. Median monthly rainfall (mm) for Meadows (BOM site 23730) for different periods relative to the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
					Drought	Post-drought
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	mm (%)	mm (%)
Jan	20	20	19	24	0 (-2%)	4 (22%)
Feb	17	17	17	26	-1 (-5%)	9 (52%)
Mar	27	28	24	22	-4 (-13%)	-6 (-22%)
Apr	59	63	32	41	-31 (-49%)	-22 (-34%)
May	91	91	100	80	9 (10%)	-11 (-12%)
Jun	107	107	124	103	18 (16%)	-3 (-3%)
Jul	122	122	126	135	4 (3%)	14 (11%)
Aug	105	111	95	104	-16 (-14%)	-7 (-6%)
Sep	94	95	87	92	-8 (-8%)	-3 (-3%)
Oct	68	71	60	42	-12 (-16%)	-30 (-42%)
Nov	39	40	48	31	8 (21%)	-8 (-21%)
Dec	32	33	32	23	-1 (-2%)	-10 (-30%)
Annual	**837**	**874**	**800**	**800**	**-74 (-8%)**	**-73 (-8%)**

Table 9 summarises median monthly rainfall for WAP development and post-WAP development periods, with changes in median monthly rainfall recorded during the post-WAP development phase compared to the WAP development period also shown. These results show that reductions in rainfall are high during March (in autumn), and September, October and November (in spring) during the post-WAP development period, relative to the WAP development period.

Table 9. Median monthly rainfall (mm) for Meadows (BOM site 23730) for different WAP development periods

Month	All years (1900 to 2022)	WAP development (1974 to 2006)	Post-WAP development (2007 to 2022)	Change (WAP dev. to Post-WAP dev.) (mm)	(%)
Jan	20	25	24	-1	-4%
Feb	17	16	22	7	42%
Mar	27	32	22	-10	-30%
Apr	59	48	46	-2	-4%
May	91	84	88	4	5%
Jun	107	106	103	-3	-3%
Jul	122	126	137	11	9%
Aug	105	111	104	-8	-7%
Sep	94	95	69	-25	-27%
Oct	68	71	42	-30	-42%
Nov	39	46	31	-15	-32%
Dec	32	28	28	0	0%
Annual	**837**	**823**	**800**	**-23**	**-3%**

3.1.4 Trend and shift analyses of rainfall

Detailed analysis of Meadows (23730)

CUSUM charts were prepared for the time series of rainfall at Meadows (23730) aggregated to annual totals (Figure 6). The annual CUSUM chart does not show any data points falling outside of the 'action' bounds (yellow shading), other than a period in the 1910s to 1920s falling above the upper action limit. This latter behaviour can be attributed to a high rainfall period that includes the highest annual rainfall year on record in 1917 (refer to Figure 5(a)). The cumulative sum has generally fallen below the long-term mean since the 2000s, however, with the exception of some years impacted by high rainfall in the mid- to late-2010s. A minor downward trend (indicted by the red line) is suggested in the cumulative sum up to 2022, although further years of data are required to confirm if this is a developing trend or the result of natural variation.

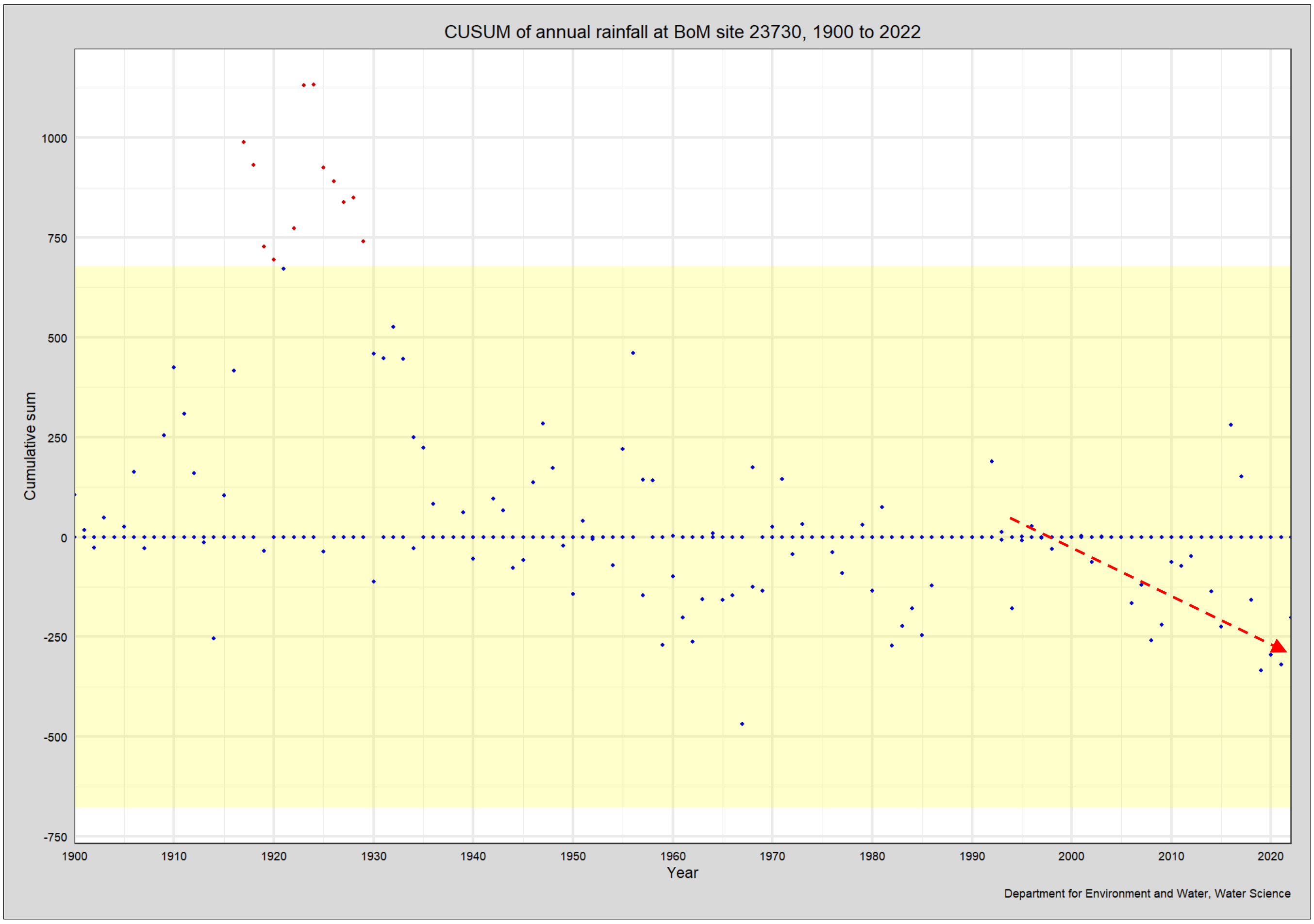


Figure 6. CUSUM chart of annual rainfall (1900 to 2022) for Meadows (BOM site 23730)

Figure 7 shows the CUSUM charts of seasonal rainfall totals. These results show:

- The cumulative sums of summer, winter and autumn rainfall during the last few decades are generally distributed close to the long-term mean and remained within the action limits.
- Spring rainfall showed a progressive reduction in cumulative sum from the early 2000s, falling outside the lower action limit by the mid-2010s. A jump in cumulative sum was then experienced in 2016, before again falling below the long-term average and outside the action limits towards the end of the period. This supports previous analysis that showed strong reductions in median spring rainfall in the post-drought period.

Figure 8 shows CUSUM charts of monthly rainfall totals. These results indicate October rainfall totals have entered a significant downward trend in cumulative sum since the commencement of the Millennium drought, with data points falling outside the action limits towards the end of the period. A minor jump in CUSUM value is shown at the end of the analysis period for the high rainfall year of 2022, but this remains significantly below the long-term average. No other calendar months showed data points falling outside the action limits in a CUSUM analysis for this recent period.

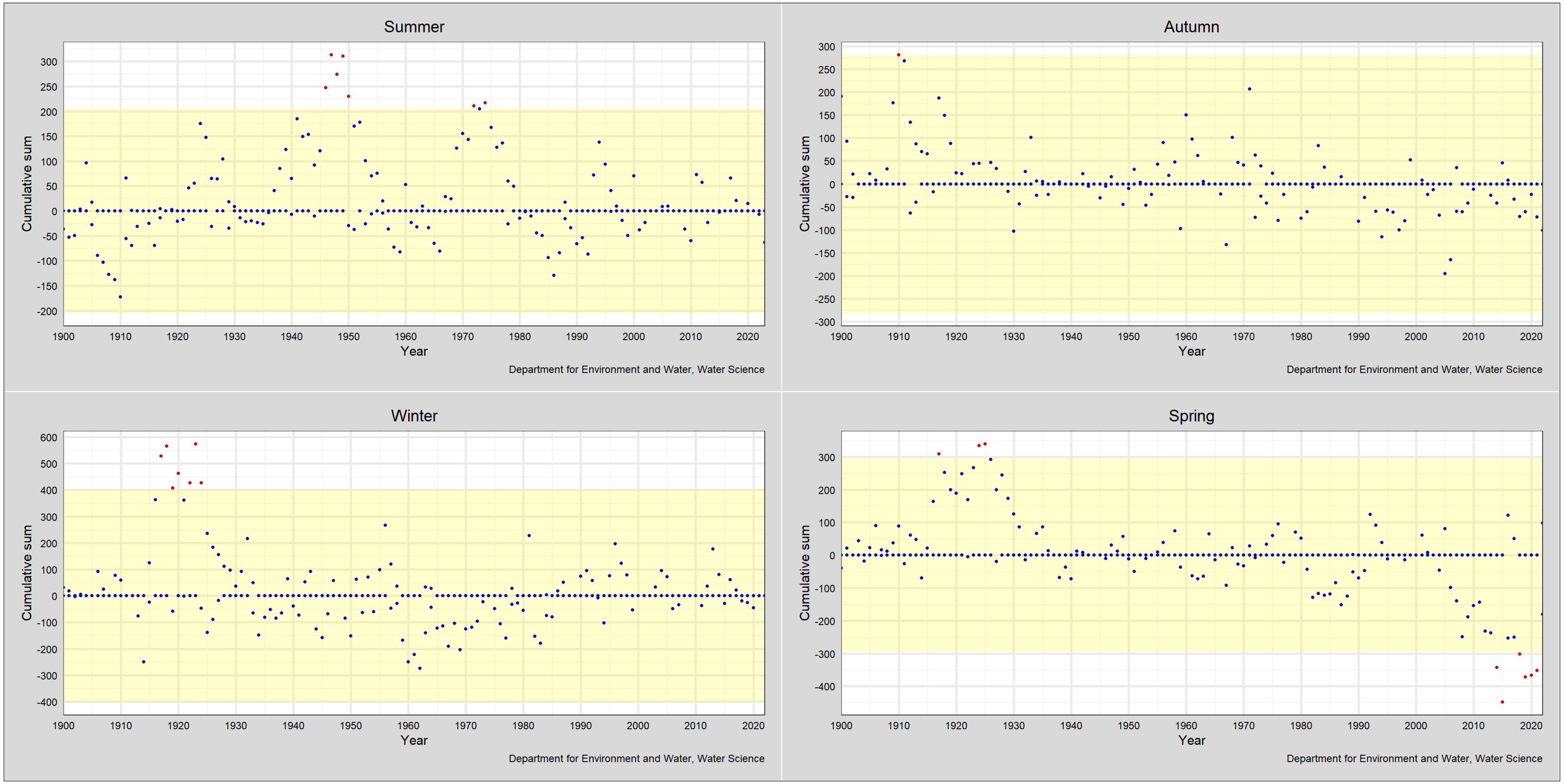


Figure 7. CUSUM charts of seasonal rainfall (1900 to 2022) for Meadows (BOM site 23730)

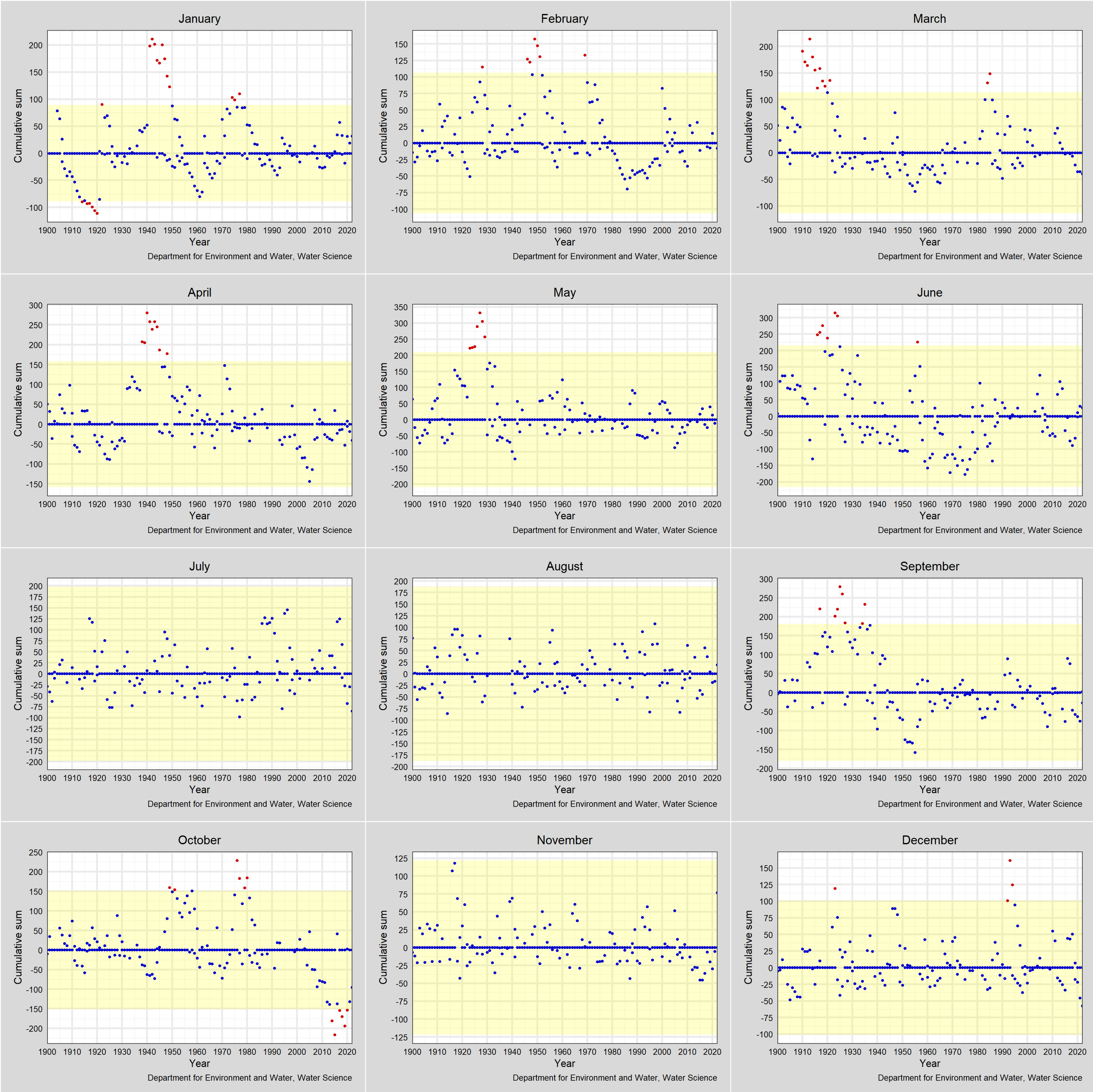


Figure 8. CUSUM charts of monthly rainfall (1900 to 2022) for Meadows (BOM site 23730)

Table 10 summarises the results of the statistical tests for data from Meadows. For the Mann-Kendall Test, a negative 'tau' value indicates that a time series has a monotonic downward trend, and vice versa, and a 'p' value less than 0.05 indicates that the trend is statistically significant at a 5% level. These are highlighted in red in the table. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate the presence of a monotonic trends but with a slightly lesser degree of statistical significance (between 5% and 10%).

For the Wilcoxon and Welch's tests, a p value less than 0.05 indicates that there is a significant difference or 'shift' (at a 5% level) in the distribution of 2 samples that represent observations across different periods. These are highlighted in red in the table. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate a shift, but with a lesser degree of statistical significance (between 5% and 10%).

Results of the statistical tests presented in Table 10 show:

- The Mann-Kendall test shows evidence of statistically significant declining trends in long-term (from 1900) annual, seasonal (in autumn and spring) and monthly rainfall (April, September and October).
- Wilcoxon and Welch's tests show evidence of statistically significant shifts:
  - between pre- and post-1996 periods, in annual, seasonal (autumn and spring) and monthly (April, September and October) rainfall.
  - between WAP development and post-WAP development periods, in seasonal median (spring) and October median and mean rainfall.

Table 10. Summary of statistical tests for separating rainfall data for Meadows (BOM site 23730) at different years, and aggregating across various periods

Period	Mann-Kendall (1900-2022)		Drought periods (pre- and post-1996)		WAP periods (WAP dev. and post-WAP dev)	
	tau	p value	Wilcoxon *p value*	Welch's p value	Wilcoxon *p value*	Welch's p value
Annual	-0.179	0.003	0.016	0.015	0.116	0.237
Summer	0.019	0.761	0.558	0.376	0.673	0.668
Autumn	-0.170	0.005	0.009	0.008	0.288	0.440
Winter	-0.029	0.635	0.588	0.498	0.551	0.517
Spring	-0.171	0.005	0.016	0.030	0.026	0.077
Jan	0.084	0.171	0.830	0.564	0.762	0.791
Feb	-0.013	0.832	0.506	0.429	0.707	0.682
Mar	-0.052	0.385	0.426	0.163	0.268	0.098
Apr	-0.121	0.048	0.008	0.010	0.513	0.624
May	-0.055	0.364	0.481	0.227	0.621	0.642
Jun	-0.058	0.343	0.676	0.556	0.424	0.396
Jul	0.010	0.875	0.510	0.532	0.580	0.590
Aug	-0.007	0.916	0.411	0.398	0.538	0.544
Sept	-0.131	0.032	*0.097*	*0.075*	0.173	0.298
Oct	*-0.117*	*0.054*	0.028	0.022	0.033	0.019
Nov	-0.041	0.504	0.256	0.281	0.244	0.283
Dec	-0.019	0.756	0.362	0.277	0.297	0.383

These results suggest that there is a statistically significant declining trend in long-term annual rainfall at the Meadows (23730) site, driven by the autumn and spring months. A period of changed rainfall behaviour is more clearly apparent from the start of the Millennium drought, and the impacts of this change again occur in total rainfall during spring and autumn seasons.

Statistical analysis summary of Macclesfield (BoM site 23728)

Analyses and results of rainfall records at Macclesfield (BoM site 23728) are provided in Appendices 7.2 and 7.3, with a summary of the statistical analysis as follows:

- Review of annual rainfall total CUSUM plots provide results similar to that of Meadows (BoM site 23730)
- Mann-Kendall analysis suggests a significant decreasing trend in annual, spring and autumn rainfall when considered in the context of drought-related periods, with the months of September and October showing the most significant parts of the decreasing trend. In the context of WAP-related periods, the most significant decrease occurred in spring, specifically in the month of October.
- Tests of whether a decrease in rainfall has occurred in the period since 1996 compared to pre-drought (Wilcoxon rank sum and Welch's t-test) suggest significant evidence of a shift in annual, spring and autumn periods, with April, September and October being the months displaying the most significant shifts. In the WAP period context, a significant shift is detected only in spring, in the month of October.

In the context of annual rainfall over WAP-related periods (from 1974 onwards), no statistically significant trend or shift is apparent.

3.2 Bremer River catchment

3.2.1 Overview of rainfall sites

Six rainfall (BoM) sites were selected in the Bremer River catchment, based on the criteria outlined in Section 2.2. The locations of the stations broadly represent the spatial change in elevation and rainfall within the catchment, as shown in Figure 2. The Mount Barker and Nairne stations are in the higher elevation, headwater areas of the catchment that generate the majority of runoff contributing to the overall streamflow in the Bremer river. Kanmantoo, Callington and Langhorne Creek are located in the progressively declining alitudes and rainfall within the catchment. The contribution of runoff from these sections of the catchment towards the overall streamflow in the Bremer river is considered to be relatively low. The sites selected and overall quality of data within the SILO records for those sites for the period 1900 to 2022 are summarised in Table 11. Each of these 6 stations has over 90% of daily data recorded by the BoM.

Table 11. Rainfall sites and SILO quality codes (1900 to 2022) in the Bremer catchment

Site ID	Site name	Catchment	SILO Data Quality Codes		
			0	15	25
23733	Mount Barker	Bremer	99%	1%	0%
24515	Langhorne Creek	Bremer	98%	2%	<1%
23724	Kanmantoo	Bremer	97%	3%	<1%
23722	Harrogate	Bremer	96%	2%	2%
24508	Callington	Bremer	94%	6%	<1%
23739	Nairne	Bremer	93%	6%	1%

3.2.2 Annual Rainfall – All sites

Table 12 summarises statistics for annual rainfall collated from the 6 sites in the Bremer River catchment. These statistics demonstrate that the catchment has a diverse climate, with the upper reaches of the catchment being considerably wetter than the downstream parts of the catchment.

Table 12. Summary statistics for selected annual rainfall data (mm) for Bremer River catchment (1900 to 2022)

Statistics	Mount Barker (23733)	Nairne (23739)	Harrogate (23722)	Kanmantoo (23724)	Langhorne Ck (24515)	Callington (24508)
Annual average	759	669	567	474	388	380
Annual median	731	653	574	476	384	381
Annual maximum	1,294	1,088	1,085	823	639	751
Annual minimum	382	346	248	209	202	148
Standard deviation	160	143	131	110	85	90

Figure 9 shows the distribution of annual rainfall for the 6 rainfall sites in the Bremer River catchment across the drought-related periods as boxplots, while Figure 10 shows the distribution of annual rainfall between the WAP development and post-WAP development phases for the 6 sites, while Table 14 shows the absolute medians and relative changes. At 5 of these sites (except for Nairne), median annual rainfall increased during the post-WAP development phase by amounts ranging from 4% (Callington) to 13% (Kanmantoo). The distribution of annual rainfall for the last 15 years (Post-WAP development) at each of the stations generally shows a normal distribution with some tending towards negative skewness (Mount Barker, Harrogate and Kanmantoo). At Nairne the IQR appears similar between WAP development and post-WAP development periods, with a narrower variation between minimum and maximum values in the post-WAP development period.

Table 13 shows the absolute median values and relative changes across the various drought-related periods. In 5 of these stations (except for Callington), median annual rainfall reduced during the drought period compared to pre-drought conditions by amounts ranging from 4% (Mount Barker and Harrogate) to 12% (Nairne). In the case of Callington, only a minor difference between pre-drought and drought periods was shown (3% change), with the drought period distribution showing a significant negative skewness. Median annual rainfall increased in the post-drought period relative to drought for all sites. In 5 of these stations (except for Nairne) median rainfall in the post-drought period exceeded the median rainfall for the pre-drought period by amounts varying from 4% (Kanmantoo) to 12% (Callington), representing the wettest period. At Nairne, a relatively small difference between post-drought and pre-drought medians is shown (post-drought reduced by 3% from pre-drought).

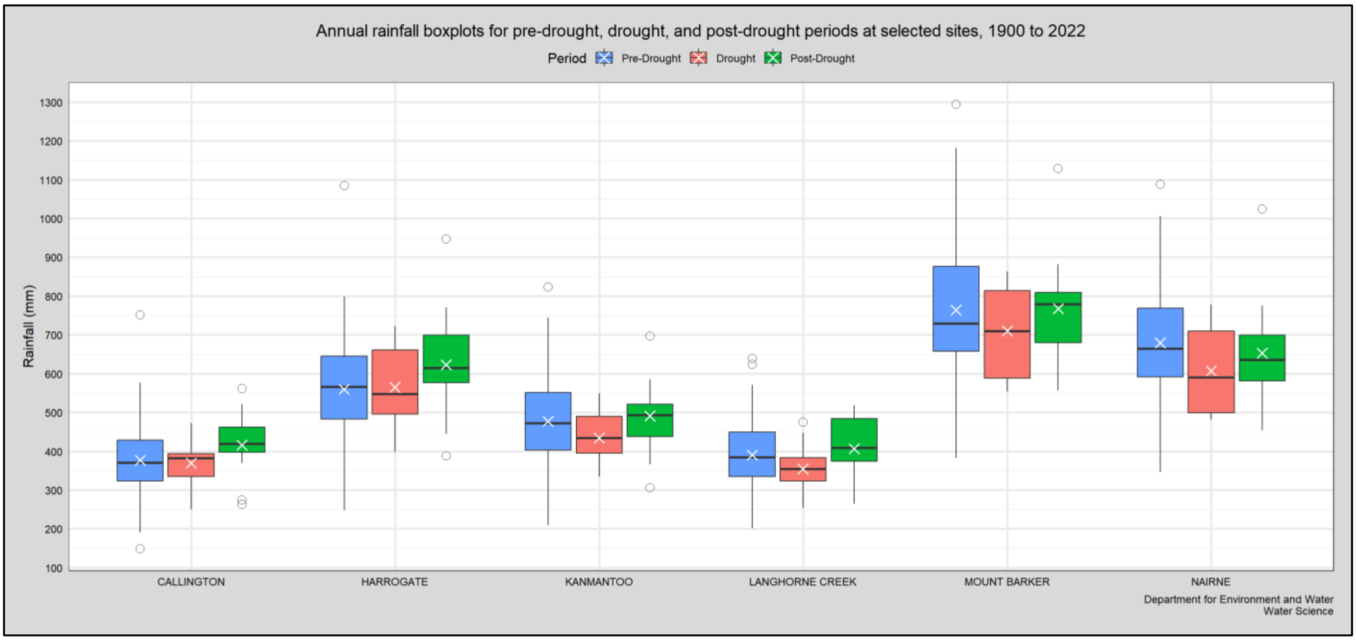


Figure 9. Distribution of annual rainfall in Bremer River catchment during drought-related periods (median (—), average (X), and outliers (O) shown)

Figure 10 shows the distribution of annual rainfall between the WAP development and post-WAP development phases for the 6 sites, while Table 14 shows the absolute medians and relative changes. At 5 of these sites (except for Nairne), median annual rainfall increased during the post-WAP development phase by amounts ranging from 4% (Callington) to 13% (Kanmantoo). The distribution of annual rainfall for the last 15 years (Post-WAP development) at each of the stations generally shows a normal distribution with some tending towards negative skewness (Mount Barker, Harrogate and Kanmantoo). At Nairne the IQR appears similar between WAP development and post-WAP development periods, with a narrower variation between minimum and maximum values in the post-WAP development period.

Table 13. Median annual rainfall (mm) for different periods for the Bremer River catchment (1900 to 2022)

Period	Mount Barker (23733)	Nairne (23739)	Harrogate (23722)	Kanmantoo (23724)	Langhorne Ck (24515)	Callington (24508)
All years (1900 to 2022)	731	653	574	476	384	381
Pre-drought (1900 to 1996)	729	664	567	472	384	370
Drought (1997 to 2008)	699	587	544	420	343	380
Post-drought (2009 to 2022)	782	643	616	492	407	416
Change compared to Pre-drought						
Drought (%)	-30 (-4%)	-77 (-12%)	-23 (-4%)	-53 (-11%)	-41 (-11%)	10 (3%)
Post-drought (mm)	53 (7%)	-21 (-3%)	50 (9%)	20 (4%)	23 (6%)	46 (12%)

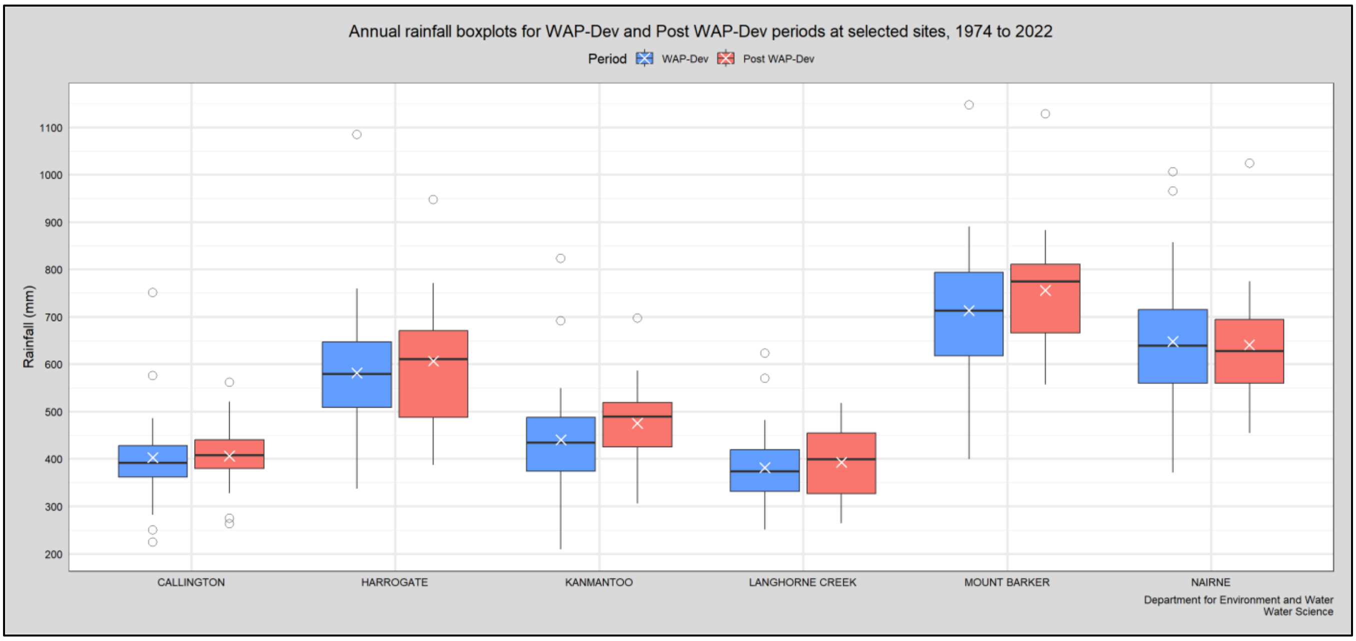


Figure 10. Distribution of annual rainfall in Bremer River catchment during WAP periods (median (—), average (X), and outliers (O) shown)

Table 14. Median annual rainfall (mm) for different WAP periods across the Bremer River catchment (1900 to 2022)

Period	Mount Barker (23733)	Nairne (23739)	Harrogate (23722)	Kanmantoo (23724)	Langhorne Ck (24515)	Callington (24508)
All years (1900 to 2022)	731	653	574	476	384	381
Pre-WAP (1900 to2006)	728	658	567	468	382	371
WAP development (1974 to 2006)	713	639	579	434	374	392
Post-WAP development (2007 to 2022)	775	628	611	490	400	408
Change (WAP dev. to Post-WAP dev.)	62 (9%)	-11 (-2%)	32 (5%)	56 (13%)	26 (7%)	16 (4%)

3.2.3 Detailed rainfall analyses – Nairne (23739)

The time series of rainfall from Nairne (23739) is analysed in the following plots. Data from Nairne was chosen for presentation of results in this section given the site (along with Mt Barker) is located in one of the headwater areas that generate the majority of runoff contributing to streamflow in the Bremer River. It also shows some differing results to the other rainfall stations in the catchment that require closer scrutiny.

Annual rainfall analysis

Rainfall totals for Nairne (23739) at annual and decadal levels, with various period medians and trends included, are plotted in Figure 11(a) to (f). The trends of annual rainfall and decadal medians suggest gradually drying conditions over the period of record from 1900 to 2022, with the last 3 decades representing the lowest median decadal rainfall values on record (refer to Figure 11(a), (b), (e) and (f)). Annual deviations from the long-term median rainfall for Nairne (23739), shown in Figure 11(b), indicates that 2 of the past 10 years were considered 'above-median' years, as per the classification in Table 1.

Medians for the drought-related periods (Figure 11(c)) show that median rainfall of the drought period is substantially below the long-term and pre-drought median, while the post-drought median has recovered to similar values for the long-term and pre-drought medians. For WAP development and post-WAP development periods (Figure 11(d)) the data indicate similar median values between the 2 periods, both of which are below the long-term median.

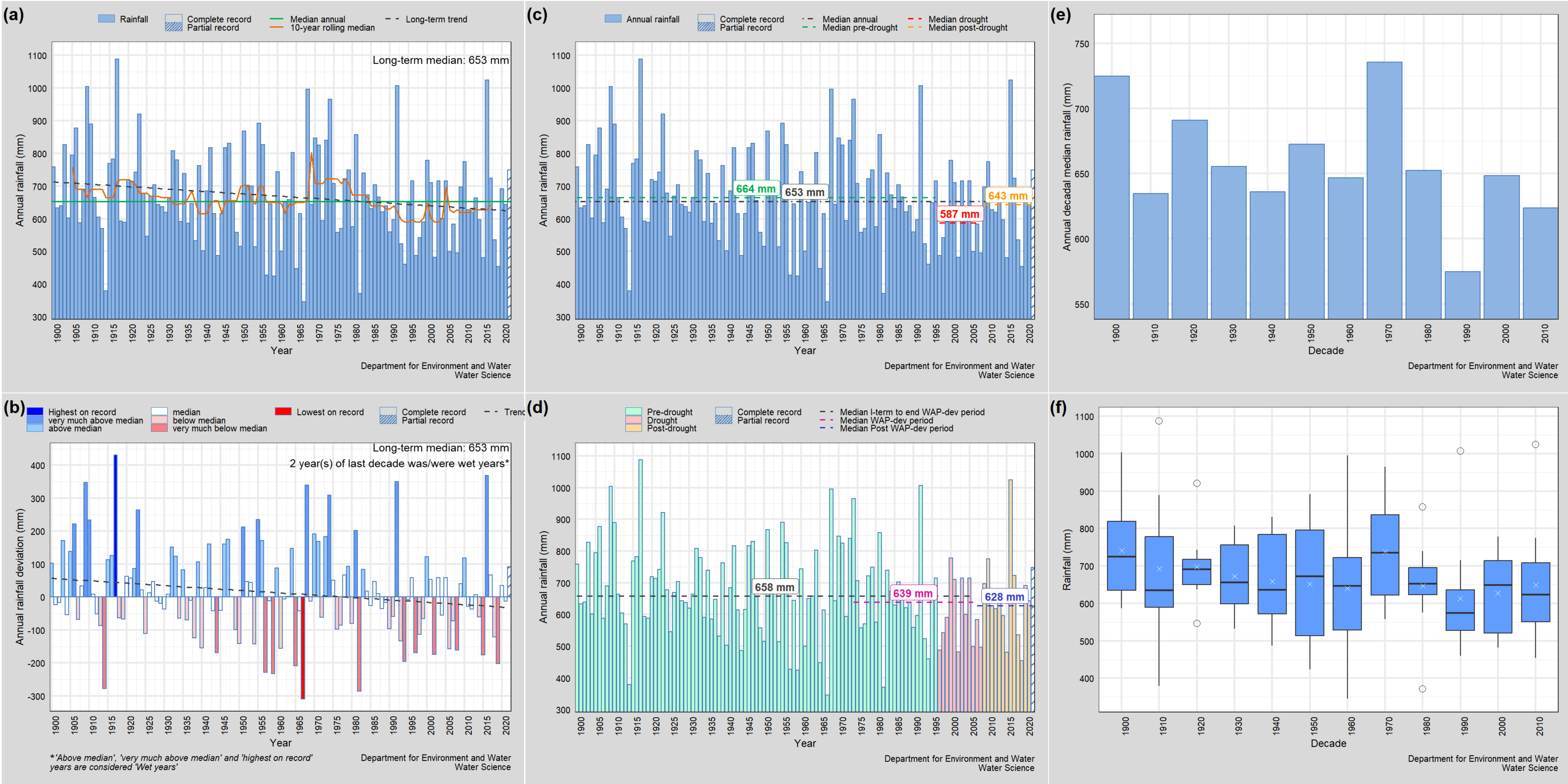


Figure 11. Rainfall plots at Nairne (BOM site 23739) for 1900 to 2022 showing (a) long-term median, 10-year rolling median and linear trend, (b) deviation of annual rainfall from long-term median with linear trend, (c) annual rainfall showing median values of drought-related periods, (d) annual rainfall showing median values during the WAP development and Post-WAP-development periods, (e) median annual rainfall per decade, (f) boxplots of distribution of annual median rainfall per decade.

Seasonal rainfall analysis

The previous section outlined evidence showing drier conditions at the Nairne rainfall station in recent decades when rainfall was analysed at annual and decadal timescales, but with indications of potential recovery to pre-drought conditions for the post-drought period. To further investigate the rainfall at this station in terms of its seasonal behaviour, historical daily rainfall at Nairne (23739) was aggregated to seasonal totals and compared on a season-by-season basis.

Table 15 summarises median seasonal rainfall over the 3 drought-related climate periods used, together with the difference in annual and seasonal medians during the drought and post-drought periods in comparison to the pre-drought medians. This shows:

- The post-drought winter median is the highest in the comparison periods (wettest) and is the only season to show an increase in the post-drought period median relative to pre-drought (by 15%).
- Total rainfall during autumn and spring generally accounts for almost 50% of annual rainfall. Median post-drought rainfall for autumn was the lowest in all the comparison periods for autumn (driest), while spring had similar medians in both drought and post-drought periods that were both below the pre-drought median (16 to 17% lower).
- Summer median rainfall was the lowest of all the seasons (approximately 10% of annual total) and remained relatively consistent across the comparison periods at around 65 to 67 mm.

These results suggest that the relative increase in winter rainfall in the post-drought from the pre-drought period has masked the relative decrease experienced in the autumn and winter periods, indicating the wet season has been effectively compressed in recent times, occurring in the winter months to a larger degree than historically experienced.

Table 15. Median seasonal rainfall (mm) for Nairne (BOM site 23739) for different periods around the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought mm (%)	Post-drought mm (%)
Summer	66	67	65	66	-2 (-3%)	-1 (-1%)
Autumn	150	150	138	121	-12 (-8%)	-29 (-19%)
Winter	256	256	231	294	-24 (-10%)	39 (15%)
Spring	162	169	141	143	-29 (-17%)	-26 (-16%)
Annual	**653**	**664**	**587**	**643**	**-77 (-12%)**	**-21 (-3%)**

Table 16 summarises seasonal median rainfall totals for the periods that describe the development and post-development of the WAP. These results demonstrate similar outcomes to the analysis of drought-related periods, in that the post-WAP development phase (2007 onwards) is typified by significant reductions in median rainfall during spring and autumn (15% and 17%, respectively) and higher winter rainfall (increase of 54 mm or 22%) when compared to the period used for WAP development (1974 to 2006).

Table 16. Median seasonal rainfall (mm) for Nairne (BOM site 23739) for different WAP development periods

Season	All years	WAP development	Post-WAP-development	Change (WAP-dev. to Post WAP-dev.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Summer	66	64	66	2	3%
Autumn	150	150	124	-26	-17%
Winter	256	241	294	54	22%
Spring	162	153	130	-23	-15%
Annual	**653**	**587**	**643**	**-11**	**-2%**

Monthly rainfall analysis

Table 17 summarises median rainfall for each calendar month for the 3-drought related periods and the relative change in medians of drought and post-drought periods from pre-drought. The results indicate:

- During the drought period, the greatest percentage reductions in median rainfall were observed in the months of September (15%), October (15%) and April (13%), with a more minor reduction in May (8%). Conversely, an increase of over 50% was observed in December, with other months showing a substantial increase being August (14%) and November (19%). Rainfall in January, February, March and July each showed less than 2 mm variation from the pre-drought median.
- Winter months (June, July and August) have recovered to, or increased above, pre-drought conditions, with June showing the largest increase (15%).
- Spring months (September, October and November) have shown a decrease in post-drought median rainfall from pre-drought, with October showing the largest decrease (29%).
- October (followed by April) was the most impacted across the drought periods, with the monthly median decreasing progressively through the 3 comparison periods (driest).
- June has been on the other end of the spectrum, with the monthly median increasing progressively through the 3comparison periods (wettest).

Table 18 summarises median monthly rainfall for periods that define the development and implementation of the WAP, with changes in median monthly rainfall recorded during the post-WAP development phase compared to the WAP development period also shown. These results show that reductions in rainfall during September (32%) and October (32%) remain the key changes in which climatic impacts are observed to affect the post-WAP development relative to WAP development periods, with November (11 mm or 29%) and April (6 mm or 14%) also showing reductions. Other months show median rainfalls that are largely consistent across the 2 WAP-related periods, remaining within 4 mm between the medians.

Table 17. **Median monthly rainfall (mm) for Nairne (BOM site 23739) for different periods relative to the drought**

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
					Drought	Post-drought
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	mm (%)	mm (%)
Jan	18	17	19	18	2 (9%)	1 (4%)
Feb	15	15	14	15	-2 (-10%)	0 (-1%)
Mar	19	20	21	19	1 (6%)	-1 (-3%)
Apr	42	44	38	34	-6 (-13%)	-10 (-23%)
May	66	67	62	64	-5 (-8%)	-3 (-4%)
Jun	76	73	80	84	7 (9%)	11 (15%)
Jul	89	88	86	90	-2 (-2%)	2 (2%)
Aug	85	83	94	89	12 (14%)	6 (7%)
Sep	70	73	62	68	-11 (-15%)	-5 (-7%)
Oct	51	57	49	41	-8 (-15%)	-17 (-29%)
Nov	33	33	40	26	6 (19%)	-7 (-21%)
Dec	25	24	36	21	12 (51%)	-4 (-15%)
Annual	**653**	**664**	**587**	**643**	**-77 (-12%)**	**-21 (-3%)**

Table 18. **Median monthly rainfall (mm) for Nairne (BOM site 23739) for different periods around WAP development**

Month	All years	WAP develop ment	Post-WAP development	Change (WAP dev to imp.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Jan	18	20	18	-2	-9%
Feb	15	13	15	2	16%
Mar	19	21	19	-2	-9%
Apr	42	41	36	-6	-14%
May	66	64	64	0	0%
Jun	76	81	82	1	1%
Jul	89	92	90	-1	-2%
Aug	85	92	89	-4	-4%
Sep	70	70	48	-22	-32%
Oct	51	51	35	-16	-32%
Nov	33	37	26	-11	-29%
Dec	25	25	22	-3	-12%
Annual	**653**	**587**	**643**	**-11**	**-2%**

3.2.4 Trend and shift analyses of rainfall

Detailed analysis of Nairne (23739)

CUSUM charts were prepared for the time series of rainfall at Nairne (23739) aggregated to annual totals (Figure 12). The annual CUSUM chart does not show any data points falling outside of the action bounds (yellow shading). The cumulative sum has generally remained below the long-term mean since the early 1990s, other than the occasional year just above the mean, and years impacted by high rainfall in the 2010s. No significant evidence of a trend in CUSUM is apparent in the period since commencement of the drought.

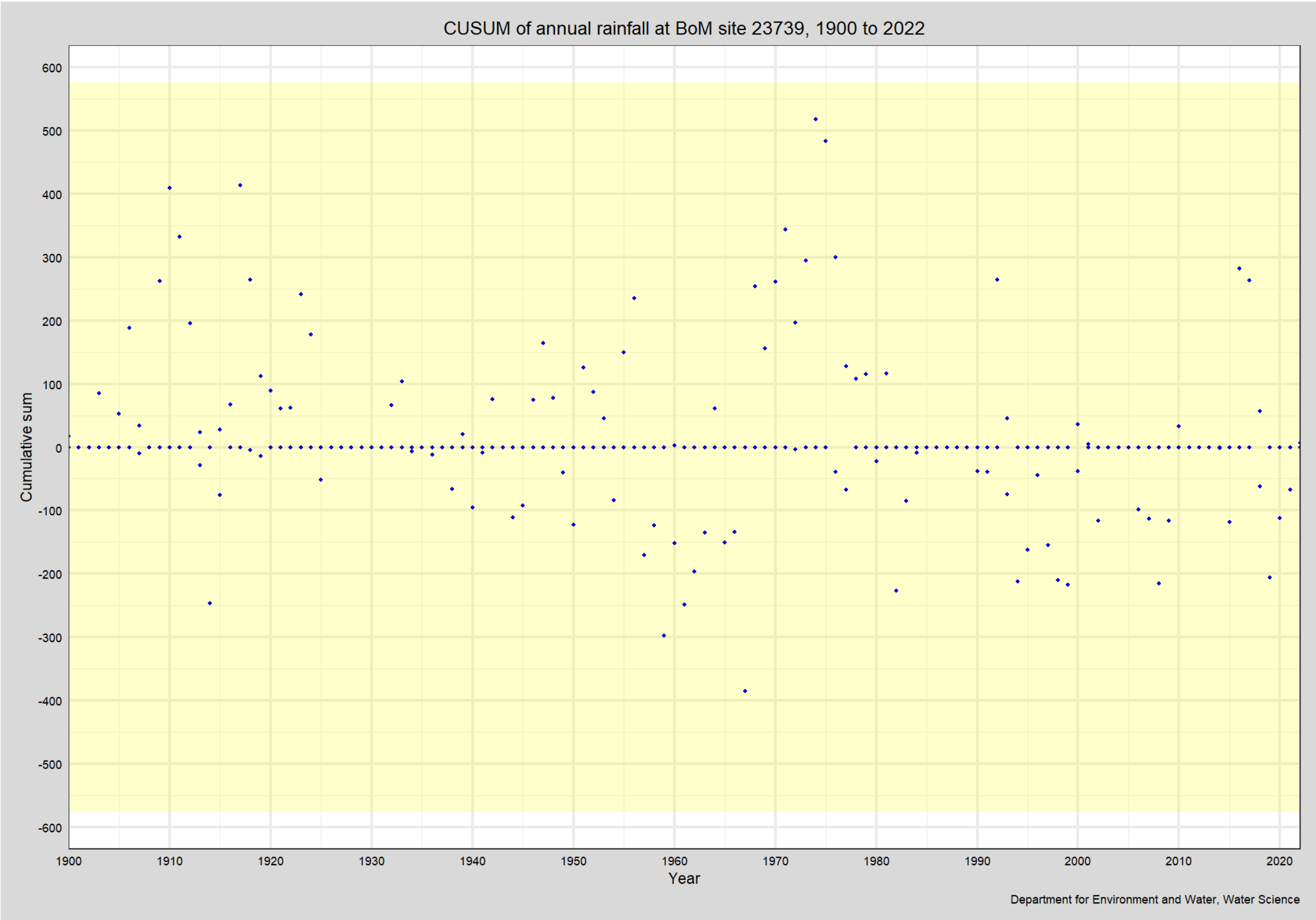


Figure 12. CUSUM chart of annual rainfall (1900 to 2022) for Nairne (BOM site 23739)

Figure 13 shows the CUSUM charts of seasonal rainfall totals. These results show:

- The cumulative sums of summer and winter rainfall during the last few decades are generally distributed close to the long-term mean and remained within the action limits.
- Spring and autumn rainfall show that the majority of data points since the 1990s sit below the long-term mean. In both seasons the data points track towards the lower action limits within this period; autumn shows the cumulative sum decrease towards the lower action limit by the end of the 1990s before gradually increasing back towards the long-term mean over the rest of the period, while spring shows a data point fall outside the lower action limit in the mid-2010s, and largely remaining between the long-term mean and lower action limit for the remainder of the period. This supports previous analysis showing declining spring and autumn rainfall in the post-drought period.

Figure 14 shows CUSUM charts of monthly rainfall totals. These results indicate:

- October rainfall totals reveal a significant downward trend in its cumulative sum since the commencement of the Millennium drought and a single data point falling outside the action limits in the mid-2010s, aligning closely with the behaviour for spring. No other calendar months showed data points falling outside the action limits in a CUSUM analysis for this recent period, although rainfall in the majority of months has shown temporary increases above the upper action limit during the pre-drought period (that is, January to June, October and December), coinciding with high rainfall years.
- May rainfall shows a similar behaviour to the autumn cumulative sum, decreasing towards the lower action limit across the 1990s before gradually increasing towards the long-term mean by the 2010s.
- High rainfall years in early- and mid-2010s are indicated by some temporary 'jumps' in cumulative sum above the long-term mean in certain months, such as February, March, September and December.

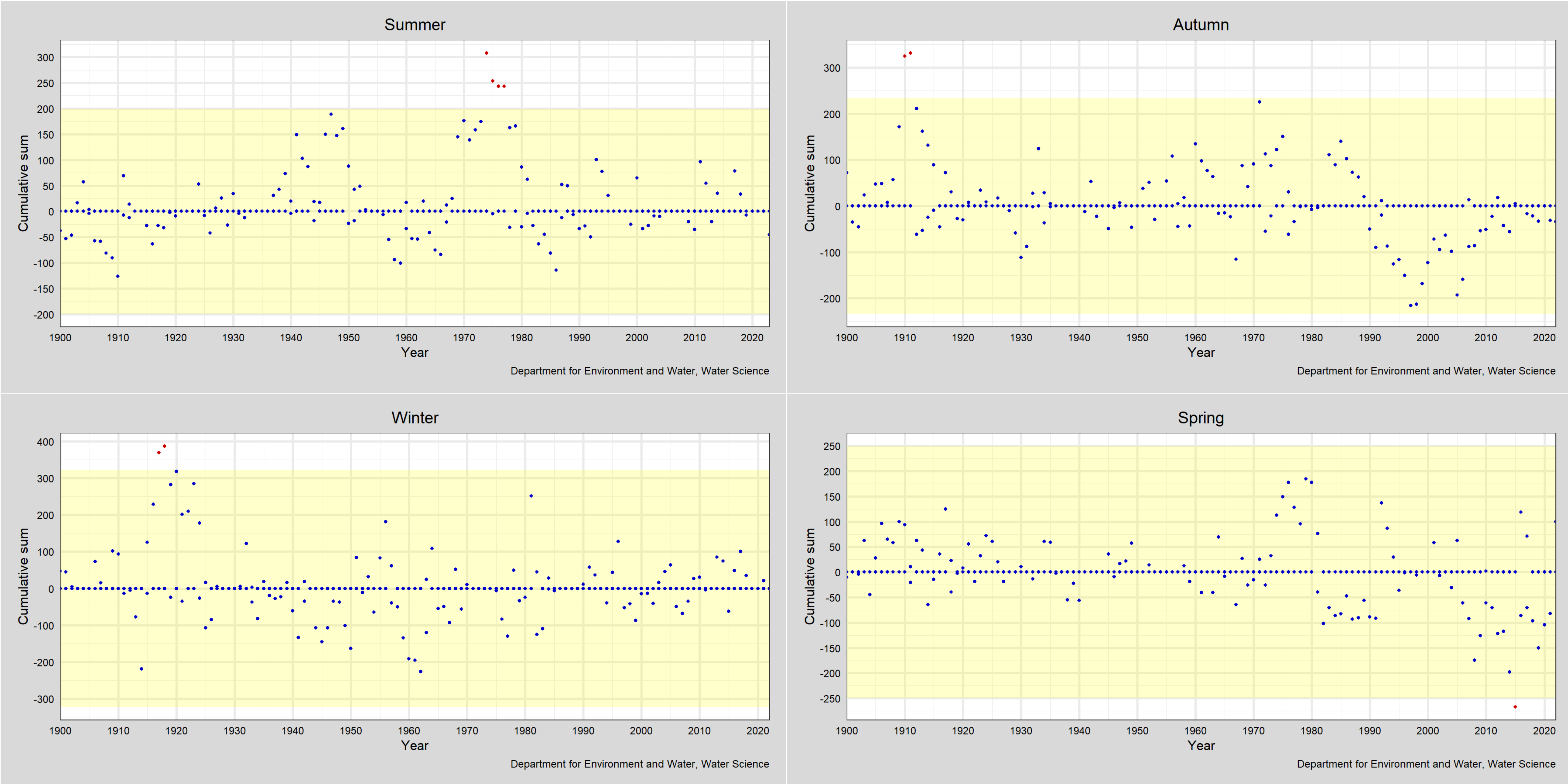


Figure 13. CUSUM charts of seasonal rainfall (1900 to 2022) for Nairne (BOM site 23739)

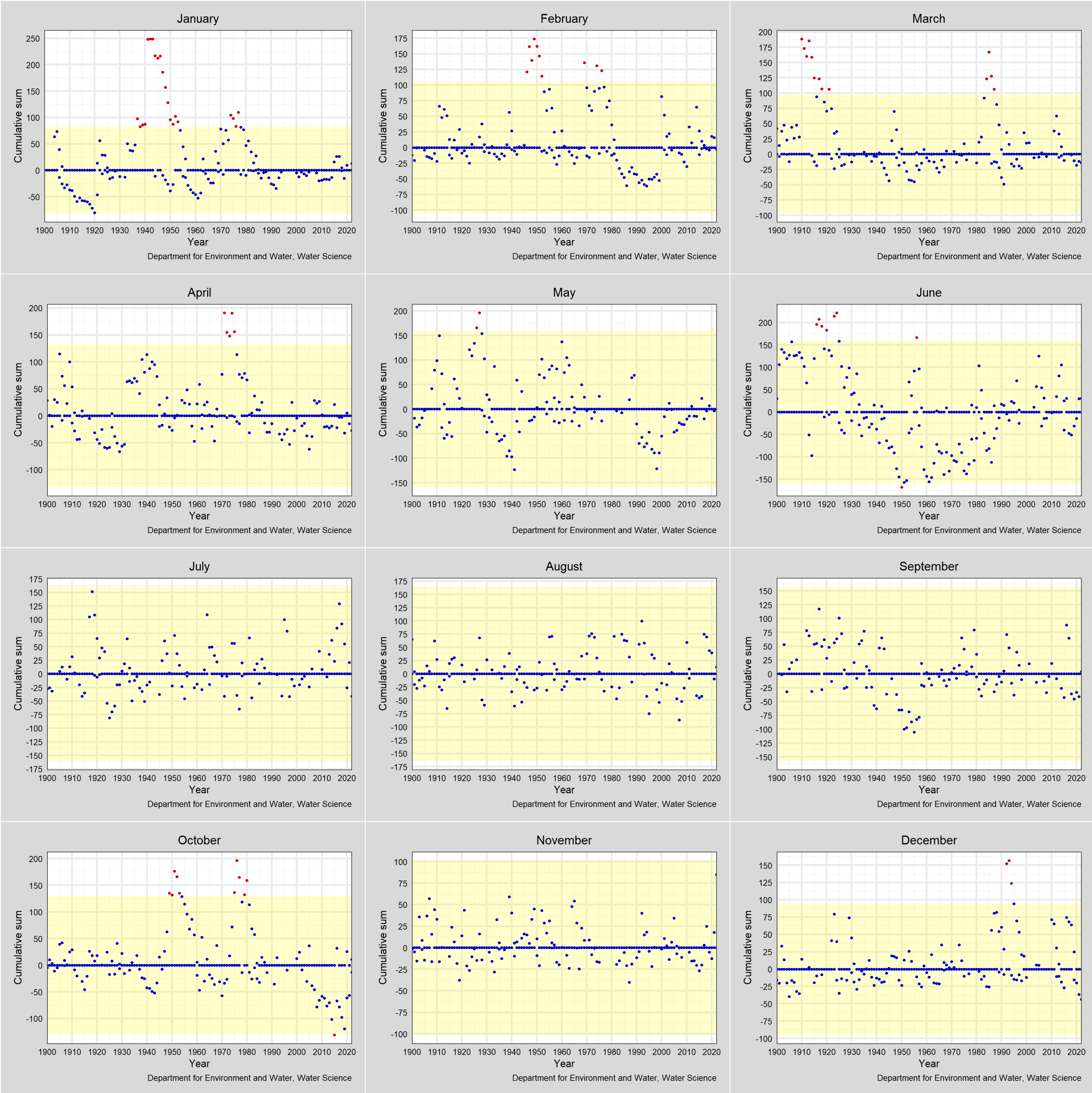


Figure 14. CUSUM charts of monthly rainfall (1900 to 2022) for Nairne (BOM site 23739)

Table 19 summarises the results of the statistical tests for data from Nairne. Results for the other sites are provided in Appendices 7.3 and 7.4. Further explanation of the tests is provided in section 2.7. For the Mann-Kendall Test, a negative 'tau' value indicates that a time series has a monotonic downward trend, and vice versa, and a p value less than 0.05 indicates that the trend is statistically significant at a 5% level. These are highlighted in red. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate the presence of a monotonic trend but with a slightly lesser degree of statistical significance (between 5% and 10%).

For the Wilcoxon and Welch's tests, a p value less than 0.05 indicates that there is a significant difference or shift (at a 5% level) in median value of 2 samples that represent observations across different periods. These are highlighted in red in the table. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate a shift, but with a lesser degree of statistical significance (between 5% and 10%).

Table 19. Summary of statistical tests for separating rainfall data for Nairne (BOM site 23739) at different years, and aggregating across various periods

Period	**Mann-Kendall (1900-To 2022)**		**Drought periods (pre- and post-1996)**		**WAP-development (pre- and post-2007)**	
	tau	**p value**	**Wilcoxon *p value***	**Welch's p value**	**Wilcoxon *p value***	**Welch's p value**
Annual	-0.120	0.050	*0.054*	*0.061*	0.445	0.496
Summer	0.027	0.656	0.558	0.415	0.779	0.666
Autumn	*-0.117*	*0.055*	*0.055*	0.008	0.421	0.445
Winter	0.002	0.977	0.664	0.558	0.853	0.753
Spring	-0.148	0.015	*0.057*	0.109	0.129	0.180
Jan	0.049	0.419	0.650	0.153	0.707	0.625
Feb	-0.019	0.755	0.635	0.550	0.762	0.720
Mar	-0.046	0.452	0.551	0.239	0.449	0.231
Apr	-0.069	0.259	0.035	0.019	0.513	0.498
May	-0.045	0.460	0.377	0.108	0.653	0.662
Jun	-0.033	0.594	0.797	0.728	0.645	0.595
Jul	0.031	0.615	0.504	0.514	0.707	0.748
Aug	-0.003	0.965	0.376	0.339	0.657	0.595
Sept	*-0.109*	*0.075*	0.112	0.100	0.190	0.252
Oct	*-0.114*	*0.061*	*0.055*	*0.051*	0.046	0.050
Nov	0.020	0.743	0.745	0.699	0.526	0.672
Dec	0.039	0.529	0.511	0.533	0.317	0.524

Results of the statistical tests presented in the table show:

- The Mann-Kendall test shows evidence of statistically significant declining trends in long-term annual, seasonal (in autumn and spring) and monthly rainfall (September and October).
- Wilcoxon and Welch's tests show evidence of statistically significant shifts:
  - between pre- and post-1996 periods, in annual, seasonal (autumn and spring) and monthly (April and October) rainfall
  - between WAP development and post-WAP development periods, in October rainfall.

These results suggest that a period of changed climate is evident from the start of the Millennium drought that has had a more seasonal impact on rainfall patterns. These impacts at the Nairne (23739) site have been shown to occur predominantly during spring and autumn periods.

Statistical analysis summary of other Bremer catchment sites

Review of the statistical analysis of annual, seasonal and rainfall totals for other sites in the Bremer catchment is summarised below:

- Review of annual rainfall total CUSUM plots for other stations within the Bremer catchment provides insufficient evidence of any shifts in rainfall on an annual basis since the start of the Millennium drought.
- Mount Barker (23733) – Since the commencement of the drought, CUSUM analysis has indicated spring and autumn have shifted below the long-term mean, while summer and winter rainfall has remained relatively close to the long-term mean. Long-term trends (Mann-Kendall) indicate decreasing trends in annual, spring (especially October) and autumn periods. Wilcoxon rank sum and Welch's t-test suggests statistically significant shifts have occurred since the commencement of the drought for autumn (April) and October, but not with annual rainfall. In the WAP-related context, only October shows a shift of significance in post-WAP development period rainfall.
- Harrogate (23722) – Since the early 1990s, the majority of CUSUM data points during the last few decades have shown historically high rainfall in winter and summer seasons. These results are reflected in the long-term trends (Mann-Kendall) with winter (July) and summer (January) each showing significant increasing trends. Comparing periods either side of 1996 shows no significant negative shifts in rainfall, however (Wilcoxon rank sum/Welch's t-test). In the context of WAP-related periods, October shows a negative shift in rainfall in the post-WAP development period (Wilcoxon rank sum/Welch's t-test).
- Kanmantoo (23724) – There is little evidence of any sustained seasonal shifts in rainfall based on CUSUM analysis. Only January shows a significant increasing trend in rainfall (Mann-Kendall), while a shift in rainfall since the start of the drought was detected in Autumn and the month of October (Wilcoxon rank sum/Welch's t-test). In a WAP-related context, only October shows a significant negative shift in rainfall in the post-WAP development period (Wilcoxon rank sum/Welch's t-test).
- Langhorne Creek (24515) – Similar to Kanmantoo, there is little evidence of any sustained seasonal shifts in rainfall based on CUSUM analysis since 1996, although long-term trends (Mann-Kendall) suggest a significant increasing trend in summer, specifically in January. No evidence of a statistically significant shift in rainfall was detected either post-1996 or post-WAP development (Wilcoxon rank sum/Welch's t-test).
- Callington (24508) – CUSUM analysis shows summer and winter rainfall since the commencement of the drought has remained above the long-term mean. This is partially demonstrated in long-term trends, with summer showing a statistically significant increasing trend (Mann-Kendall). In the context of drought, no statistically significant negative shift was detected, while for WAP-related periods October showed a negative shift of significance (Wilcoxon rank sum/Welch's t-test).
- CUSUM data from 4 of the 5 stations (with Callington the exception) had a common feature in October rainfall totals, revealing a significant downward shift in its cumulative sum since the commencement of the Millennium drought.

3.3 Onkaparinga River catchment

3.3.1 Overview of rainfall stations

Six rainfall (BoM) sites were selected in the Onkaparinga River catchment, based on the criteria outlined in Section 2.2. The locations of the stations broadly represent the spatial change in elevation and rainfall within the catchment, as shown in Figure 2. The catchment has generally high rainfall throughout, with the Uraidla, Bridgewater and Cherry Gardens stations showing the highest annual rainfall totals. The sites selected and overall quality of data within the SILO records for those sites for the period 1900 to 2022 are summarised in Table 20. Three of these 6 stations have over 90% of daily data recorded by the BoM, with the remainder having between 84% and 87% of recorded data.

Table 20. Rainfall sites and SILO quality codes (1900 to 2022) in the Onkaparinga catchment

Site ID	Site name	Catchment	SILO Data Quality Codes		
			0	15	25
23750	Uraidla	Onkaparinga	92%	7%	1%
23707	Bridgewater Post Office	Onkaparinga	87%	11%	2%
23709	Cherry Gardens	Onkaparinga	96%	3%	1%
23726	Lobethal	Onkaparinga	86%	13%	1%
23720	Hahndorf Post Office	Onkaparinga	91%	7%	2%
23713	Echunga Golf Course	Onkaparinga	84%	11%	5%

3.3.2 Annual rainfall – all sites

Table 21 summarises statistics for annual rainfall collated from the 6 sites in the Onkaparinga River catchment. These statistics demonstrate that the catchment has a generally wet climate, with the lowest annual median rainfall of 784 mm at Echunga.

Table 21. Summary statistics for selected annual rainfall data (mm) for Onkaparinga River catchment (1900 to 2022)

Statistics	Uraidla (23750)	Bridgewater (23707)	Cherry Gardens (23709)	Lobethal (23726)	Hahndorf (23720)	Echunga (23713)
Annual average	1,088	1028	922	874	841	805
Annual median	1,059	1,007	918	886	823	784
Annual maximum	1791	1758	1379	1551	1356	1292
Annual minimum	561	482	427	441	383	414
Standard deviation	237	227	184	197	178	169

Figure 15 shows the distribution of annual rainfall for the 6 rainfall sites in the Onkaparinga River catchment across the drought-related periods as boxplots, while Table 22 shows the absolute median values and relative changes across the various drought-related periods. In 4 stations, median annual rainfall reduced during the drought period relative to pre-drought conditions, namely Hahndorf (14%), Cherry Gardens (8%), Lobethal (7%) and Echunga (5%). For the other two stations, Uraidla (the highest annual rainfall in the catchment) and Bridgewater (second highest annual rainfall) showed a relatively consistent median rainfall between the pre-drought and drought periods, varying by only 3% and -1%, respectively. The main difference apparent between pre-drought and drought period is the rainfall distribution at each site, with significantly lower maximum and minimum values (represented by the boxplot whiskers) during the drought period in each case. This suggests that there was less variation in annual rainfall totals relative to pre-drought, particular at the high rainfall end.

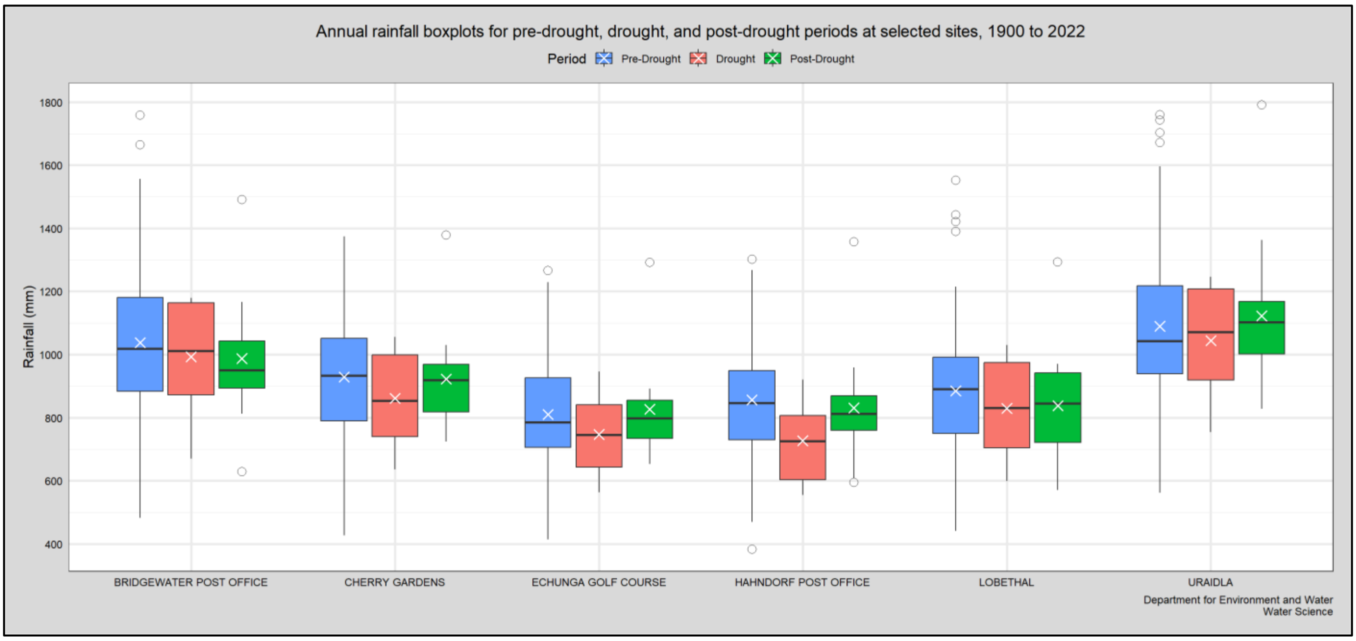


Figure 15. Distribution of annual rainfall in Onkaparinga River catchment during drought-related periods (median (—), average (X), and outliers (O) shown)

Table 22. Median annual rainfall (mm) for different periods for the Onkaparinga River catchment (1900 to 2022)

Period	Uraidla (23750)	Bridgewater (23707)	Cherry Gardens (23709)	Lobethal (23726)	Hahndorf (23720)	Echunga (23713)
All years (1900 to 2022)	1,059	1,007	918	886	823	784
Pre-drought (1900 to 1996)	1,042	1,018	933	891	846	785
Drought (1997 to 2008)	1,072	1,011	854	831	726	746
Post-drought (2009 to 2022)	1,103	950	919	845	812	798
Change compared to Pre-drought						
Drought (mm)	30	-7	-79	-60	-120	-39
(%)	(3%)	(-1%)	(-8%)	(-7%)	(-14%)	(-5%)
Post-drought (mm)	61	-68	-13	-46	-34	12
(%)	(6%)	(-7%)	(-1%)	(-5%)	(-4%)	(2%)

In the post-drought period, the change in rainfall behaviour relative to pre-drought was dependent on site location. Median rainfall was reduced at Bridgewater (7% less than that of the pre-drought period), Lobethal (5% less) and Hahndorf (4%). Recovery to pre-drought rainfall was indicated at Cherry Gardens and Echunga (less than 2% difference), while in Uraidla the median annual rainfall increased above pre-drought conditions (6%).

Figure 16 shows the distribution of annual rainfall between the WAP development and post-WAP development phases for the 6 sites, while Table 23 shows the absolute medians and relative changes related to the WAP periods. The difference in rainfall between WAP development and post-WAP development periods was again dependent on the location of each site. Median rainfall values were similar in each period at Cherry Gardens and Hahndorf (less than 2% difference), were lower in the post-WAP development period at Lobethal (5% less) and Bridgewater (4% less) and were higher at Uraidla (4%) and Echunga (5%). No consistent distribution changes were evident across the stations and comparison periods, with the data showing either normal distributions or various levels of skewness.

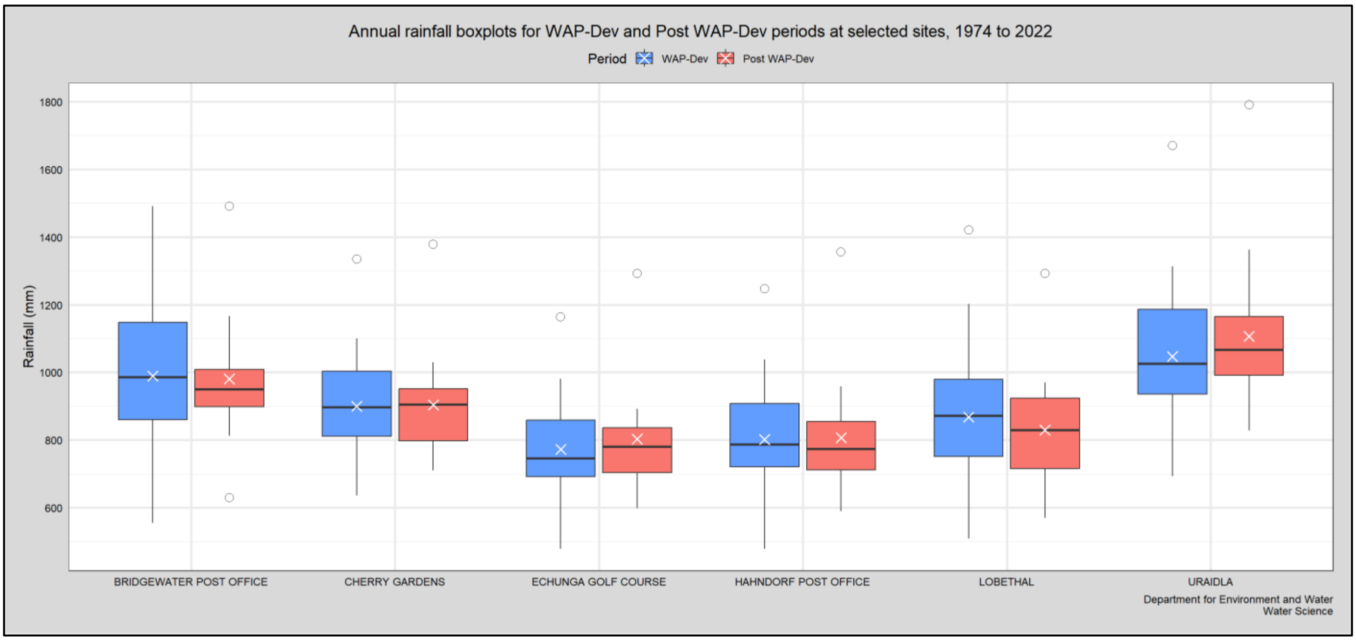


Figure 16. Distribution of annual rainfall in Onkaparinga River catchment during WAP periods (median (—), average (X), and outliers (O) shown)

Table 23. Median annual rainfall (mm) for different WAP periods across the Onkaparinga River catchment (1900 to 2022)

Period	Uraidla (23750)	Bridgewater (23707)	Cherry Gardens (23709)	Lobethal (23726)	Hahndorf (23720)	Echunga (23713)
All years (1900 to 2022)	1,059	1007	918	886	823	784
Pre-WAP (1900 to 2006)	1059	1026	928	891	833	784
WAP development (1974 to 2006)	1,026	987	897	872	787	746
Post WAP-development (2007 to2022)	1,067	950	905	829	774	780
Change (WAP dev. to Post-WAP dev.)	41 (4%)	-37 (-4%)	8 (1%)	-43 (-5%)	-13 (-2%)	34 (5%)

3.3.3 Detailed rainfall analyses – Hahndorf (23720)

The time series of rainfall from Hahndorf (23720) is analysed in the following plots. Data from Hahndorf was chosen for presentation of results in this section given the site is closest in proximity to another rainfall site, Woodside (23829), used in the model of Mitchell Creek sub-catchment for environmental water requirement metric calculation (DEW 2021), but not used in this analysis due to recent years containing only patched point (non-recorded) data. The site also contains over 90% of recorded data, which limits the effects of bias on the analysis.

Annual rainfall analysis

Rainfall totals for Hahndorf (23720) at annual and decadal levels, with various period medians and trends included, are plotted in Figure 17(a) to (f). The trends of annual rainfall and decadal medians suggest gradually drying conditions over the period of record from 1900 to 2022, with the last 3 decades representing the lowest median decadal rainfall values on record (refer to Figure 17(a), (b), (e) and (f)). Annual deviations from the long-term median rainfall for Hahndorf (23720), shown in Figure 17(b), indicate that 2 of the past 10 years were considered above median years, as per the classification in Table 1. This includes the highest annual rainfall total on record in 2016.

Medians for the drought-related periods (Figure 17(c)) show the median rainfall of the drought period is substantially below the long-term and pre-drought median, while the post-drought median has increased but remains below the long-term and pre-drought medians. For WAP development and post-WAP development periods (Figure 17(d)) the data indicate similar median values between the 2 periods, both of which were below the long-term median.

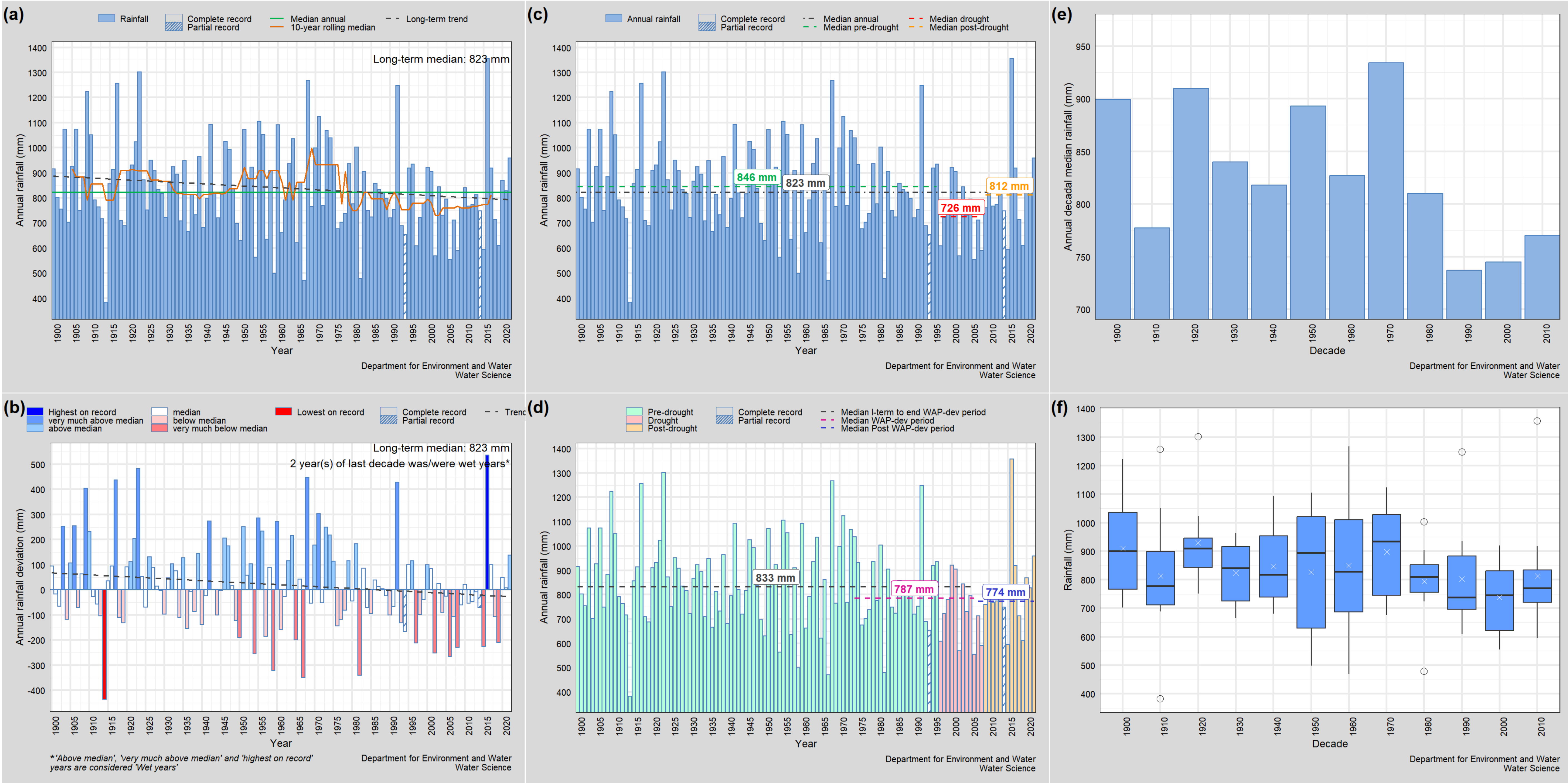


Figure 17. Rainfall plots at Hahndorf (BOM site 23720) for 1900 to 2022 showing (a) long-term median, 10-year rolling median and linear trend, (b) deviation of annual rainfall from long-term median with linear trend, (c) annual rainfall showing median values of drought-related periods, (d) annual rainfall showing median values during the WAP development and Post-WAP-development periods, (e) median annual rainfall per decade, (f) boxplots of distribution of annual median rainfall per decade.

Seasonal rainfall analysis

The previous section outlined evidence indicating drier conditions at the Hahndorf rainfall station in recent decades when rainfall was analysed at an annual timescale. To further investigate drier conditions, and to determine whether reductions in rainfall were consistent across the year, historical daily rainfall at Hahndorf (23720) was aggregated to seasonal totals.

Table 24 summarises median seasonal rainfall over the 3 drought-related climate periods used, together with the difference in annual and seasonal medians during the drought and post-drought periods in comparison to the pre-drought medians. These results show:

- Post-drought winter and summer medians are greater than the medians of their respective pre-drought, drought and all-years comparison periods, noting that summer rainfall is only a minor contributor to total annual rainfall at the station. Median rainfall during winter and summer of the drought period was reduced relative to the pre-drought period, with a difference of 8% and 15%, respectively.
- Total rainfall during autumn and spring, which generally accounted for almost 50% of annual rainfall, showed substantial reductions in median rainfall in both drought and post-drought periods relative to pre-drought. In the drought period, median rainfall for autumn was 7% less than the pre-drought median, while for spring it was reduced by 18%. In the post-drought period, the difference in spring rainfall median relative to pre-drought was less than for the drought (9%), indicating some recovery towards pre-drought annual rainfall, whereas for autumn the rainfall had decreased further (relative to pre-drought) by 10%.

Table 24. Median seasonal rainfall (mm) for Hahndorf (BOM site 23720) for different periods around the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Summer	76	76	65	78	-11 (-15%)	2 (3%)
Autumn	180	185	172	166	-13 (-7%)	-19 (-10%)
Winter	345	342	315	349	-26 (-8%)	7 (2%)
Spring	202	210	172	190	-38 (-18%)	-20 (-9%)
Annual	**823**	**846**	**726**	**812**	**-120 (-14%)**	**-34 (-4%)**

Table 25 summarises seasonal median rainfall totals for the periods that describe the development and post-development of the WAP. These results show:

- The post-WAP development phase (2007 onwards) was typified by significant reductions in rainfall during spring (17% less) and, to a lesser extent, autumn (4%) relative to the WAP development period.
- Winter rainfall in the post-WAP development period was comparable to the period used for WAP development (less than 1% difference)
- Summer rainfall post-WAP development showed an increase of 15% over that of the WAP development period, noting the relatively small contribution of summer rainfall to annual totals.

Table 25. Median seasonal rainfall (mm) for Hahndorf (BOM site 23720) for different WAP development periods

Season	All years	WAP development	Post WAP-development	Change (WAP-dev. to Post WAP-dev.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Summer	76	64	74	9	15%
Autumn	180	173	166	-7	-4%
Winter	345	345	347	3	1%
Spring	202	194	160	-33	-17%
Annual	**823**	**787**	**774**	**-13**	**-2%**

Monthly rainfall analysis

Table 26 summarises the median rainfall for each calendar month for periods relative to the Millennium drought. The percentage change of median annual rainfall of the drought and post-drought periods from the pre-drought period are also shown. These results show:

- Median rainfall in the drought period decreased relative to pre-drought for the majority of months, including January (22% less), April (25% less), July (17% less), September (9% less), October (25% less) and December (10% less). Only June (9%), August (6%) and November (19%) showed an increase in drought period rainfall relative to pre-drought, while similar rainfall medians were apparent across the comparison periods in February, March and May (less than 2 mm difference in median rainfall).
- Median rainfall in the post-drought period showed the most significant reductions in rainfall (relative to pre-drought) in October (33%), November (20%) and December (28%). In contrast, the months with the most significant increases in rainfall were February (37%), May (16%), June (12%) and August (5%). January, March and September showed relatively similar median rainfall values relative to pre-drought.

Table 26. Median monthly rainfall (mm) for Hahndorf (BOM site 23720) for different periods relative to the drought

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Jan	21	21	16	23	-5 (-22%)	2 (8%)
Feb	16	15	14	21	-2 (-10%)	6 (37%)
Mar	23	23	22	22	-1 (-4%)	-1 (-3%)
Apr	52	52	39	48	-13 (-25%)	-4 (-7%)
May	83	82	84	95	2 (2%)	13 (16%)
Jun	104	102	111	114	9 (9%)	12 (12%)
Jul	119	122	102	106	-21 (-17%)	-17 (-14%)
Aug	110	107	113	112	6 (6%)	5 (5%)
Sep	85	87	79	85	-8 (-9%)	-1 (-1%)
Oct	62	71	54	48	-18 (-25%)	-24 (-33%)
Nov	36	36	43	29	7 (19%)	-7 (-20%)
Dec	31	33	30	24	-3 (-10%)	-9 (-28%)
Annual	823	846	726	812	**-120 (-14%)**	**-34 (-4%)**

Table 27 summarises median monthly rainfall for periods that define the WAP development and post-WAP development periods. Changes in median monthly rainfall recorded during the post-WAP development phase when compared to the WAP development period are also shown. These results show:

- The most significant reduction in median rainfall between post-WAP development and WAP development periods occurred in October, with a reduction of 20 mm, or 32%. June (14% less) and July (10% less) also showed significant reductions, with March showing a more minor reduction of 4 mm (14% owing to low rainfall totals).
- Median rainfall for April (31%) and May (11%) showed the largest increase between post-WAP development and WAP development periods.
- Other months showed only minor differences between post-WAP development and WAP development periods.

Table 27. Median monthly rainfall (mm) for Hahndorf (BOM site 23720) for different periods around WAP development

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Jan	21	19	23	3	17%
Feb	16	12	15	3	24%
Mar	23	25	22	-4	-14%
Apr	52	41	53	13	31%
May	83	83	92	9	11%
Jun	104	108	94	-15	-14%
Jul	119	124	112	-13	-10%
Aug	110	111	112	1	1%
Sep	85	85	84	-1	-2%
Oct	62	61	41	-20	-32%
Nov	36	35	29	-6	-18%
Dec	31	30	27	-3	-11%
Annual	**823**	**787**	**774**	**-13**	**-2%**

3.3.4 Trend and Shift analyses of rainfall

Detailed analysis of Hahndorf (23720)

CUSUM charts were prepared for the time series of rainfall at Hahndorf (23720) aggregated to annual totals (Figure 18). The annual CUSUM chart does not show any data points falling outside of the action bounds (yellow shading). However, since the early 1990s the cumulative sum has generally fallen below the long-term mean, with a minor downward trend (indicted by the red line) in the cumulative sum up to the late 2010s apparent, reaching historical lows at the end of the drought. A jump in the cumulative sum subsequently occurred in 2016, coinciding with the record wet year experienced at this time, with the years following demonstrating a return to below-average rainfall.

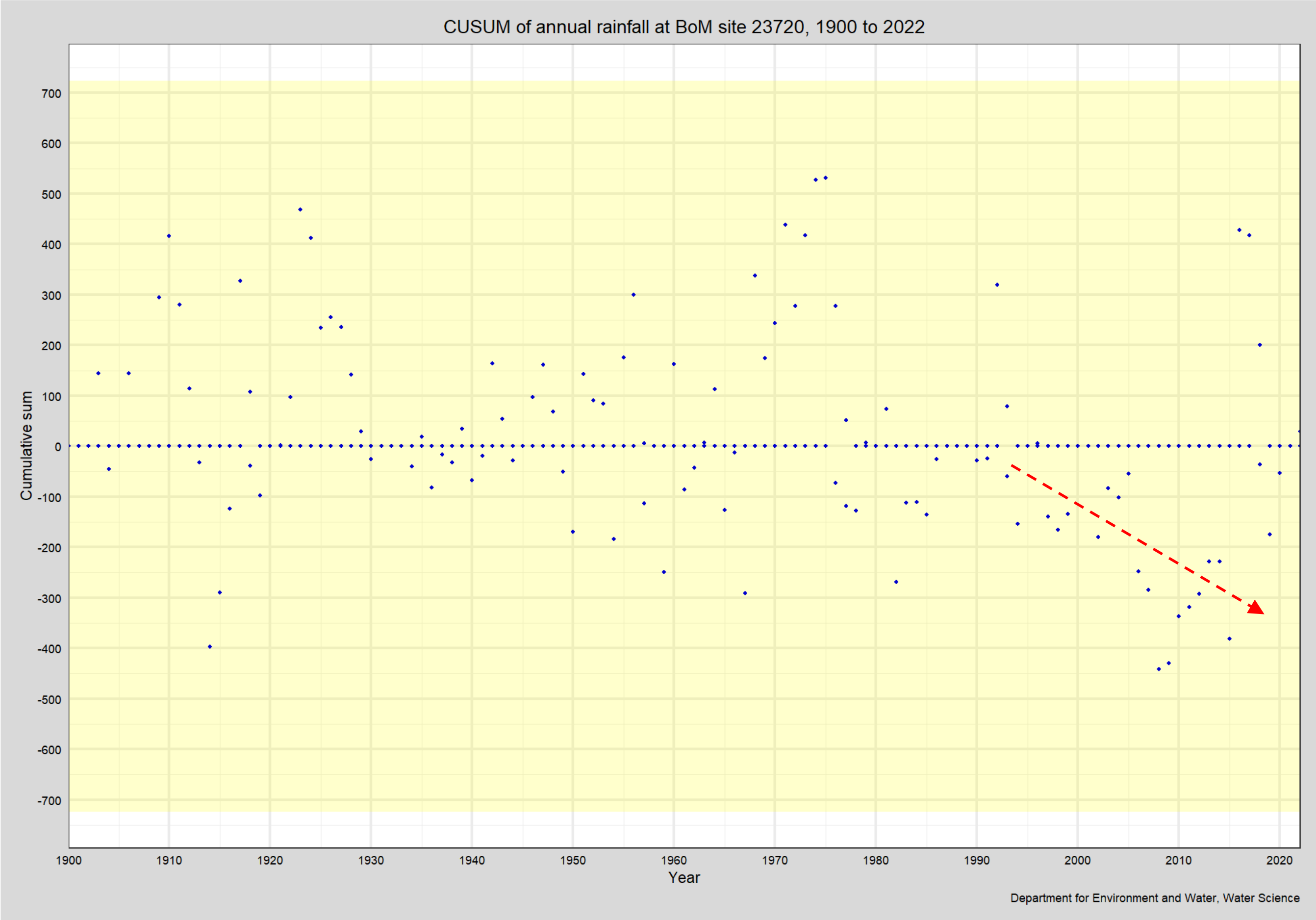


Figure 18. CUSUM chart of annual rainfall (1900 to 2022) for Hahndorf (BOM site 23720)

Figure 19 shows the CUSUM charts of seasonal rainfall totals. These results show:

- The cumulative sum of summer and winter rainfall has generally varied around the long-term average over recent decades and remained within the action limits.
- The 1990s saw the cumulative sum of autumn rainfall fall below historical minimum values, before gradually rebounding to values just below the long-term average. A reduced variability in rainfall during the period is also apparent.
- Spring rainfall showed a reduction in cumulative sum from the early 2000s, falling outside the lower action limit by the mid-2010s. A jump in cumulative sum was then experienced in 2016, similar to the annual rainfall behaviour (Figure 17Figure 18), before again falling below the long-term average towards the end of the period.

Figure 20 shows CUSUM charts of monthly rainfall totals. These results indicate:

- October rainfall totals indicate a significant downward trend in its cumulative sum since the commencement of the Millennium drought, with multiple data points falling outside the lower action limit in the 2010s, aligning closely with the behaviour for spring. In contrast, July showed a single data point increasing above the upper action limit in 2016, coinciding with the highest annual rainfall total on record. No other calendar months showed data points falling outside the action limits in a CUSUM analysis for this recent period, although rainfall in many months showed temporary increases above the upper action limit at different times during the pre-drought period, coinciding with high rainfall years.

- High rainfall years in early- and mid-2010s are indicated by some temporary jumps in cumulative sum above the long-term mean for certain months, such as January to March, September and December.
- Some months (for example, April and May) show a reduced variation in rainfall about the long-term mean in the years since the commencement of the drought.

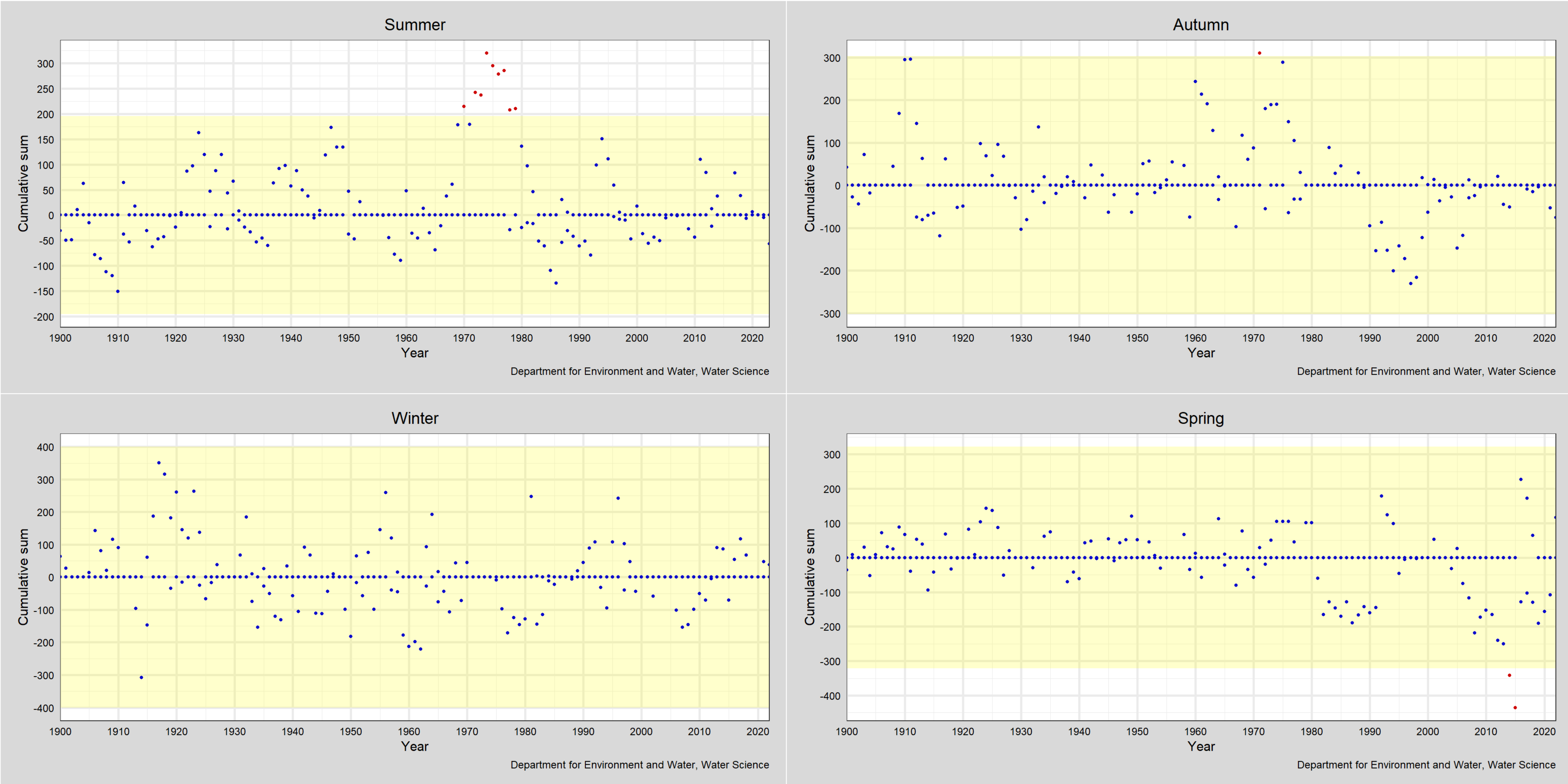


Figure 19. CUSUM charts of seasonal rainfall (1900-2022) for Hahndorf (BOM site 23720)

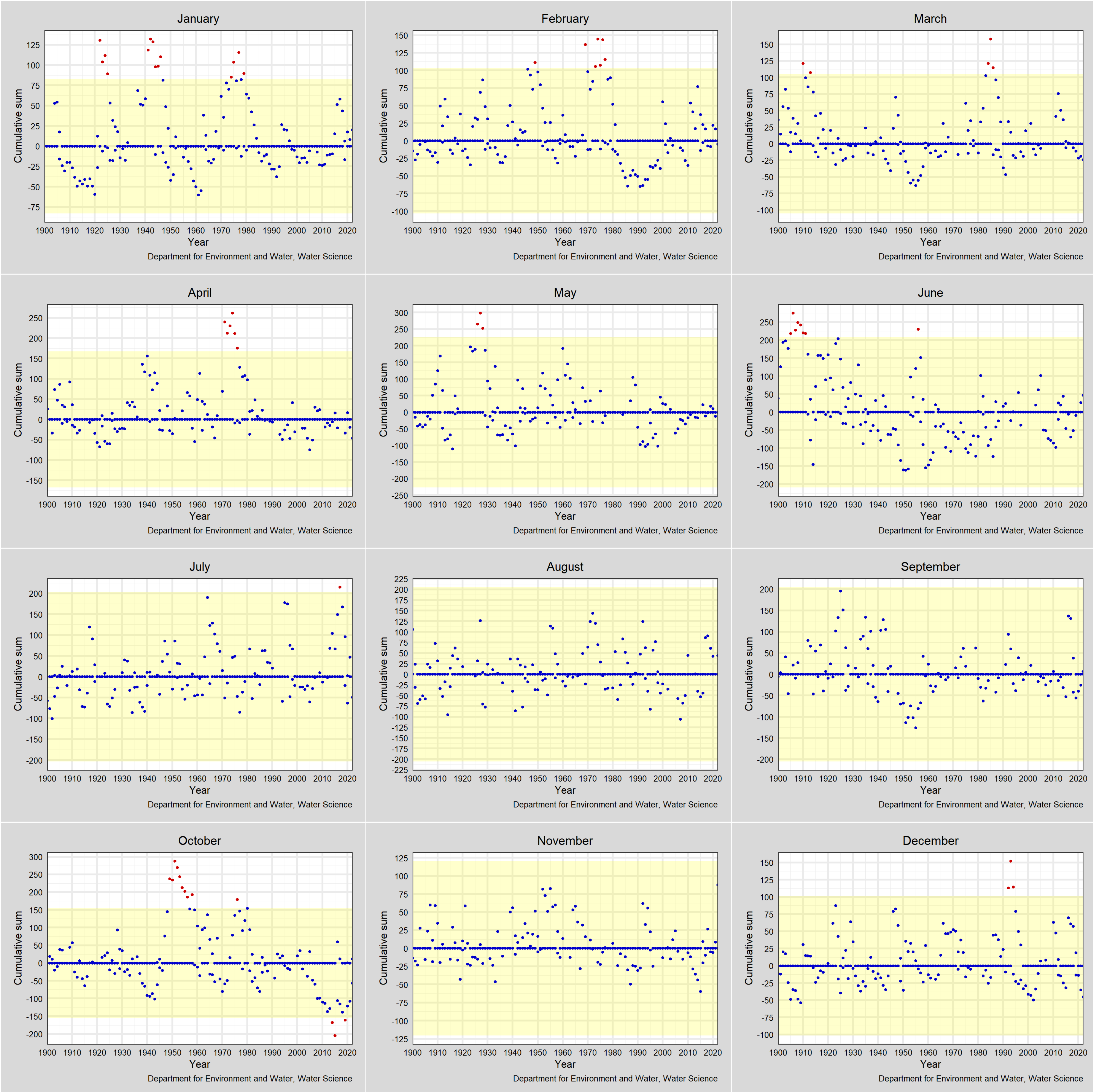


Figure 20. CUSUM charts of monthly rainfall (1900-2022) for Hahndorf (BOM site 23720)

Table 28 summarises the results of the statistical tests for data from Hahndorf. Results for the other sites are provided in Appendices 7.3 and 7.4. Further explanation of the tests is provided in section 2.7. For the Mann-Kendall Test, a negative 'tau' value indicates that a time series has a monotonic downward trend, and vice versa, and a p value less than 0.05 indicates that the trend is statistically significant at a 5% level. These are highlighted in red. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate the presence of a monotonic trend but with a slightly lesser degree of statistical significance (between 5% and 10%).

Table 28. Summary of statistical tests for separating rainfall data for Hahndorf (BOM site 23720) at different years, and aggregating across various periods

Period	Mann-Kendall (1900 to 2022)		Drought periods (pre- and post-1996)		WAP-development (pre- and post-2007)	
	tau	p value	Wilcoxon *p value*	Welch's p value	Wilcoxon *p value*	Welch's p value
Annual	-0.125	0.040	0.016	0.026	0.437	0.544
Summer	0.020	0.743	0.387	0.294	0.837	0.785
Autumn	-0.081	0.187	*0.095*	0.021	0.449	0.459
Winter	-0.027	0.662	0.399	0.299	0.785	0.727
Spring	-0.159	0.009	0.013	*0.067*	0.082	0.239
Jan	0.035	0.573	0.594	0.269	0.806	0.794
Feb	0.003	0.967	0.544	0.501	0.725	0.784
Mar	-0.027	0.657	0.564	0.272	0.589	0.249
Apr	-0.044	0.473	*0.069*	0.032	0.596	0.573
May	-0.001	0.990	0.566	0.183	0.555	0.562
Jun	-0.062	0.308	0.589	0.450	0.504	0.444
Jul	0.010	0.871	0.229	0.334	0.667	0.697
Aug	-0.006	0.918	0.457	0.373	0.726	0.715
Sept	-0.080	0.190	0.148	0.153	0.203	0.391
Oct	*-0.107*	*0.078*	0.026	0.019	0.045	*0.052*
Nov	-0.003	0.962	0.423	0.445	0.404	0.591
Dec	0.003	0.963	0.247	0.279	0.420	0.551

For the Wilcoxon and Welch's tests, a p value less than 0.05 indicates that there is a significant difference (at a 95% confidence level) in median value of 2 samples that represent observations across different periods. Results of the statistical tests presented in the table show:

- The Mann-Kendall test shows evidence of statistically significant declining trends in long-term annual, seasonal (in spring) and monthly rainfall (October).
- Wilcoxon and Welch's tests show evidence of statistically significant shifts:
  - between pre- and post-1996 periods, in annual, seasonal (autumn and spring) and monthly (April and October) mean and median rainfall
  - between WAP development and post-WAP development periods, in October rainfall.

These results suggest that there is an overall drying trend in annual, and in particular Spring, rainfall, and a period of changed climate is more clearly apparent when comparing the periods either side of the Millennium drought.

The impacts at the Hahndorf (23720) site of this change in total rainfall are most apparent during spring and (to a lesser extent) autumn periods. Evidence of change on a monthly basis is strongest in October (both post-WAP and post-drought periods) and weakest (post-drought only) in April.

Statistical analysis summary of other Onkaparinga catchment sites

Review of the statistical analysis of annual, seasonal and rainfall totals for other sites in the Onkaparinga catchment is summarised below:

- Review of annual rainfall total CUSUM plots for other stations within the Onkaparinga catchment provide insufficient evidence of any strong shifts in annual rainfall since the start of the Millennium drought relative to pre-drought rainfall behaviour. On a monthly basis however, all stations show October to have a decreasing shift in rainfall since the commencement of the drought, falling below the lower action limit at all stations.
- Uraidla (23750) – CUSUM analysis showed spring rainfall reducing below the lower action limit (at a historical low), while autumn decreased to a historical low during the drought before returning to the long-term mean post-drought. No statistically significant long-term trends (Mann-Kendall) or shifts (Wilcoxon rank sum/Welch's t-test) based on drought-related periods were detected, although in the context of WAP-related periods spring (October) showed a significant negative shift in the post-WAP development period.
- Bridgewater (23707) – CUSUM analysis was consistent with that of Uraidla. Statistically significant long-term decreasing trends were detected in both annual and spring (October) periods (Mann-Kendall). In drought-related periods, spring (October) and April showed a significant negative shift in rainfall from the start of the drought (Wilcoxon rank sum/Welch's t-test), while for WAP-related periods only spring (October) showed a negative shift in the post-WAP development period.
- Cherry Gardens (23709) – CUSUM analysis was consistent with that of Uraidla and Bridgewater. No significant long-term trend was detected (Mann-Kendall), and only spring (October) rainfall showed evidence of a statistically significant negative shift post-drought (Wilcoxon rank sum/Welch's t-test). Comparing WAP-related periods, statistically significant negative shifts in rainfall were detected in spring, in the months of September and October
- Lobethal (23726) – CUSUM analysis showed spring to have reached historical lows in rainfall post-drought, influenced strongly by the downward shift in October rainfall similarly detected. This resulted in detection of a significant decreasing trend in spring (Mann-Kendall). Significant negative shifts in rainfall post-1996 were detected in annual, spring (October) and autumn (April), while for the post-WAP development period negative shifts were detected in spring (October) only (Wilcoxon rank sum/Welch's t-test).
- Echunga (23713) – CUSUM analysis was consistent with that of Lobethal. Significant decreasing long-term trends were detected in annual, spring (October) and autumn periods (Mann-Kendall). Significant negative shifts were detected for the same periods in the post-1996 period with the addition of April (in autumn), although no shift was detected on an annual basis. In the post-WAP development period, only October showed a significant negative shift in rainfall.

3.4 Torrens River catchment

3.4.1 Overview of rainfall stations

Four rainfall (BoM) sites were selected in the Torrens River catchment, based on the criteria outlined in Section 2.2. The locations of the stations broadly represent the spatial change in elevation and rainfall within the catchment, as shown in Figure 2. The sites selected and overall quality of data within the SILO records for those sites for the period 1900 to 2022 are summarised in Table 29. Each of these 4 stations has over 85% of daily data recorded by the BoM.

Table 29. Proportion of daily SILO rainfall series (1900 to 2022) in the Torrens River catchment with various quality codes

Site ID	Site name	Catchment	SILO Data Quality Codes		
			0	15	25
23705	Birdwood Dept Of Transport	Torrens	**96%**	**4%**	**<1%**
23719	Gumeracha District Council	Torrens	**86%**	**9%**	**5%**
23731	Cudlee Creek (Millbrook)	Torrens	**85%**	**1%**	**14%**
23737	Mount Pleasant	Torrens	**91%**	**8%**	**1%**

3.4.2 Annual rainfall – All sites

Table 30 summarises statistics for annual rainfall collated from the 4 sites in the Torrens River catchment. These statistics demonstrate the spatial distribution of rainfall across the catchment, with Cudlee Creek (23731) the rainfall station with the highest median value of ≈850 mm per year and Mount Pleasant the lowest with a median of almost 650 mm per year.

Table 30. Summary statistics for selected annual rainfall data (mm) for Torrens River catchment (1900 to 2022)

Statistics	Cudlee Creek (23731)	Gumeracha (23719)	Birdwood (23705)	Mount Pleasant (23737)
Annual average	850	788	713	661
Annual median	852	792	699	644
Annual maximum	1411	1315	1189	1104
Annual minimum	453	381	375	325
Standard deviation	190	180	162	157

Figure 21 shows the distribution of annual rainfall for the 4 rainfall stations in the Torrens River catchment across the drought periods as boxplots, while Table 31 shows the absolute medians and relative changes related to the WAP periods. At the highest rainfall station in Cudlee Creek (23731), median rainfall was relatively consistent between pre-drought and drought periods, with a difference of only 2%. The drought period, however, showed negative skewness with a very short upper whisker, signifying a greater proportion of rainfall occurring in the lower quartile end of the distribution. Note also that a significant proportion of the estimated data at Cudlee Creek (14% with code 25, see Table 30) occurred in the late 2000s to early 2010s, which may have impacted this particular rainfall distribution during the drought period. At the 3 other stations median rainfall showed a significant decrease in the drought period, at Gumeracha (7% less), Birdwood (9% less) and Mount Pleasant (14% less).

In the post-drought period, the period median at Gumeracha (23719) and Mount Pleasant (23737) was similar to pre-drought (less than 2% difference), indicating the rainfall at these stations had recovered. At Cudlee Creek and Birdwood however, the medians were decreased in each case (7% and 6%, respectively), suggesting rainfall had not fully recovered at these stations.

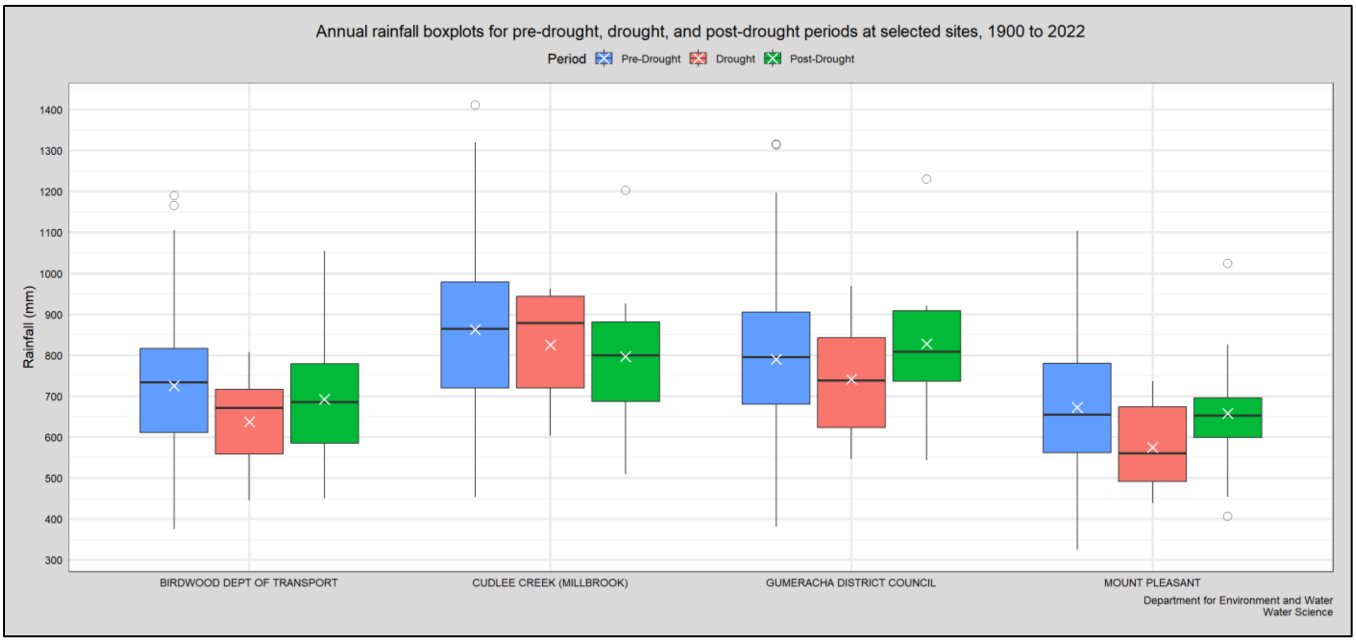


Figure 21. Distribution of annual rainfall in the Torrens River catchment during drought periods (median (—), average (X), and outliers (O) shown)

Table 31. Median annual rainfall (mm) for different periods for the Torrens River catchment (1900 to 2022)

Period	**Cudlee Creek (23731)**	**Gumeracha (23719)**	**Birdwood (23705)**	**Mount Pleasant (23737)**
All years (1900 to 2022)	852	792	699	644
Pre-drought (1900 to 1996)	864	796	734	655
Drought (1997 to 2008)	879	739	671	560
Post-drought (2009 to 2022)	799	808	686	652
Change compared to Pre-drought				
Drought (mm)	15	-57	-63	-95
%)	(2%)	(-7%)	(-9%)	(-14%)
Post-drought (mm)	-65	13	-48	-3
(%)	(-7%)	(2%)	(-6%)	(0%)

Figure 22 shows the distribution of annual rainfall between the WAP development and post-WAP development phases for the 4 sites, while Table 32 shows the absolute medians and relative changes related to the WAP periods. Birdwood and Mount Pleasant showed similar medians across both periods (less than 2% difference), although the distributions in each period varied from one another; the box plot for the WAP development period at each site suggested a normal distribution, while in the post-WAP development period a negative skewness in the distribution was apparent. At Cudlee Creek, the post-WAP development median was reduced from WAP development (6% less), while at Gumeracha the opposite was true (7% increase in median).

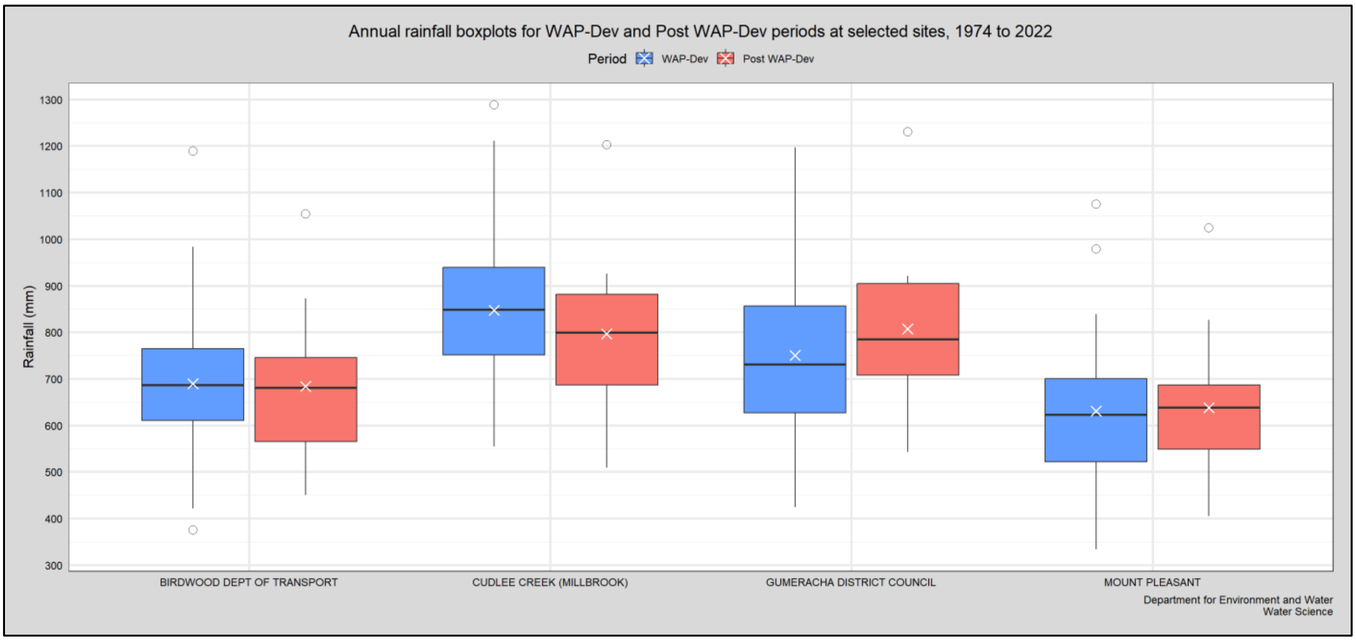


Figure 22. Distribution of annual rainfall in the Torrens River catchment during WAP periods (median (—), average (X), and outliers (O) shown)

Table 32. Median annual rainfall (mm) for different WAP periods across the Torrens River catchment (1900 to 2022)

Period	Cudlee Creek (23731)	Gumeracha (23719)	Birdwood (23705)	Mount Pleasant (23737)
All years (1900 to2022)	852	792	699	644
Pre-WAP (1900 to 2006)	864	792	707	649
WAP development (1974 to 2006)	849	731	687	623
Post-WAP-development (2007 to 2022)	799	785	681	638
Change (WAP development to Post-WAP-development)	-49 (-6%)	54 (7%)	-6 (-1%)	15 (2%)

3.4.3 Detailed rainfall analyses – Birdwood (23705)

The time series of rainfall from Birdwood (23705) is analysed in the following plots, with data for the remaining 3 stations in the Torrens River catchment included in Appendix 7.4.

Annual rainfall analysis

Rainfall totals for Birdwood (23705) at annual and decadal levels, with various period medians and trends included, are plotted in Figure 23(a) to (f). The trends of annual rainfall and decadal medians suggest gradually drying conditions over the period of record from 1900 to 2022, with the last 3 decades representing 3 of the 5 lowest median decadal rainfall values on record (refer to Figure 23(a), (b), (e) and (f)). Annual deviations from the long-term median rainfall for Birdwood, shown in Figure 23(b), indicate that 2 of the past 10 years were considered above-median years, as per the classification in Table 1.

Medians for the drought-related periods (Figure 23(c)) show the median rainfall of the drought period is below the pre-drought median by over 60 mm, although less than 30 mm below the long-term median. The post-drought median increased back towards the long-term median, but remains below the pre-drought median by almost 50 mm. For WAP development and post-WAP development periods (Figure 23(d)) the data indicate similar median values between the two periods, both of which were below the long-term median.

Figure 23. Rainfall plots at Birdwood (BOM site 23705) for 1900 to 2022 showing (a) long-term median, 10-year rolling median and linear trend, (b) deviation of annual rainfall from long-term median with linear trend, (c) annual rainfall showing median values of drought-related periods, (d) annual rainfall showing median values during the WAP development and Post-WAP-development period€(e) median annual rainfall per decade, (f) boxplots of distribution of annual median rainfall per decade.

Seasonal rainfall analysis

The previous section outlined evidence indicating drier conditions at the Birdwood rainfall station in recent decades when rainfall was analysed at an annual timescale. To further investigate drier conditions, and to determine whether reductions in rainfall are consistent across the year, historical daily rainfall at Birdwood was aggregated to seasonal totals.

Table 33 summarises median seasonal rainfall over the 3 drought-related climate periods used, together with the difference in annual and seasonal medians during the drought and post-drought periods in comparison to the pre-drought medians. These results show:

- Post-drought winter and summer medians were similar to the respective pre-drought medians (less than 2% difference), noting that summer rainfall is only a minor contributor to total annual rainfall at the station. Median rainfall during winter and summer of the drought period was reduced relative to the pre-drought period, with a difference of 9% and 6%, respectively.
- Total rainfall during spring showed significant (at 91% confidence level) reduction in median rainfall in both drought and post-drought periods relative to pre-drought. In the drought period, median rainfall for spring was 12% less than the pre-drought median, while for the post-drought period there was a greater reduction (18%).
- Variations in Autumn rainfall for both drought and post-drought periods relative to pre-drought were consistently small, varying from pre-drought by 4 mm (3%) and 5 mm (4%), respectively.

Table 33. Median seasonal rainfall (mm) for Birdwood (BOM site 23705) for different periods around the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Summer	66	67	61	66	-6 (-9%)	-1 (-1%)
Autumn	145	146	142	141	-4 (-3%)	-5 (-4%)
Winter	285	291	273	284	-18 (-6%)	-7 (-2%)
Spring	176	192	168	158	-24 (-12%)	-34 (-18%)
Annual	**699**	**734**	**671**	**686**	**-63 (-9%)**	**-48 (-6%)**

Table 34 summarises seasonal median rainfall totals for the periods that describe the development and post development of the WAP. These results show:

- The post-WAP development phase (2007 onwards) was typified by significant reductions in rainfall during spring (19% less) and, to a lesser extent, winter (6%) relative to the WAP development period.
- Autumn rainfall in the post-WAP development period was comparable to the period used for WAP development.
- Summer rainfall for post-WAP development showed an increase of 12% over that of the WAP development period, noting the relatively small contribution of summer rainfall to annual totals.

Table 34. **Median seasonal rainfall (mm) for Birdwood (BOM site 23705) for different periods around the Post WAP-development**

Season	All years	Pre-WAP	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1900 to 2022)	(1900 to 2006)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Summer	66	66	60	66	7	12
Autumn	145	145	143	144	0	0
Winter	285	285	285	269	-16	-6
Spring	176	192	176	143	-33	-19
Annual	**699**	**707**	**687**	**681**	**-6**	**-1**

Monthly rainfall analysis

Table 35 summarises the median rainfall for each calendar month for periods relative to the Millennium drought. The percentage change of median annual rainfall of the drought and post-drought periods from the pre-drought period are also shown. These results show:

- Median rainfall in the drought period decreased relative to pre-drought for months including January (30% less), April (8% less), June (7% less), July (14% less) and September (14% less). Only May (9%), November (23%) and December (31%) showed an increase in drought period rainfall relative to pre-drought, while little change (either by absolute or percentage difference) in rainfall medians was apparent across the comparison periods in February, March, August and October.
- Median rainfall in the post-drought period showed the most significant reductions in rainfall (relative to pre-drought) in October (34%), July (21%), September (13%), December (17%) and May (5%). Other months showed little difference in median rainfall values relative to pre-drought.

Table 35. **Median monthly rainfall (mm) for Birdwood (BOM site 23705) for different periods relative to the drought**

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought mm (%)	Post-drought mm (%)
Jan	18	18	13	20	-5 (-30%)	2 (10%)
Feb	14	15	16	13	1 (9%)	-1 (-8%)
Mar	17	17	17	17	0 (2%)	0 (2%)
Apr	42	41	38	44	-3 (-8%)	2 (6%)
May	68	68	74	64	6 (9%)	-4 (-5%)
Jun	87	87	81	90	-6 (-7%)	3 (3%)
Jul	95	100	86	79	-14 (-14%)	-21 (-21%)
Aug	98	96	93	98	-3 (-3%)	2 (2%)
Sep	75	80	69	70	-11 (-14%)	-11 (-13%)
Oct	56	57	58	38	0 (0%)	-20 (-34%)
Nov	31	31	38	29	7 (23%)	-1 (-4%)
Dec	24	23	30	19	7 (31%)	-4 (-17%)
Annual	**699**	**734**	**671**	**686**	**-63 (-9%)**	**-48 (-6%)**

Table 36 summarises median monthly rainfall for the WAP development and post-WAP development periods. Changes in median monthly rainfall recorded during the post-WAP development phase when compared to the WAP development period are also shown. These results show:

- The most significant reduction in median rainfall between post-WAP development and WAP development periods occurred in October, with a reduction of 29 mm, or 45%. June (7% less), September (12% less) and November (21% less) also showed significant reductions, with February, March and December showing more minor reductions owing to low rainfall totals in those months.
- April (13%) and August (18%) showed the largest increase in median rainfall between post-WAP development and WAP development periods
- Other months showed only minor differences between post-WAP development and WAP development periods.

Table 36. Median monthly rainfall for Birdwood (BOM site 23705) for different periods around the Post WAP-development

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1900 to 2022)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Jan	18	20	20	0	-2
Feb	14	13	11	-2	-15
Mar	17	19	17	-1	-6
Apr	42	41	47	5	13
May	68	66	66	0	0
Jun	87	91	85	-6	-7
Jul	95	100	97	-3	-3
Aug	98	83	98	15	18
Sep	75	76	67	-9	-12
Oct	56	63	35	-29	-45
Nov	31	36	29	-8	-21
Dec	24	24	21	-3	-13
Annual	**699**	**687**	**681**	**-6**	**-1**

3.4.4 Trend and Shift analyses of rainfall

Detailed analysis of Birdwood (23705)

CUSUM charts were prepared for the time series of rainfall at Birdwood (23705) aggregated to annual totals (Figure 24). The annual CUSUM chart does not show any data points falling outside of the action bounds (shaded). The cumulative sum has generally remained below the long-term mean since the early 1990s, other than the occasional year just above the mean, and years impacted by high rainfall in the mid-2010s. No significant evidence of a trend in CUSUM is apparent in the period since commencement of the drought in comparison to the historical data.

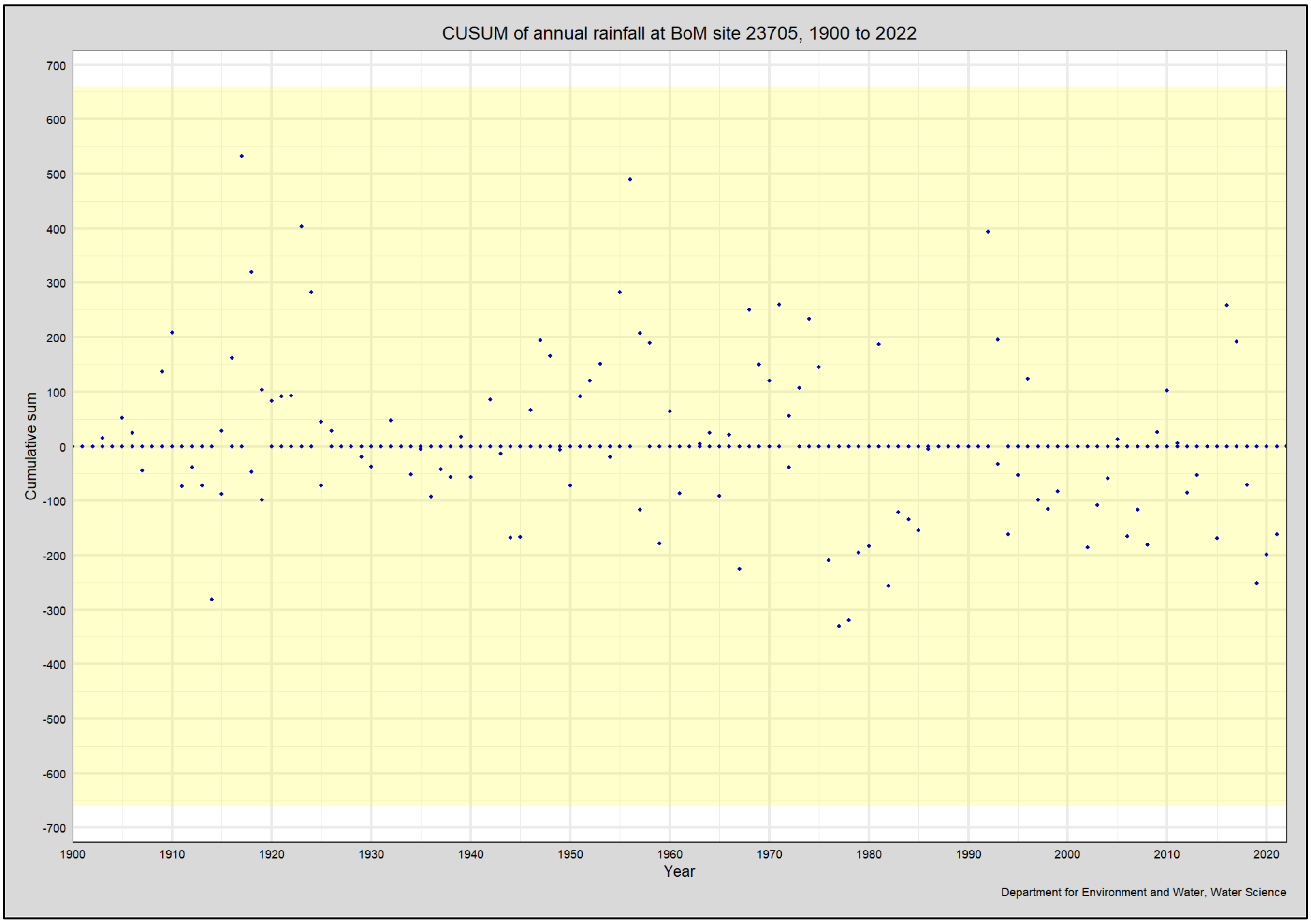


Figure 24. CUSUM chart of annual rainfall (1900 to 2022) for Birdwood (BOM site 23705)

Figure 25 shows the CUSUM charts of seasonal rainfall totals. These results show:

- The cumulative sum of winter rainfall has generally varied around the long-term average over recent decades and remained within the action limits. There also appears to be a reduced variability of rainfall about the long-term mean for winter since the early 2000s.
- Summer rainfall was shown to remain largely above the long-term mean since the onset of the drought, in particular during the 2010s in which a data point increased above the upper action limit.
- The drought period saw the cumulative sum of autumn rainfall fall below historical minimum values, before rebounding to values around the long-term average in the post-drought period. A reduced variability in rainfall during the latter period is also apparent.

- Spring rainfall showed a reduction in cumulative sum from the early 2000s. A jump in cumulative sum was then experienced in 2016, similar to the annual rainfall behaviour (Figure 24), before again falling below the long-term average towards the end of the period. The high rainfall year in 2022 shows another apparent jump of cumulative sum to above the long-term mean.

Figure 26 shows CUSUM charts of monthly rainfall totals. These results indicate:

- October rainfall totals indicate a significant downward trend in its cumulative sum since the commencement of the Millennium drought, with multiple data points falling outside the lower action limit in the 2010s, aligning closely with the behaviour for spring.
- Warmer months from December to March all showed jumps in cumulative sum towards or above the upper action limit in recent decades, particularly over the post-drought period.
- May showed a reduced variability in the post-drought period, sitting around the long-term mean and aligning with the autumn cumulative sum behaviour. June also showed an apparent reduction in variability while sitting below the long-term mean line.
- Other months show little evidence of a shift in behaviour from pre-drought conditions.

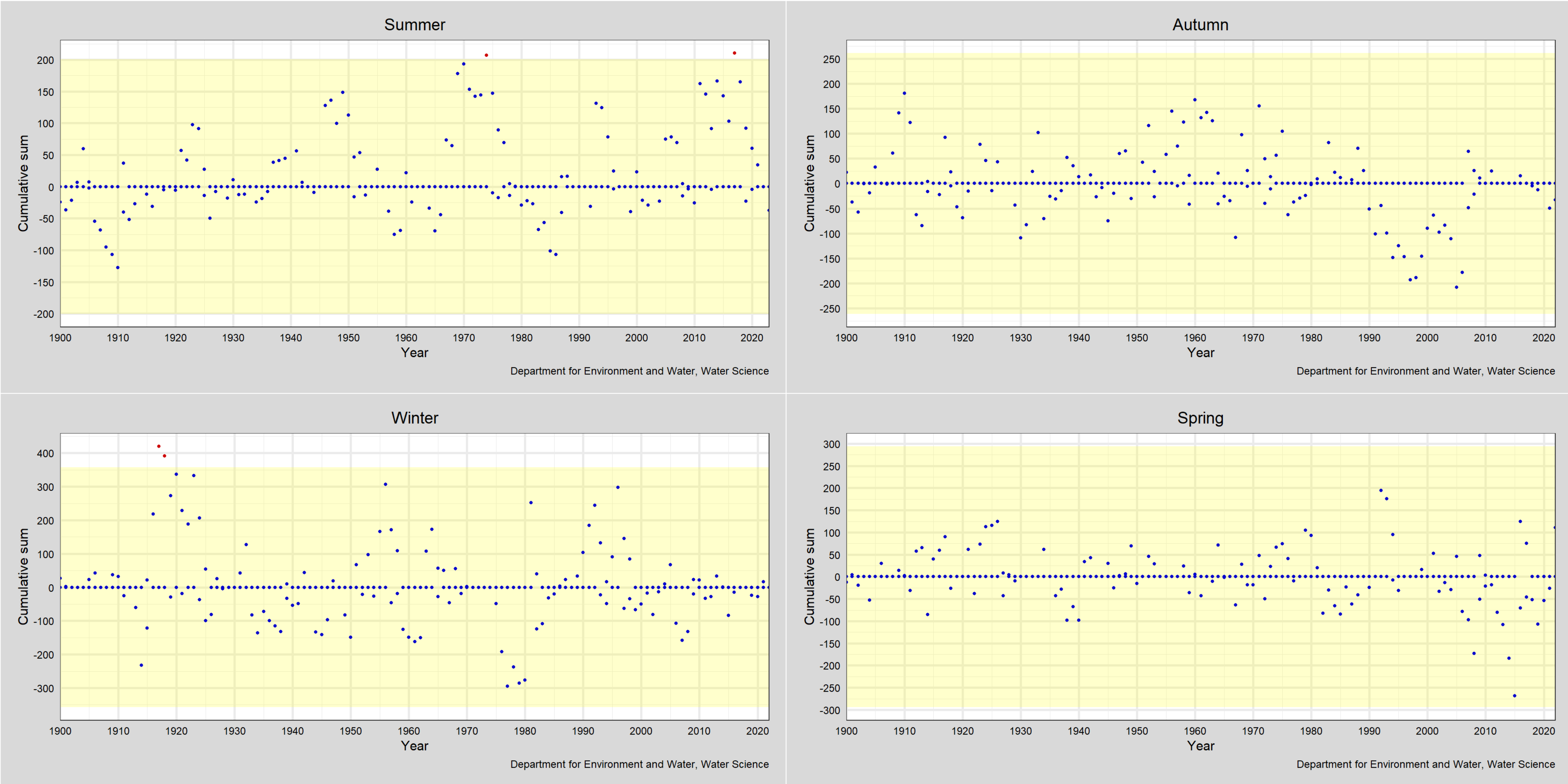


Figure 25. CUSUM charts of seasonal rainfall (1900 to 2022) for Birdwood (BOM site 23705)

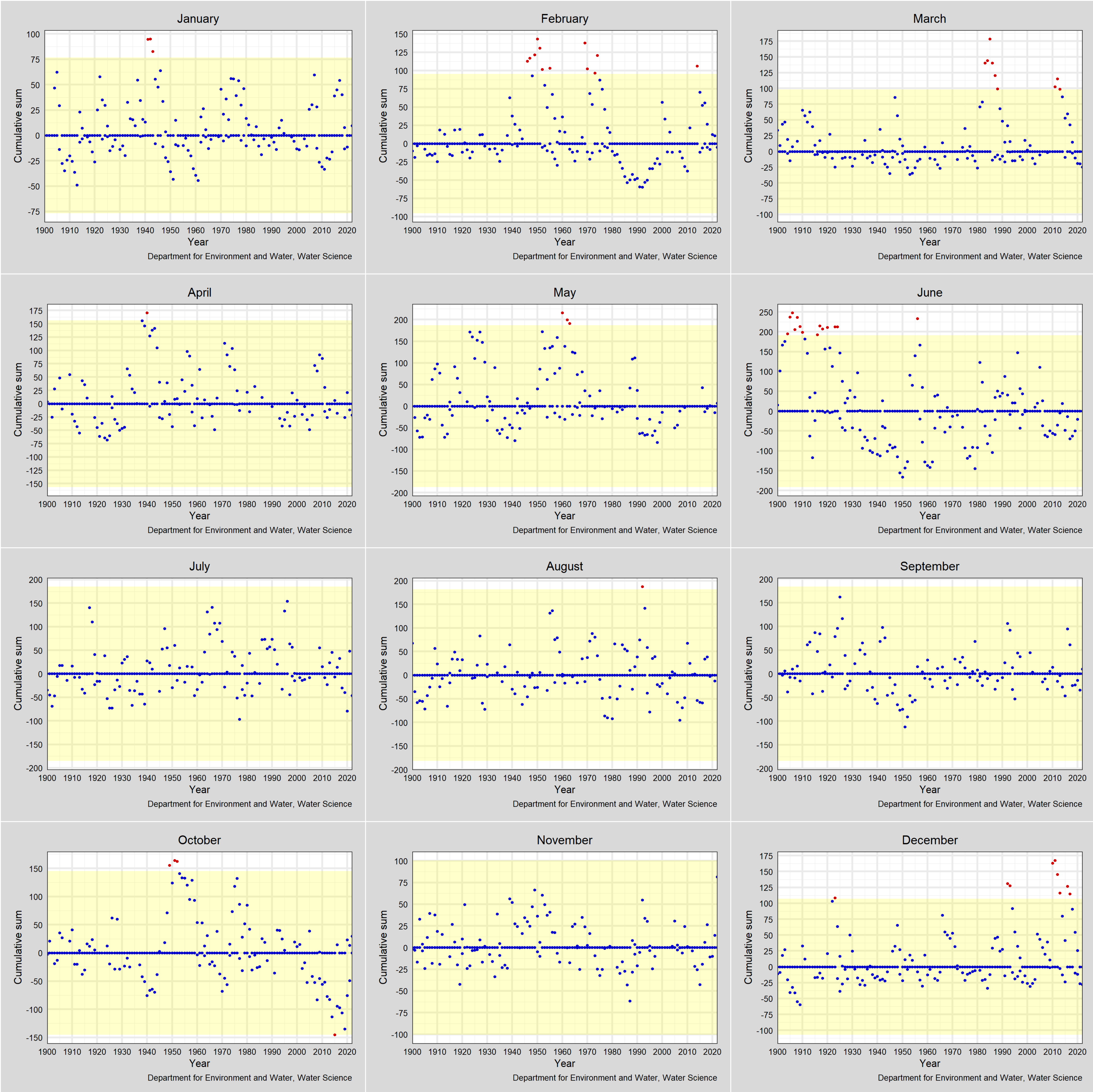


Figure 26. CUSUM charts of monthly rainfall (1900 to 2022) for Birdwood (BOM site 23705)

Table 37 summarises the results of the statistical tests for data from Birdwood. Results for the other sites are provided in Appendices 7.3 and 7.4. For the Mann-Kendall Test, a negative 'tau' value indicates that a time series has a monotonic downward trend, and vice versa, and a p value less than 0.05 indicates that the trend is statistically significant at a 5% level. These are highlighted in red. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate the presence of a monotonic trends but with a slightly lesser degree of statistical significance (between 5% and 10%).

For the Wilcoxon and Welch's tests, p value less than 0.05 indicates that there is a significant difference or shift (at a 5% level) in median and mean value, respectively, of 2 samples that represent observations across different periods. These are highlighted in red in the table. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate a shift, but with a lesser degree of statistical significance (between 5% and 10%).

Results of the statistical tests presented in the table show:

- The Mann-Kendall test shows only weak evidence of a declining trend during spring.
- Wilcoxon and Welch's tests show evidence of statistically significant shifts:
  - between pre- and post-1996 periods, in annual, seasonal (autumn and winter), and monthly (May and October) mean rainfall.
  - between WAP development and post-WAP development periods in October rainfall.

Table 37. Summary of statistical tests for separating rainfall data for Birdwood (BOM site 23705) at different years, and aggregating across various periods

Period	Mann-Kendall (1900 to 2022)		Drought periods (pre- and post-1996)		Post WAP-development (pre- and post-2007)	
	tau	p value	Wilcoxon *p value*	Welch's p value	Wilcoxon *p value*	Welch's p value
Annual	-0.077	0.206	*0.053*	0.040	0.421	0.448
Summer	0.037	0.546	0.581	0.713	0.871	0.850
Autumn	-0.061	0.317	0.151	0.042	0.746	0.781
Winter	-0.049	0.427	0.111	*0.051*	0.335	0.273
Spring	*-0.107*	*0.080*	*0.092*	0.155	0.107	0.197
Jan	0.043	0.483	0.589	0.487	0.555	0.601
Feb	-0.034	0.583	0.411	0.592	0.589	0.793
Mar	-0.028	0.651	0.485	0.398	0.496	0.393
Apr	0.000	0.998	0.259	0.214	0.772	0.789
May	-0.028	0.646	0.383	*0.059*	0.732	0.724
Jun	-0.072	0.241	0.388	0.188	0.234	0.131
Jul	0.029	0.638	0.192	0.136	0.559	0.481
Aug	-0.012	0.844	0.267	0.180	0.547	0.522
Sept	-0.062	0.307	0.229	0.216	0.148	0.239
Oct	-0.087	0.153	0.045	0.044	*0.062*	0.048
Nov	0.016	0.795	0.772	0.704	0.534	0.723
Dec	0.043	0.479	0.593	0.722	0.564	0.747

Statistical analysis summary of other Torrens catchment sites

Review of the statistical analysis of annual, seasonal and rainfall totals for other sites in the Torrens catchment is summarised below:

- Review of annual rainfall total CUSUM plots for other stations within the Torrens catchment show over the last 3 decades that rainfall across the catchment was sitting below the long-term mean. Gumeracha in particular showed a noticeable decrease of cumulative sum towards the lower action limit over the 3-year period from 2019 to 2021, before rebounding towards long-term mean at the end of the period of record, coinciding with the high rainfall year in 2022. This may have been impacted by October rainfall, which shows strong indications of a downwards shift since the early 2000s at each station.
- Cudlee Creek (23731) – CUSUM analysis shows autumn and spring rainfall reached historical lows in the post-1996 period. A decreasing downward trend is indicated on an annual basis (Mann-Kendall) with a significant negative shift post-1996 detected both annually and in October (Wilcoxon rank sum/Welch's t-test). In a WAP-related period context, spring and October each show a significant negative shift.
- Gumeracha (23719) – CUSUM behaviour was consistent with Cudlee Creek. Significant decreasing trends were detected in annual, spring and October periods (Mann-Kendall), while October showed a significant shift both in the period since commencement of drought and in the post-WAP development period.
- Mount Pleasant (23737) – CUSUM behaviour was consistent with Cudlee Creek and Gumeracha. A significant decreasing long-term trend was only detected in spring (Mann-Kendall); however negative shifts in rainfall in the post-1996 period were detected in annual, spring (October) autumn and winter (Wilcoxon rank sum/Welch's t-test). In a WAP-related period context, only October showed any evidence of a shift in rainfall post-WAP development.

3.5 Fleurieu region

3.5.1 Overview of rainfall stations

Six rainfall (BoM) sites were selected to represent the Fleurieu and Willunga region of the western MLR PWRA (Figure 2), based on the criteria outlined in Section 2.2. The sites selected and overall quality of data within the SILO records for those sites for the period 1900 to 2022 are summarised in Table 38. Each of these 6 stations have over 85% of daily data recorded by the BoM.

Table 38. Proportion of daily SILO rainfall series (1900 to 2022) in the Fleurieu region with various quality codes

Site ID	Site name	SILO Data Quality Codes		
		0	15	25
23743	Victor Harbor (Rivington Grange)	87%	1%	12%
23753	Willunga	88%	11%	11%
23744	Second Valley (Poolamacca)	93%	1%	6%
23754	Yankalilla	86%	9%	5%
23741	Normanville	91%	3%	6%
23742	Port Elliot Caravan Park	91%	8%	1%

3.5.2 Annual rainfall – all sites

Table 39 summarises key statistics for annual rainfall in the Fleurieu region, showing the spatial variability of rainfall across the region. Victor Harbor (23743) showed the largest annual median of 700 mm, varying down to Port Elliot (23742) at just under 500 mm.

Table 39. Summary statistics for selected annual rainfall data (mm) in the Fleurieu (1900 to 2022)

Statistics (mm)	Victor Harbour (23743)	Willunga (23753)	Second Valley (23744)	Yankalilla (23754)	Normanville (23741)	Port Elliot (23742)
Annual average	700	640	597	580	524	496
Annual median	700	636	593	581	511	494
Annual maximum	1,067	971	982	987	804	913
Annual minimum	394	339	334	361	327	266
Standard deviation	134	130	132	122	110	101

Figure 27 shows the distribution of annual rainfall for the 6rainfall stations in the Fleurieu catchment across the drought periods as boxplots, while Table 40 shows the absolute medians and relative changes related to the WAP periods. In the drought period, the period medians were significantly below the pre-drought medians at Victor Harbor (12% less), Willunga (5%), Yankalilla (11%) and Port Elliot (5%). In contrast, the Second Valley (23744) station showed a median increase from pre-drought of 8%. Normanville (23741) showed a relatively consistent median between the two periods.

In the post-drought period, only Yankalilla showed a significant decrease from the pre-drought median (11% less, Wilcoxon p = 0.03), consistent with the reduction in drought period median. All other stations showed similar (or increased in the case of Second Valley, at 11% change) medians with pre-drought conditions, suggesting recovery has occurred across much of the catchment.

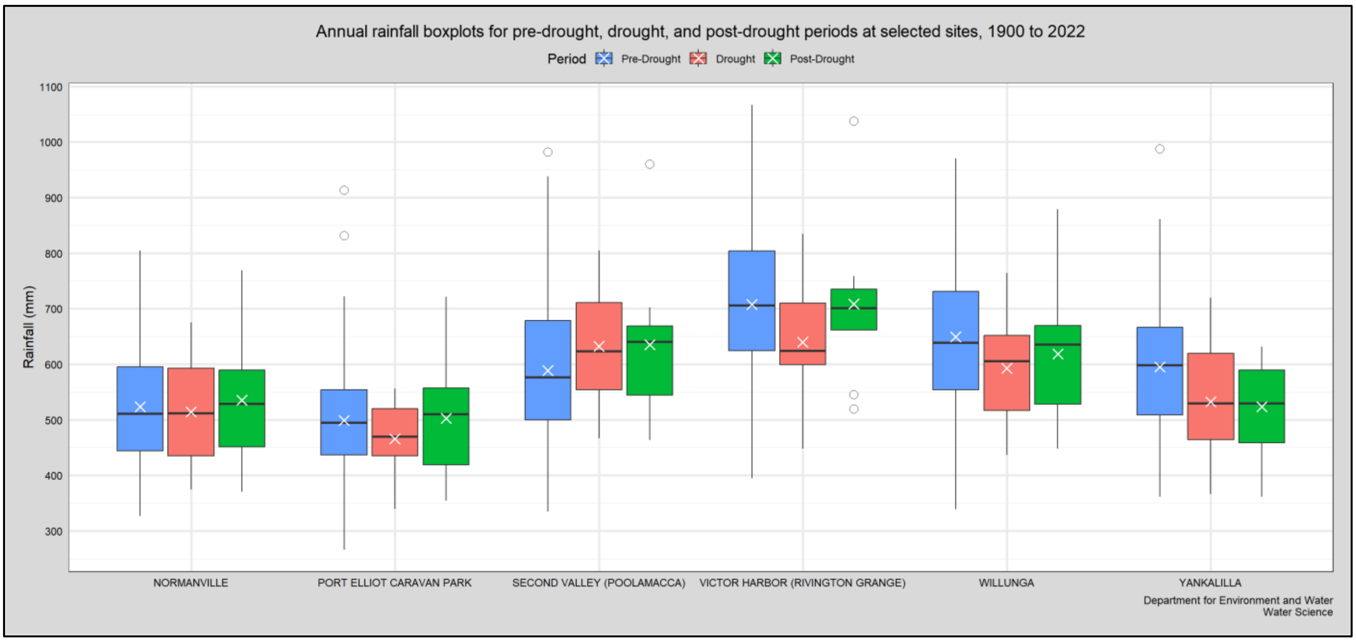


Figure 27. Distribution of annual rainfall in the Fleurieu catchment during drought periods (median (—), average (X), and outliers (O) shown)

Table 40. Median annual rainfall (mm) for different drought related periods across the Fleurieu region (1900 to 2022)

Period	Victor Harbor (23743)	Willunga (23753)	Second Valley (23744)	Yankalilla (23754)	Norman-ville (23741)	PT Elliot C.P. (23742)
All years (1900 to 2022)	700	636	593	581	511	494
Pre-drought (1900 to 1996)	706	639	576	598	511	495
Drought (1997 to 2008)	624	606	624	530	512	470
Post-drought (2009 to 2022)	701	636	640	530	529	510
Change compared to Pre-drought						
Drought (mm)	-82	-33	48	-69	1	-25
(%)	(-12%)	(-5%)	(8%)	(-11%)	(0%)	(-5%)
Post-drought (mm)	-5	-3	64	-68	18	15
(%)	(-1%)	(0%)	(11%)	(-11%)	(4%)	(3%)

Figure 28 shows the distribution of annual rainfall between the WAP development and post-WAP development phases for the 4 sites, while Table 41 shows the absolute medians and relative changes related to the WAP periods. The most significant increases in the post-WAP development period from WAP development were shown at Port Elliot (8%), Second Valley (7%) and Willunga (4%). Yankalilla was the only station showing a relative decrease in the latter period (5% less), while the remaining stations show similar values between the 2 periods (only 2% difference).

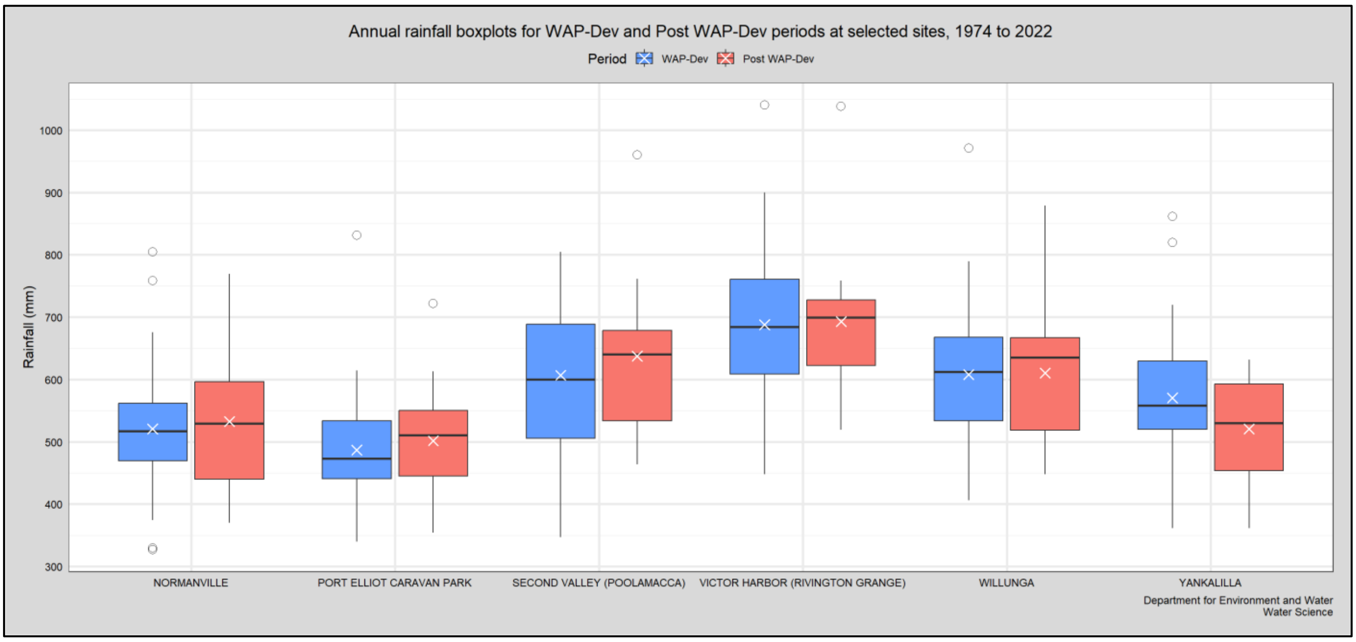


Figure 28. Distribution of annual rainfall in the Fleurieu catchment during WAP periods (median (—), average (X), and outliers (O) shown)

Table 41. Median annual rainfall (mm) for different WAP-development related periods across the Fleurieu region (1900 to 2022)

Period	Victor Harbor (23743)	Willunga (23753)	Second Valley (23744)	Yankalilla (23754)	Normanville (23741)	PT Elliot C.P. (23742)
All years (1900 to2022)	700	636	593	581	511	494
Pre-WAP (1900 to 2006)	700	638	582	592	511	493
WAP development (1974 to 2006)	684	612	600	558	517	473
Post-WAP development (2007 to 2022)	699	636	640	530	529	510
Change (WAP dev. to Post-WAP dev.) mm (%)	15 (2%)	23 (4%)	41 (7%)	-29 (-5%)	12 (2%)	37 (8%)

3.5.3 Detailed rainfall analyses – Second Valley (Poolamacca) (23744)

The time series of rainfall from Second Valley (23744) is analysed in the following plots, with data for the remaining stations in the Fleurieu regions included in Appendix 7.4.

Annual rainfall analysis

Rainfall totals for Second Valley at annual and decadal levels, with various period medians and trends included, are plotted in Figure 29(a) to (f). The trends of annual rainfall and decadal medians suggest little evidence of a change throughout the period of record from 1900 to 2022, with the last 3 decades representing 3of the 5 highest median decadal rainfall values on record (refer to Figure 29(a), (b), (e) and (f)). Annual deviations from the long-term median rainfall for Birdwood, shown in Figure 29(b), indicate that 5 of the past 10 years were considered above-median years, as per the classification in Table 1.

Medians for the drought-related periods (Figure 29(c)) show the median rainfall increasing from pre-drought to drought and through to post-drought periods, with the latter indicating the highest of the drought period medians. For WAP development and post-WAP development periods (Figure 29(d)) the data indicate the post-WAP development median is substantially greater than the WAP development and long-term medians.

Figure 29. **Rainfall plots at Second Valley (Poolamacca) (BOM site 23744) for 1900 to 2022 showing (a) long-term median, 10-year rolling median and linear trend, (b) deviation of annual rainfall from long-term median with linear trend, (c) annual rainfall showing median values of drought-related periods, (d) annual rainfall showing median values during the WAP development and Post-WAP development periods, (e) median annual rainfall per decade, (f) boxplots of distribution of annual median rainfall per decade.**

Seasonal rainfall analysis

The previous section outlined evidence indicating wetter conditions at the Second Valley rainfall station in recent decades when rainfall was analysed at an annual timescale. To further investigate these changes, and to determine whether these changes in rainfall are consistent across the year, historical daily rainfall at Second Valley was aggregated to seasonal totals.

Table 42 summarises median seasonal rainfall over the 3 drought-related climate periods used, together with the difference in annual and seasonal medians during the drought and post-drought periods in comparison to the pre-drought medians. These results show:

- The post-drought spring median was the only median to show a decrease from the pre-drought median, at 18% less. Winter showed a relatively consistent median with that in the pre-drought period (only 2% difference), while summer and autumn both showed an increase n median relative to pre-drought, of 28% and 8%, respectively.
- All median values in the drought period were shown to increase relative to pre-drought rainfall, from 4% in autumn to 28% in summer.

Table 42. Median seasonal rainfall for Second Valley (Poolamacca) (23744) for different periods around the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2009)	(2010 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Summer	57	52	67	67	15 (28%)	15 (28%)
Autumn	142	140	146	152	6 (4%)	12 (8%)
Winter	246	245	256	239	12 (5%)	-6 (-2%)
Spring	129	129	154	105	25 (20%)	-24 (-18%)
Annual	**593**	**576**	**624**	**640**	**48 (8%)**	**64 (11%)**

Table 43 summarises seasonal median rainfall totals for the periods that describe the development and post-development of the WAP. These results show:

- The post-WAP development phase (2007 onwards) showed a significant reduction in rainfall during spring (23% less) relative to the WAP development period.
- Summer and autumn rainfall was shown to increase (9% and 4%, respectively).
- Winter was relatively similar between the periods (2% change).

Table 43. **Median seasonal rainfall for Second Valley (Poolamacca) (23744) for different periods around WAP-development**

Season	All years	Pre-WAP	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1900 to 2022)	(1900 to 2006)	(1974 to 2006)	(2007 to 2022)	(mm)	(%)
Summer	57	56	62	67	6	9%
Autumn	142	142	146	152	6	4%
Winter	246	246	250	245	-5	-2%
Spring	129	131	136	105	-31	-23%
Annual	**593**	**582**	**600**	**640**	**41**	**7%**

Monthly rainfall analysis

Table 44 summarises the median rainfall for each calendar month for periods relative to the Millennium drought. The percentage change of median annual rainfall of the drought and post-drought periods from the pre-drought period are also shown. These results show:

- Median rainfall in the drought period decreased significantly relative to pre-drought only for April (29% less). Other sites showed an increase in rainfall (for example, November at 66% increase) or no significant change (for example July rainfall) relative to pre-drought median.
- Median rainfall in the post-drought period showed the most significant reduction in rainfall (relative to pre-drought) in September (12%). Other months showed increases to pre-drought medians (for example, May at 46%) or little difference between the periods (for example, August at 2% difference).

Table 44. Median monthly rainfall for Second Valley (Poolamacca) (23744) for different periods relative to the drought

Month	All years (1900- to 2022)	Pre-drought (1900 to 1996)	Drought (1997 to 2008)	Post-drought (2009 to 2022)	Change from Pre-drought: Drought mm (%)	Change from Pre-drought: Post-drought mm (%)
Jan	10	10	16	14	6 (59%)	4 (37%)
Feb	14	12	16	21	4 (34%)	9 (77%)
Mar	17	15	24	19	9 (58%)	4 (24%)
Apr	38	40	28	38	-12 (-29%)	-1 (-4%)
May	66	62	78	91	16 (26%)	29 (46%)
Jun	85	83	92	92	9 (11%)	9 (11%)
Jul	82	81	82	87	0 (0%)	5 (7%)
Aug	73	74	72	72	-1 (-2%)	-2 (-2%)
Sep	55	56	57	49	1 (2%)	-7 (-12%)
Oct	43	43	49	42	6 (14%)	-1 (-2%)
Nov	24	22	37	23	15 (66%)	1 (4%)
Dec	22	22	24	23	2 (11%)	2 (7%)
Annual	**593**	**576**	**624**	**640**	**48 (8%)**	**64 (11%)**

Table 45 summarises median monthly rainfall for the WAP development and post-WAP development periods. Changes in median monthly rainfall recorded during the post-WAP development phase when compared to the WAP development period are also shown. These results show:

- The largest reductions in median rainfall between post-WAP development and WAP development periods occurred in the months between July to October. January showed a minor reduction of only 2 mm, but due to low rainfall in the month resulted in a greater percentage change (10%).
- Other months showed increases to various degrees between post-WAP development and WAP-development periods.

Table 45. **Median monthly rainfall for Second Valley (Poolamacca) (23744) for different periods around the Post WAP-development**

Month	All years (1900 to 2022)	Pre-WAP (1900 to 2006)	WAP development (1974 to 2006)	Post WAP-development (2007 to 2022)	Change (WAP dev to imp.) (mm)	(%)
Jan	10	10	15	14	-2	-10%
Feb	14	14	12	16	3	25%
Mar	17	16	19	21	2	11%
Apr	38	38	31	38	7	21%
May	66	62	60	84	24	41%
Jun	85	83	84	92	8	10%
Jul	82	81	91	87	-4	-4%
Aug	73	73	77	72	-5	-7%
Sep	55	56	62	49	-13	-22%
Oct	43	44	51	42	-9	-17%
Nov	24	25	22	24	1	5%
Dec	22	22	23	24	1	5%
Annual	**593**	**582**	**600**	**640**	**41**	**7%**

3.5.4 Trend and Shift analyses of rainfall

Detailed analysis of Second Valley (Poolamacca) (23744)

CUSUM charts were prepared for the time series of rainfall at Second Valley (Poolamacca) (23744) aggregated to annual totals (Figure 30). The annual CUSUM chart does not show any data points falling outside of the action limits (yellow shading). However, since the early 1990s there are more data points above the long-term mean, and much further away from the long-term mean line, than the data points below the long-term mean, indicating a wetter period. This is similar to previous analyses indicating wetter drought and post-drought periods.

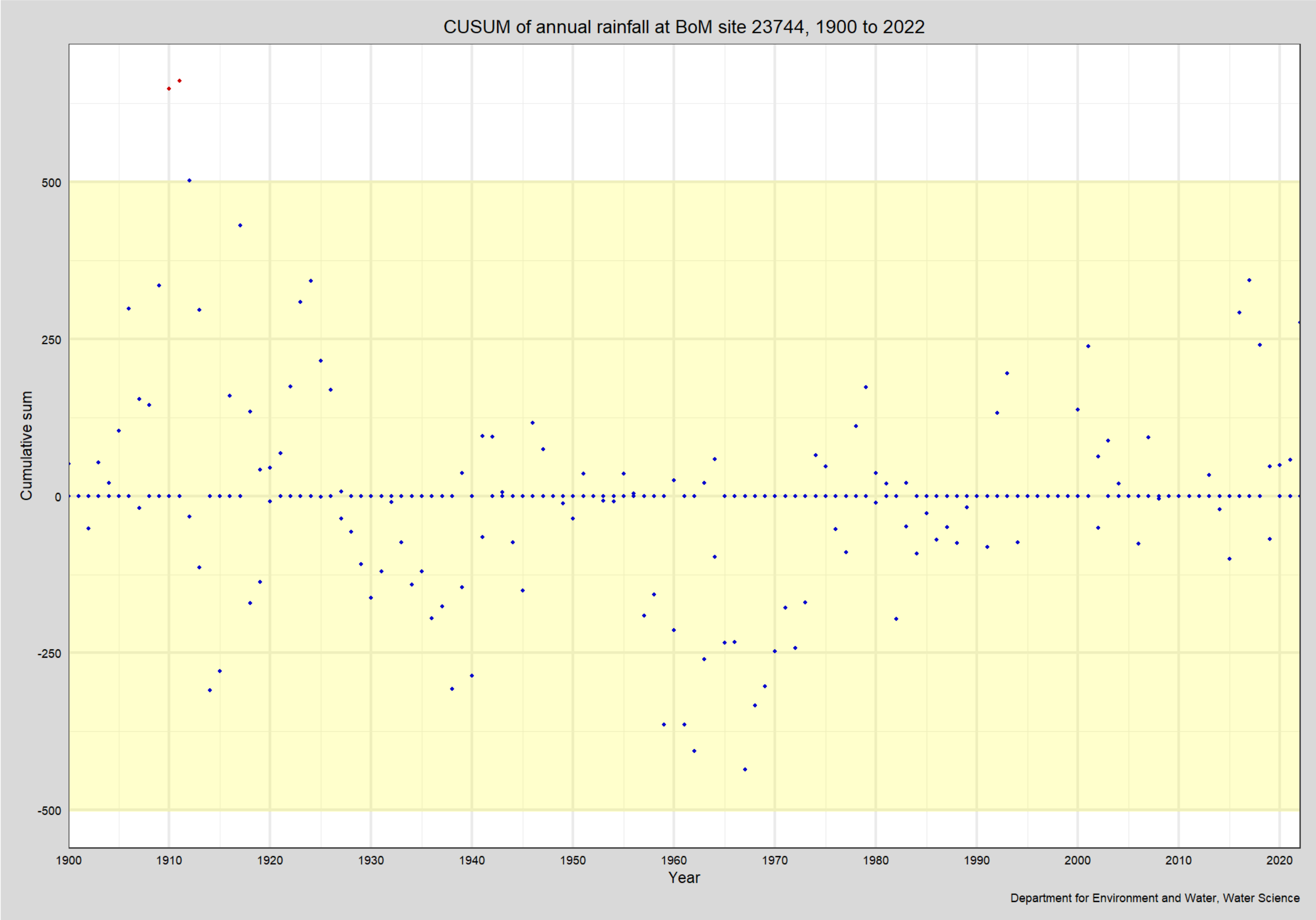


Figure 30. CUSUM chart of annual rainfall (1900 to 2022) for Second Valley (Poolamacca) (BOM site 23744)

Figure 31 shows the CUSUM charts of seasonal rainfall totals. These results show:

- The cumulative sum of winter and spring rainfall has generally remained above the long-term mean since the early 1990s, with spring also showing some negative deviations around the late 2000s and early 2010s.
- Summer and autumn rainfall was shown to remain largely around the long-term mean for the past few decades.

Figure 32 shows CUSUM charts of monthly rainfall totals. There is little evidence to suggest any significant trends in the period since the onset of the drought at this station, other than most months showing more data points congregating above the long-term mean than below in the drought and post-drought periods.

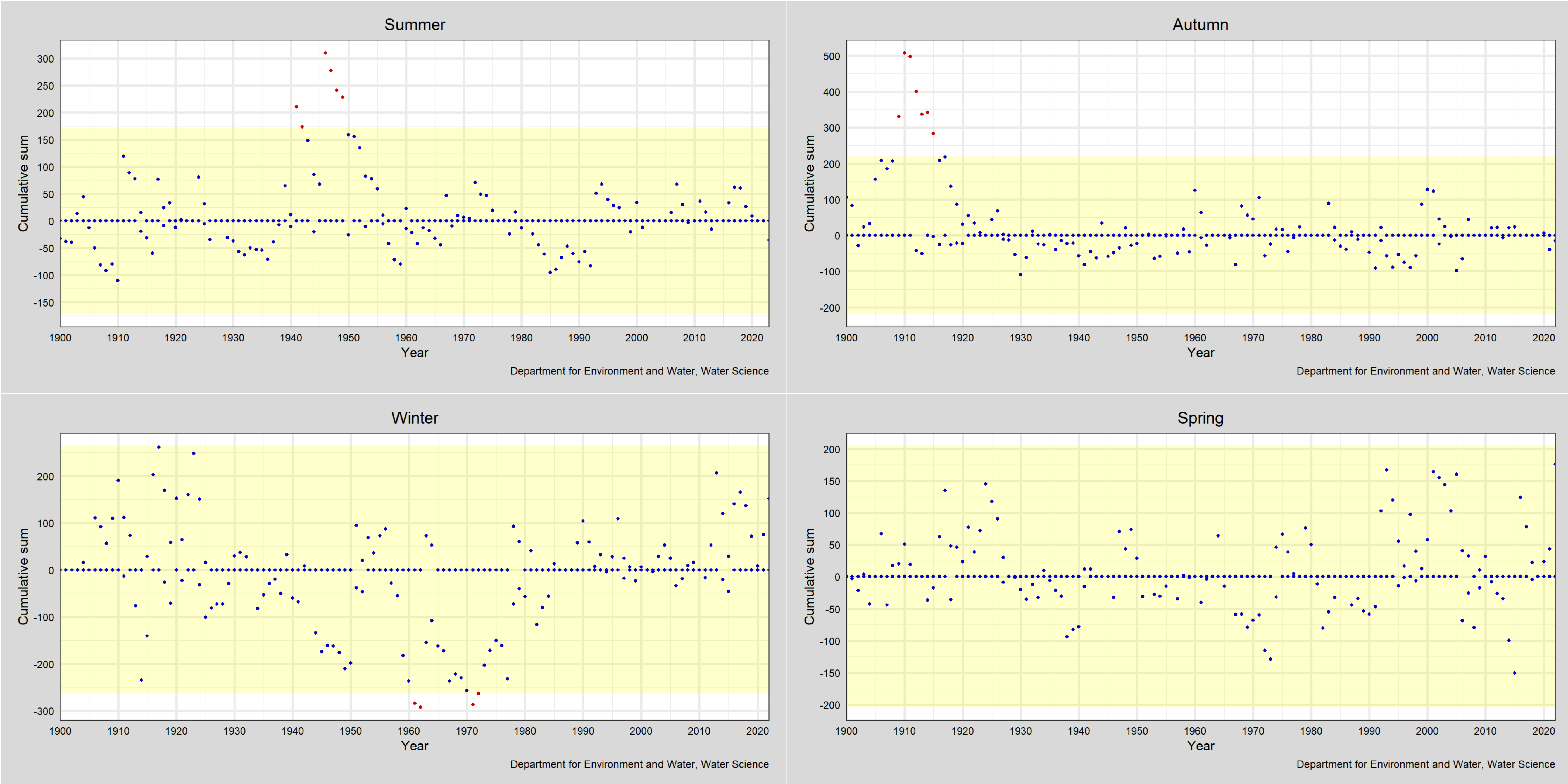


Figure 31. CUSUM charts of seasonal rainfall (1900 to 2022) for Second Valley (Poolamacca) (23744)

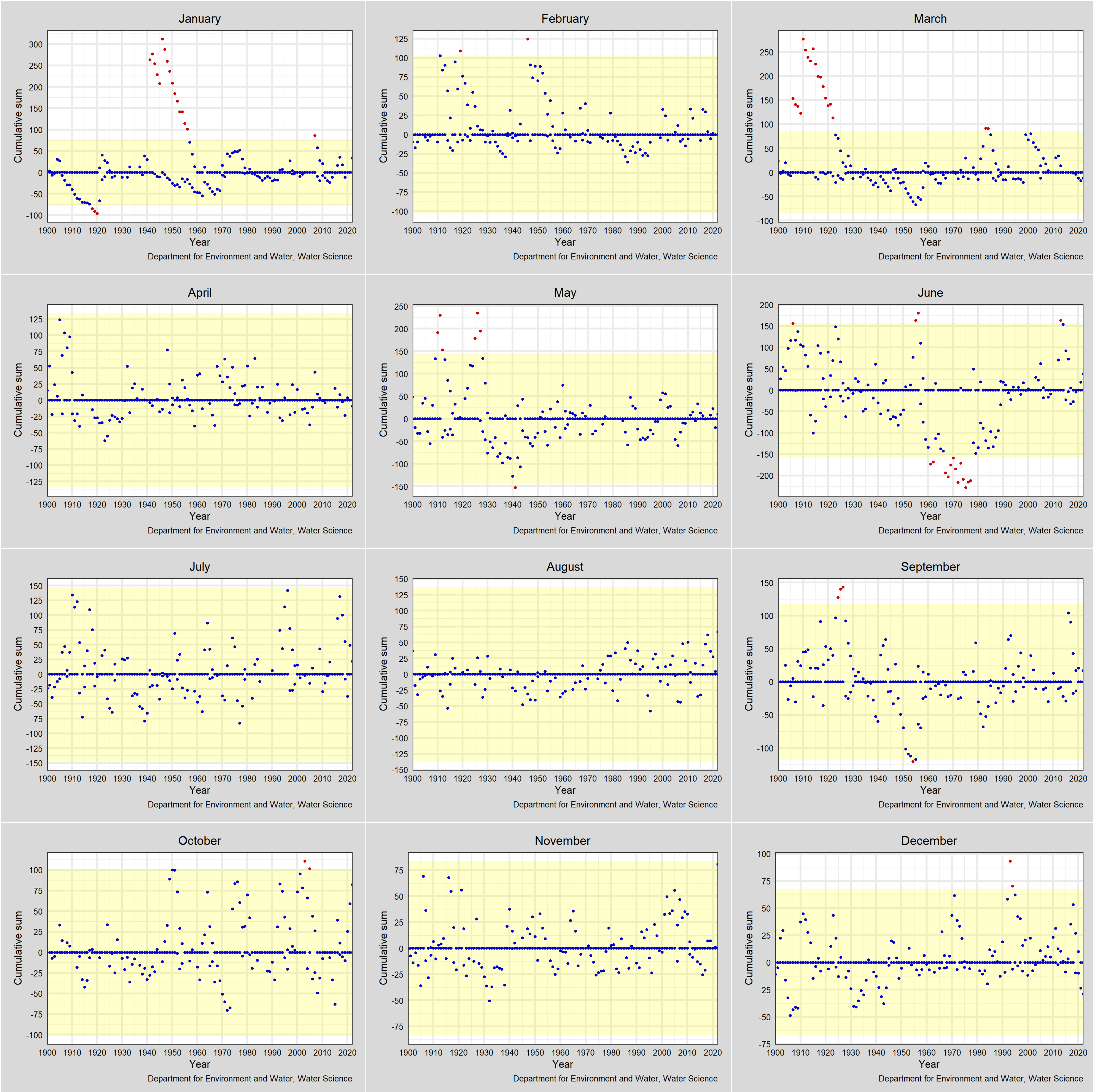


Figure 32. CUSUM charts of monthly rainfall (1900 to 2022) for Second Valley (Poolamacca) (23744)

Table 46 summarises the results of the statistical tests for data from Second Valley (Poolamacca). Results for the other sites are provided in Appendices 7.3 and 7.4. For the Mann-Kendall Test, a negative 'tau' value indicates that a time series has a monotonic downward trend, and vice versa, and a p value less than 0.05 indicates that the trend is statistically significant at a 5% level. These are highlighted in red. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate the presence of a monotonic trend but with a slightly lesser degree of statistical significance (between 5% and 10%).

For the Wilcoxon and Welch's tests, a p value less than 0.05 indicates that there is a significant difference or shift (at a 5% level) in median value of 2 samples that represent observations across different periods. These are highlighted in red in the table. Additionally, p values between 0.05 and 0.10 are highlighted in red and shown in italics to indicate a shift, but with a lesser degree of statistical significance (between 5% and 10%).

Results of the statistical tests presented in the table show:

- The Mann-Kendall test shows evidence of a statistically significant increasing trend during summer and, more specifically, January.
- Wilcoxon and Welch's tests show no evidence of statistically significant shifts in any of the periods analysed.

Table 46. Summary of statistical tests for separating rainfall data for Second Valley (Poolamacca) (23744) at different years, and aggregating across various periods

Period	Mann-Kendall (1900 to 2022)		Drought periods (pre- and post-1996)		Post WAP-development (pre- and post-2007)	
	tau	p value	Wilcoxon *p value*	Welch's p value	Wilcoxon *p value*	Welch's p value
Annual	0.019	0.756	0.948	0.963	0.862	0.890
Summer	0.121	0.047	0.981	0.873	0.956	0.958
Autumn	-0.054	0.375	0.700	0.552	0.749	0.749
Winter	0.038	0.533	0.903	0.934	0.827	0.904
Spring	-0.011	0.865	0.820	0.874	0.274	0.396
Jan	0.125	0.041	0.907	0.734	0.572	0.857
Feb	0.044	0.476	0.912	0.625	0.785	0.815
Mar	-0.002	0.976	0.900	0.650	0.479	0.178
Apr	-0.027	0.665	0.197	0.140	0.588	0.495
May	0.007	0.915	0.906	0.817	0.970	0.963
Jun	-0.011	0.861	0.885	0.874	0.673	0.800
Jul	0.037	0.540	0.715	0.682	0.721	0.732
Aug	0.088	0.150	0.864	0.877	0.812	0.823
Sept	-0.046	0.448	0.442	0.573	0.179	0.408
Oct	0.013	0.839	0.776	0.846	0.188	0.182
Nov	0.081	0.186	0.963	0.934	0.732	0.763
Dec	0.083	0.176	0.873	0.833	0.718	0.675

Statistical analysis summary of other Fleurieu catchment sites

Review of the statistical analysis of annual, seasonal and rainfall totals for other sites in the Fleurieu region (excluding Second Valley) is summarised below:

- Review of annual rainfall total CUSUM plots for other stations within the Fleurieu region generally shows little evidence of a shift in rainfall since the start of the Millennium drought. However, all stations show annual rainfall has generally remained just below the long-term mean in the last few decades. On a seasonal basis, all sites show autumn and spring rainfall reached historical lows since the early 1990s, whereas no changes in rainfall post-1996 were detected in either summer or winter for all stations.
- Victor Harbor (23743) – Significant downward trends were detected in annual, spring and September rainfall periods, while January showed a significant increasing trend (Mann-Kendall). In the context of drought-related periods, significant negative shifts in rainfall were detected in annual and autumn (April) periods (Wilcoxon rank sum/Welch's t-test). In WAP-related periods, significant negative shifts were only detected in March and October.
- Willunga (23753) – Decreasing trends were detected on annual, spring and autumn timescales (Mann-Kendall), with these periods (and additionally October) showing a significant negative shift post-1996 (Wilcoxon rank sum/Welch's t-test). In a WAP-related context, only October showed evidence of a significant shift post-WAP development.
- Yankalilla (23754) – Significant downward trends were detected on annual and spring timescales (Mann-Kendall), while significant negative shifts post-1996 were detected annually and in winter (July) and autumn (April) (Wilcoxon rank sum/Welch's t-test). In a WAP-related context, October showed a strong negative shift in rainfall post-WAP development, along with weaker evidence in March.
- Normanville (23741) – Only January showed a significant increasing long-term trend (Mann-Kendall), with no evidence of a significant shift detected in any period post-1996 (Wilcoxon rank sum/Welch's t-test). In a WAP-related period context, October showed evidence of a significant negative shift in rainfall.
- Port Elliot (23742) – No evidence of any long-term trends was detected in any period (Mann-Kendall), while only autumn (April) showed evidence of a negative shift in rainfall post-1996. On a WAP-related basis, October showed significant evidence of a negative shift in rainfall (Wilcoxon rank sum/Welch's t-test).

3.6 Rainfall summary – MLR

Results of analyses of rainfall data were presented at a catchment scale in the earlier sections. To obtain a picture of rainfall trends at MLR-scale (combined PWRAs) results of analyses of data from all 24 rainfall stations investigated are summarised in this section.

3.6.1 Rainfall recovery – Period medians

Annual and seasonal median rainfall data for the 3 drought comparison periods for each of the 24 rainfall stations investigated are provided in Appendix 7.1. To obtain a PWRAs-scale picture of the recovery status of rainfall during the post-drought period (2009 to 2022), the stations were grouped into the 3 categories by comparing the post-drought median to drought and pre-drought period medians, as defined in Section 2.5, and summarised in the table below.

Table 47. Summary of post-drought rainfall recovery status for all stations investigated

Post-drought period rainfall recovery status	Number of stations (%)				
	Annual	Seasonal			
		Winter	Spring	Summer	Autumn
Fully Recovered (wettest)	58%	75%	0%	46%	25%
Partially Recovered	33%	8%	21%	33%	25%
Yet to Recover (driest)	8%	17%	79%	21%	50%

Data presented in Table 47 show that of the 24 rainfall stations investigated across the 2 PWRAs:

- Rainfall during the spring season has clearly had the most impact since the beginning of the Millennium drought, with 79% of stations falling in the Yet to Recover (driest) category during the post-drought period.
- Rainfall during the autumn season has also been significant – although to a lesser extent than spring – since the beginning of the Millennium drought, with 50% of stations falling in the Yet to Recover (driest) category during the post-drought period.
- When considering annual totals, 91% of the stations have either fully or Partially Recovered during the post-drought period. This is attributed primarily to winter season rainfall recovery, with 83% of stations either fully or partially recovering during the post-drought period. While summer season rainfall amounts to a minor proportion of the annual totals, it is worth noting that 79% of the sites have either fully or Partially Recovered during the post-drought period.

The results presented here, along with results of other statistical analyses of rainfall data, provide evidence that suggests a change in rainfall seasonality has occurred since the beginning of the Millennium drought.

3.6.2 Periodic shifts in long-term rainfall - CUSUM analysis summary

Results of inspection of CUSUM charts prepared for the time series of rainfall aggregated to annual, seasonal and monthly totals are summarised in this section.

- The annual CUSUM charts do not show any data points falling outside of the action limits (yellow shading) at any of the rainfall stations analysed since the commencement of the drought. At many rainfall stations the behaviour indicated since the early 1990s is the cumulative sum remaining predominantly below the long-term mean line, with a limited number of isolated increases, owing to high rainfall years (for example 2016). The reduction in CUSUM is generally not unprecedented compared to historical data, however, resulting in limited indications of a sustained shift in annual rainfall across the PWRAs.
- Seasonal CUSUM charts indicate spring rainfall CUSUM values reached historical lows in almost 92% of rainfall stations, with almost 46% of stations showing some CUSUM data points falling below the lower action limits in this period. For autumn rainfall, almost 88% of stations showed rainfall CUSUM values reduce to historical lows during the drought period, while at all stations analysed CUSUM shifted back towards the long-term mean in the post-drought period. Summer and winter CUSUM data points generally remain around the long-term averages across the PWRAs in the period since the drought commencement, with only 3 of the 24 stations showing summer rainfall to deviate significantly above the long-term average in the post-drought period before reducing back towards the long-term average at the end of the analysis period.
- Monthly CUSUM charts show October rainfall underwent a significant negative shift – falling to historical lows – at 22 of the 24 rainfall stations since the commencement of the drought. A steady decline in the CUSUM was detected throughout the PWRAs from the early 2000s in 75% of stations, shifting below the lower action limit at times during the 2010s. At each station the high rainfall year of 2022 resulted in a positive jump in CUSUM values towards the long-term average, regardless of the magnitude of decrease since the drought. Further data is required to assess whether this jump in 2022 will persist or be a short-term anomaly. Other months show rainfall behaviours that vary on a station-by-station basis, with no specific patterns indicated across the PWRAs.

3.6.3 Long-term trends in annual and seaonal rainfall - Mann-Kendall test results summary

Results of the Mann-Kendall test for long-term (1900 to 2022) annual, seasonal and monthly rainfall records for each of the 24 stations investigated are provided in the tables in Appendix 7.2. Explanation of the methodology is provided in Section 2.7. To obtain a PWRAs-wide picture of the long-term trends in rainfall data of all the stations investigated, key results of the Mann-Kendall test are summarised below:

- A statistically significant declining trend in long-term annual rainfall was observed at 50% of stations (38% of stations at 5% significance levels, and 13% of stations between 5% and 10% significance levels). The stations that show no evidence of a statistically significant declining trend in annual rainfall are generally located in certain sections of the Onkaparinga and Fleurieu catchments, and in the lower elevation/lower rainfall sections of the Bremer River catchment.
- A statistically significant declining trend in long-term spring rainfall was observed at 58% of stations (33% of stations at 5% significance levels, and 25% of stations between 5% and 10% significance levels). All stations that show evidence of statistically significant declining trend in annual rainfall also show the same in spring. A high proportion of these stations show a statistically significant declining trend in October rainfall, with a smaller proportion during September.
- A statistically significant declining trend in long-term autumn rainfall was observed at 25% of stations (12.5% of stations at 5% significance levels, and 12.5% of stations between 5% and 10% significance levels). On a monthly scale, only one of these stations shows evidence of a statistically significant declining trend in April rainfall.
- A statistically significant increasing trend was observed in long-term summer rainfall at 3 stations, and January rainfall at 5 stations. All these stations are located either in the Bremer (lower elevation sections) or across the Fleurieu catchment.

3.6.4 Shift in rainfall – Wilcoxon Rank Sum and Welch's t-test results summary

The Wilcoxon and Welch's tests were undertaken to identify possible evidence of statistically significant shifts:

- between pre- and post-drought periods, in annual, seasonal and monthly rainfall data
- between WAP development and post-WAP development periods, in seasonal median (spring) and October median and mean rainfall.

Explanation of the methodology is provided in Section 2.7. Results of the 2 tests for each of the 24 stations investigated are provided in the tables in Appendix 7.3. To obtain a PWRAs-wide picture, results of all the stations investigated are summarised here.

The key results of the Wilcoxon and Welch's tests for the 24 rainfall stations investigated show a statistically significant shift between pre- and post-drought periods:

- In annual rainfall – at 50% of the sites. Of the sites with no significant evidence of a shift, 4 (out of 5) sites are in the Bremer, 1 (out of 4) sites is in the Torrens, 4 (out of 6) sites are in the Onkaparinga and 3 (out of 6) sites are in the Fleurieu region.
- In seasonal rainfall – at 60% of the sites in autumn and 40% of the sites in spring. One key statistic to note is that there no evidence of a shift in spring at any site in the Fleurieu and at 4 of the 5 sites in the Bremer.
- In monthly rainfall - at 60% of sites in October and at 40% of the sites in April rainfall.

The key results of the Wilcoxon and Welch's tests for the 24 rainfall stations investigated show a statistically significant negative shift between WAP development and post-WAP development periods:

- In seasonal rainfall – at 38% of the sites in spring. Of these sites, 5 out of 6 sites are located in the Onkaparinga, 2 out of 4 in the Torrens, and both sites in the Finniss–Angas catchment (Meadows and Macclesfield).
- In monthly rainfall – at 96% of the sites (23 out of 24 sites) in October, one site in September and two sites in March.

Note that no statistically significant shifts were detected in annual rainfall between the WAP-related periods.

In summarising the results of the analyses presented above, seasonal rainfall during spring (in October and to a lesser extent in September) and to a lesser degree in autumn (April) have undergone a statistically significant change since the start of the Millennium drought at the majority of rainfall stations. There is also evidence of a decline in long-term annual rainfall at approximately half of the stations analysed, particularly in the higher elevation areas of the MLR. Investigation using a larger sample of lower elevation stations across the MLR is required to confirm if the impacts of climate change and/or the drought were primarily in the higher elevation sections of the MLR.

4 Streamflow

Overview

The rationale behind selection of catchments and streamflow sites within them for this investigation are provided in Sections 2.1 and 2.3. The location of the streamflow sites used in the investigation are shown in Figure 33.

Analyses of streamflow records for the periods 1974 to 2022 (where records were available) were undertaken using various methods primarily to:

- trends in long-term annual, seasonal, monthly and daily streamflow data
- identify changes to annual, seasonal and monthly streamflow for 3 drought-related (pre-, during and post-) and two WAP development (WAP development and post-WAP development) periods.

The results of streamflow data analysis feed into the rainfall-runoff section, which is critical in understanding catchment behaviour and to inform future water planning.

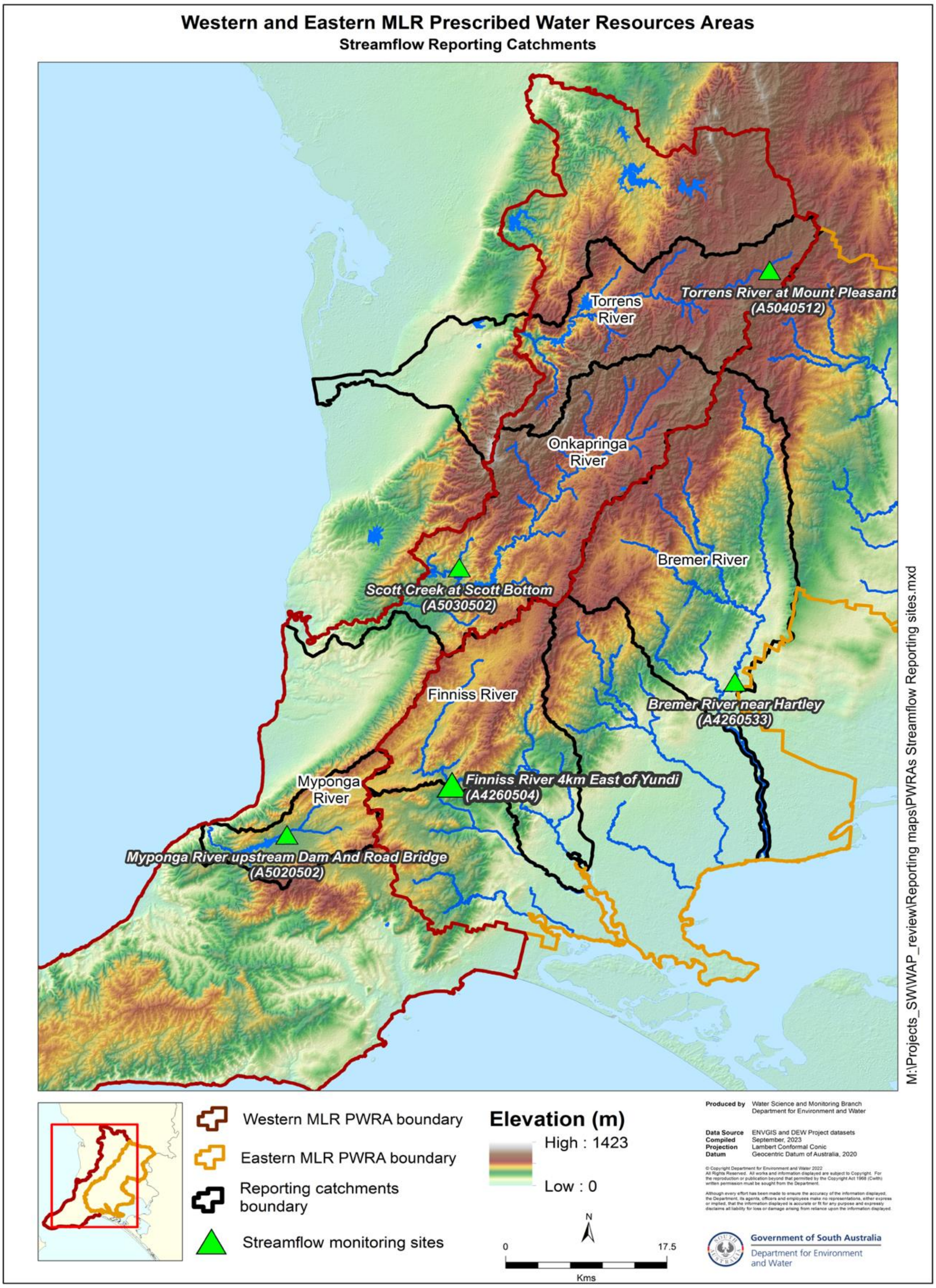


Figure 33. Streamflow reporting stations used in this report

4.1 Finniss River

Streamflow records from the Finniss River at Yundi (A4260504) gauging station were used for the analysis. The gauging station is located at the outlet of Meadows Creek, the largest and wettest sub-catchment of the Finniss River (Figure 33). Streamflow data for the period 1974 to 2022 reflects rainfall variability, reaching peak discharge volumes of 53,663 ML (1992) and a minimum annual discharge of 4,338 ML (1982), with the long-term annual median being 22,611 ML.

4.1.1 Annual streamflows

Figure 34 shows the distribution of annual streamflow at Yundi (A4260504) for the various drought- and WAP-related periods as boxplots. Median annual flow is shown to have increased slightly in the post-drought period compared to the drought but has remained lower than the pre-drought period median. Median annual flow in the post-WAP development period is lower than during the WAP development period.

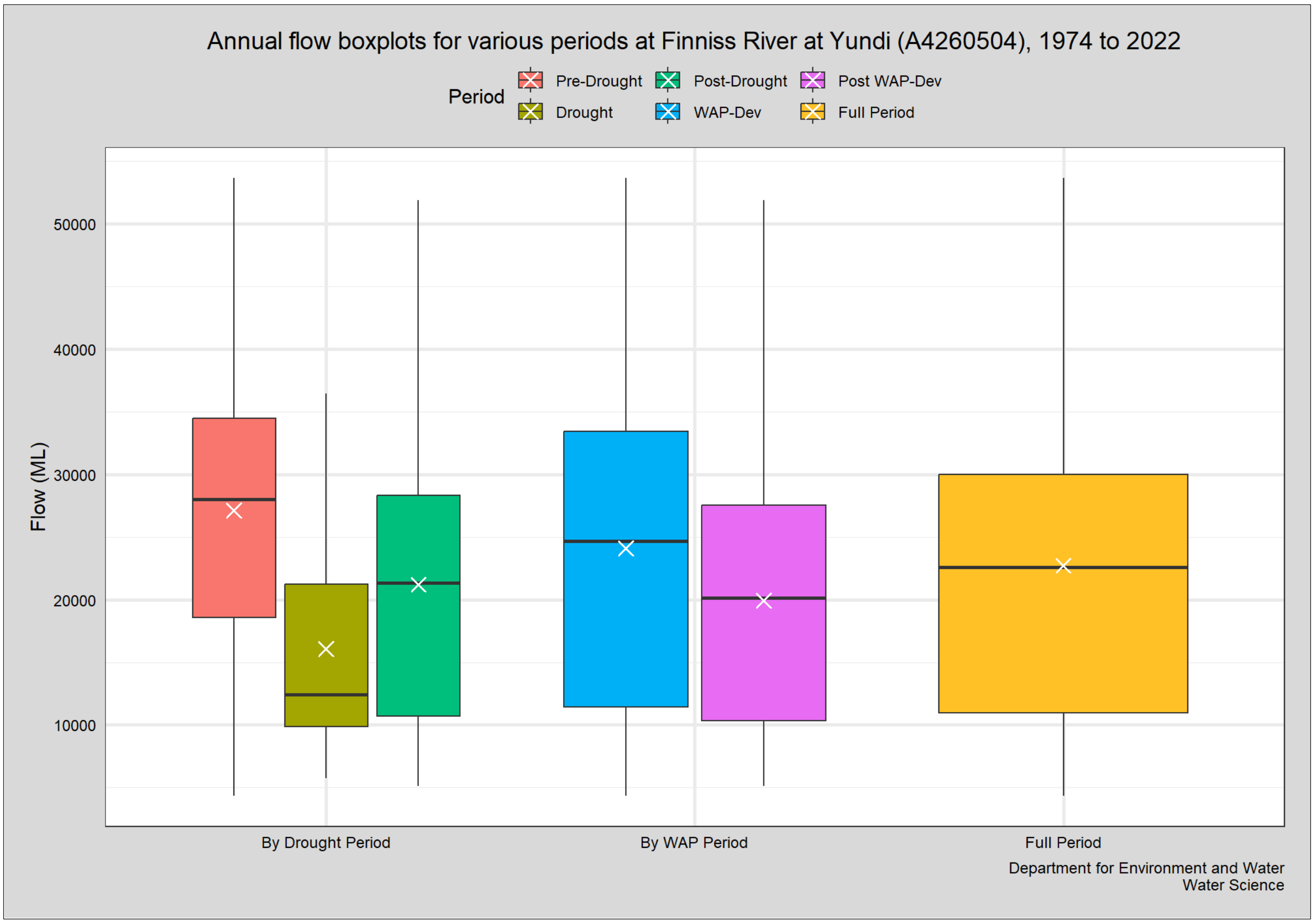


Figure 34. Distribution of annual streamflow totals for Finniss River at Yundi (A4260504) for different periods during 1974 to 2022 (median (—), average (X), and outliers (O) shown)

Figure 35 (a) shows a time series of annual streamflow totals for 1974 to 2022, with long-term median annual flow shown alongside a 10-year rolling average and long-term trend, both of which suggest a general decline in streamflow totals over the period of observation.

Figure 35 (b) shows annual deviations from the long-term median. The data show that, apart from a very wet year in 2016 followed by a relatively wetter year in 2022, recent decades have shown a greater number of below-median streamflow years compared to the pre-drought period (1974 to 1996).

Figure 35 (c) and Table 48 shows annual streamflow with median annual flows displayed for pre-drought, drought, and post-drought periods as well as the full period average. The results show that the median annual streamflow during the drought period was over 14,000 ML (≈50%) less than the pre-drought period. The median annual flow subsequently increased by almost 8000 ML in the post-drought period but remained below the pre-drought average by around 6600 ML (≈30%).

Figure 35 (d) (and Table 48) shows annual streamflow totals coloured by drought phase, with median annual flows for the WAP development and post-WAP development periods also shown. These reveal a substantial reduction in median annual flow in the period following the WAP development (that is, from 2007 onwards) by 3655 ML (15%).

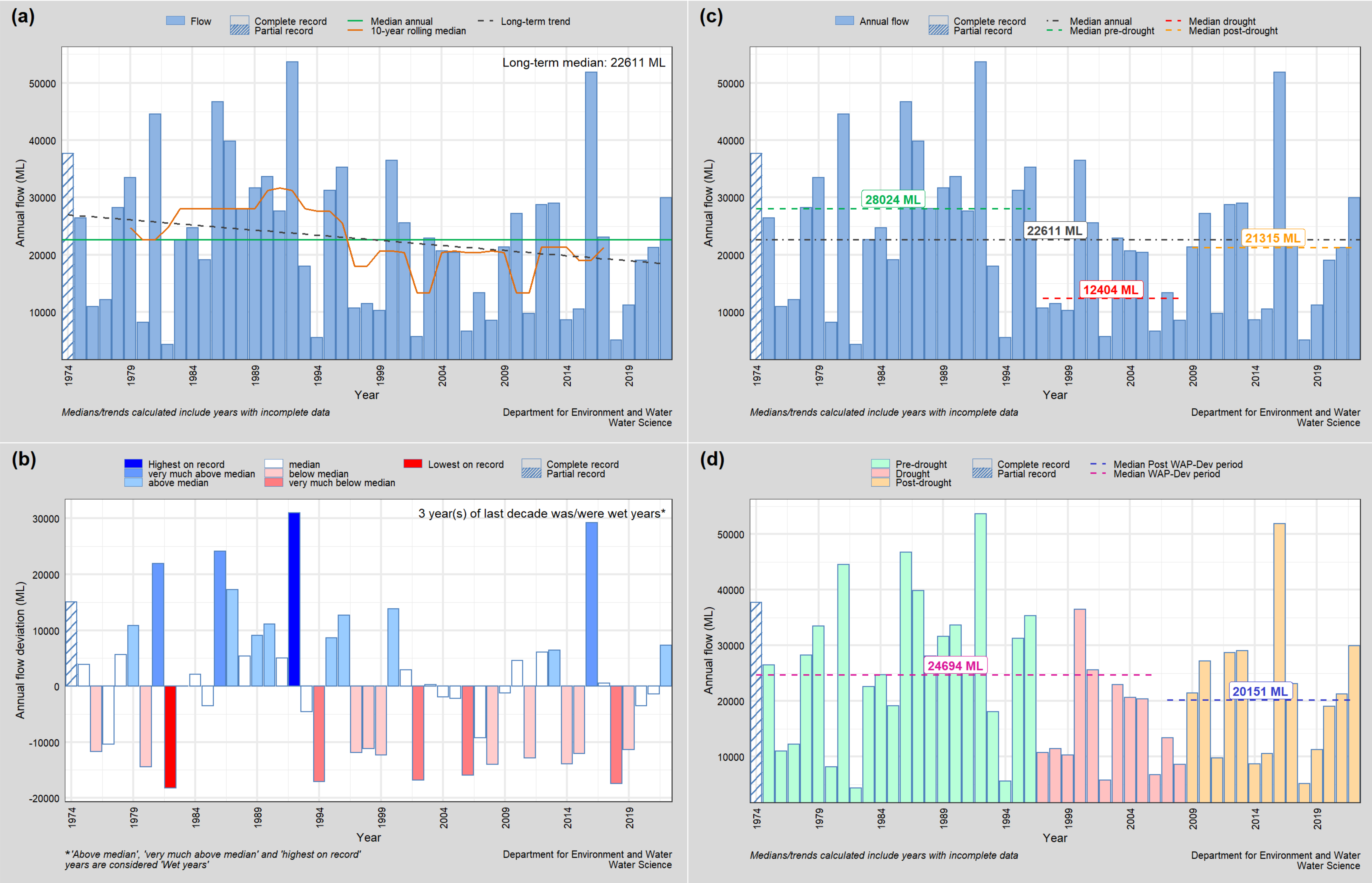


Figure 35. (a) Annual streamflow totals for Finniss River at Yundi (A4260504) for 1974 to 2022, (b) Deviations in annual streamflow totals in Finniss River at Yundi (A4260504) from long-term median, (c) Annual streamflow totals for Finniss River at Yundi (A4260504) showing medians before and after the drought (1997 to 2009), (d) Annual streamflow totals for Finniss River at Yundi (A4260504) showing medians during WAP development (1974 to 2006) and during Post WAP-development.

4.1.2 Seasonal streamflows

Results of analysis of streamflow records at the A4260504 station at seasonal time steps are summarised below in Table 48 and Table 49. Table 48 summarises the median seasonal streamflow for different periods relative to the Millennium drought. These statistics show that majority of annual flow is recorded across winter and spring seasons. While flows during autumn and summer are only a small proportion of the annual totals, they are critical in maintaining in-stream ecosystem functionality.

Median flow in each of the four seasons reduced substantially during the drought period relative to the pre-drought period, before increasing again in the post-drought period, although not to the levels of the pre-drought period. The exception is autumn, during which flows have reduced further since the drought period. Regarding recovery of seasonal flows to pre-drought conditions, none of the seasons have recovered to pre-drought conditions. The least recovery has been during autumn season (still around 60% less than pre-drought median), followed by spring (50% less) and summer, with winter experiencing the highest recovery.

Table 48. Median annual and seasonal streamflow for Finniss River at Yundi (A4260504) across periods defined by the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1974 to 1996)	(1997 to 2009)	(2010 to 2022)	Drought (ML *(%)*)	Post-drought (ML *(%)*)
Summer	98	161	65	99	-97 (-60%)	-63 (-39%)
Autumn	330	572	363	220	-208 (-36%)	-351 (-61%)
Winter	13,016	17,606	7,934	13,362	-9,672 (-55%)	-4,244 (-24%)
Spring	4,773	6,724	2,826	3,456	-3,897 (-58%)	-3,268 (-49%)
Annual	**22,611**	**28,024**	**12,404**	**21,315**	**-15,620 (-56%)**	**-6,709 (-24%)**

Table 49. summarises seasonal median flow for WAP development and post-WAP development periods. Median seasonal flows reduce in each season from WAP development to post-WAP development periods, with the largest reduction seen in the autumn and spring seasons at 59% and 45%, respectively. Winter and summer reductions are relatively lower, at only 11% and 6%, respectively.

Table 49. Median annual and seasonal streamflow for Finniss River at Yundi (A4260504) across periods representing WAP development

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1974 to 2022)	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Summer	98	102	96	-6	-6%
Autumn	330	531	220	-311	-59%
Winter	13,016	13,480	11983	-1,498	-11%
Spring	4,773	5,966	3,272	-2,694	-45%
Annual	**22,611**	**24,694**	**2,0151**	**-4,543**	**-18%**

4.1.3 Monthly streamflows

The distribution of flow across each calendar month, with monthly totals aggregated to various drought and WAP-related periods, is summarised in Table 50 and Table 51 respectively. The monthly data shows median flow in each calendar month, except for November, has a significant reduction from the commencement of the drought period. At least 75% of annual flow in each period is recorded across a 3-month period covering July to September, and the large reductions in flow during these months have a significant impact on annual flows.

Table 50 Median monthly streamflow for Finniss River at Yundi (A4260504) for drought periods

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Jan	20	27	11	20	-16 (-58%)	-7 (-25%)
Feb	16	16	7	17	-9 (-56%)	1 (6%)
Mar	25	35	15	21	-20 (-58%)	-14 (-40%)
Apr	76	121	43	57	-78 (-65%)	-64 (-53%)
May	211	399	284	147	-115 (-29%)	-252 (-63%)
Jun	1,066	1,066	1,570	938	504 (47%)	-128 (-12%)
Jul	3,935	5,582	3,090	3,207	-2,492 (-45%)	-2,375 (-43%)
Aug	5,519	7,951	3,264	5,058	-4,687 (-59%)	-2,893 (-36%)
Sep	2,807	4,392	1,759	2,355	-2,633 (-60%)	-2,037 (-46%)
Oct	815	1,039	609	547	-429 (-41%)	-491 (-47%)
Nov	201	241	215	137	-26 (-11%)	-103 (-43%)
Dec	60	88	37	64	-51 (-58%)	-25 (-28%)
Annual	**22,611**	**28,024**	**12,404**	**21,315**	**-15,620 (-56%)**	**-6,709 (-24%)**

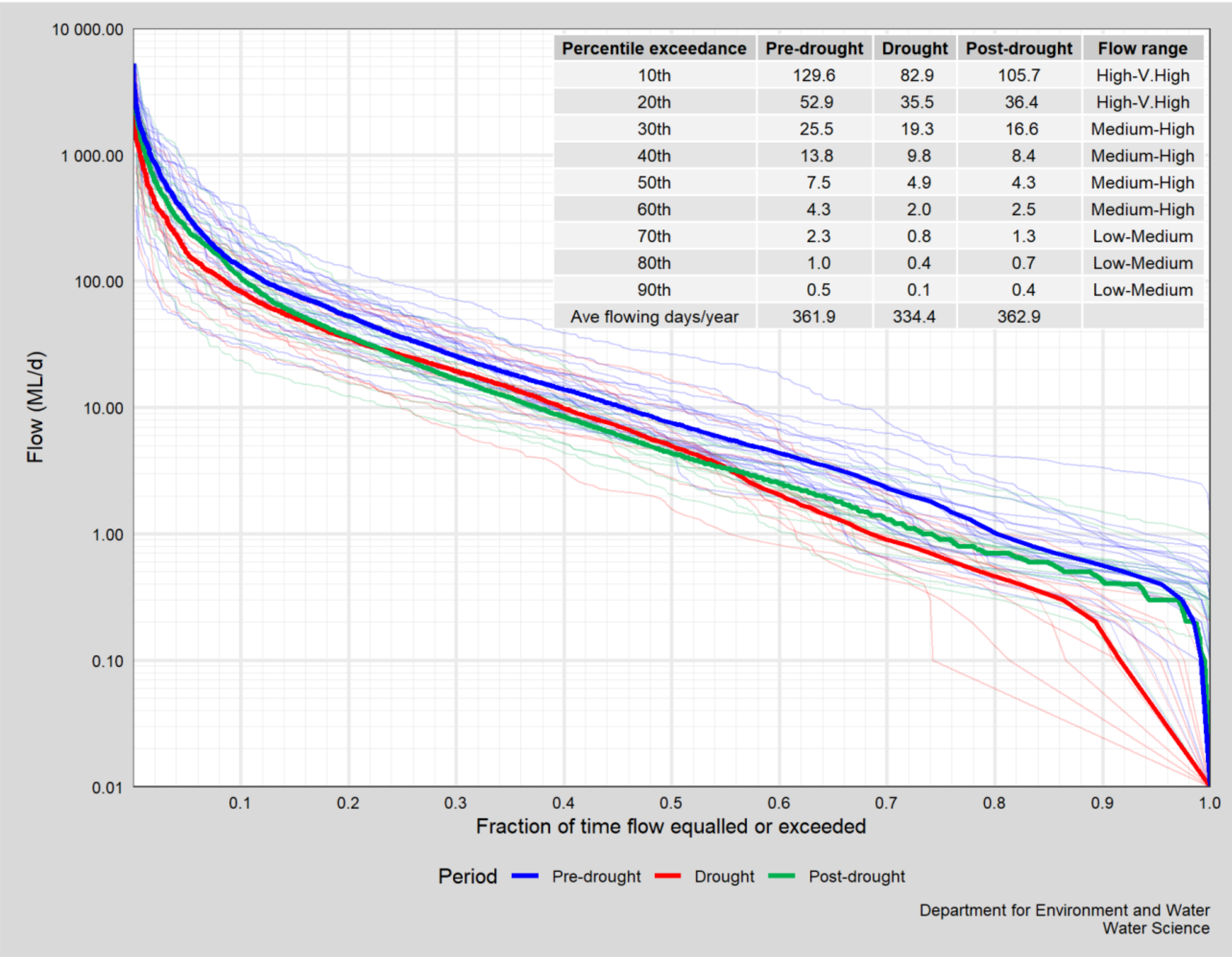
Table 51 Median monthly streamflow for Finniss River at Yundi (A4260504) for WAP periods

Month	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1974 to 2022)	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Jan	20	20	17	-3	-15%
Feb	16	16	16	0	3%
Mar	25	29	19	-9	-33%
Apr	76	106	57	-49	-46%
May	211	348	147	-202	-58%
Jun	1,066	1,222	938	-284	-23%
Jul	3,935	4,276	3,207	-1,068	-25%
Aug	5,519	6,567	5,058	-1,508	-23%
Sep	2,807	3,087	1,708	-1379	-45%
Oct	815	1,039	524	-515	-50%
Nov	201	237	137	-100	-42%
Dec	60	62	58	-4	-6%
Annual	**22,611**	**24,694**	**20,151**	**-4,543**	**-18%**

4.1.4 Daily streamflows

Further investigation of flow records at a daily time step was undertaken to evaluate the impacts of changing rainfall on daily flow patterns. The plots and data in the inset table in Figure 36 show:

- All flow ranges have been affected since the beginning of the drought.
- The medium–high flow range has been impacted the most since the drought and is yet to return to pre-drought conditions.
- The average number of flowing days in the Finniss River reduced by 27 days per year during the drought, but in the period since the drought has increased to pre-drought levels. This indicates that the proportion of time that the stream beds are wet is similar to pre-drought conditions, even though total flow (hence water depth) is lower.



Percentile exceedance	Pre-drought	Drought	Post-drought	Flow range
10th	129.6	82.9	105.7	High-V.High
20th	52.9	35.5	36.4	High-V.High
30th	25.5	19.3	16.6	Medium-High
40th	13.8	9.8	8.4	Medium-High
50th	7.5	4.9	4.3	Medium-High
60th	4.3	2.0	2.5	Medium-High
70th	2.3	0.8	1.3	Low-Medium
80th	1.0	0.4	0.7	Low-Medium
90th	0.5	0.1	0.4	Low-Medium
Ave flowing days/year	361.9	334.4	362.9	

Figure 36. Flow duration curves for daily flow in Finniss River at Yundi (A4260504) for periods related to the drought

Figure 37 shows the distribution of daily flow for the WAP development period, and for the post-WAP development period since 2007, with both distributions summarised. The results indicate the largest differences in flow between post-WAP development and WAP development periods occur between values in the 20th to 70th percentile.

The number of flowing days per year and the low, medium, and high flow ranges are some of the key metrics that characterise the flow regime of a catchment. These metrics also form part of the environmental water requirement metrics that were used to assess eco-system flow requirements in the WAPs. The results presented provide evidence of alteration of the flow regime since the beginning of the drought and during the post-WAP development period.

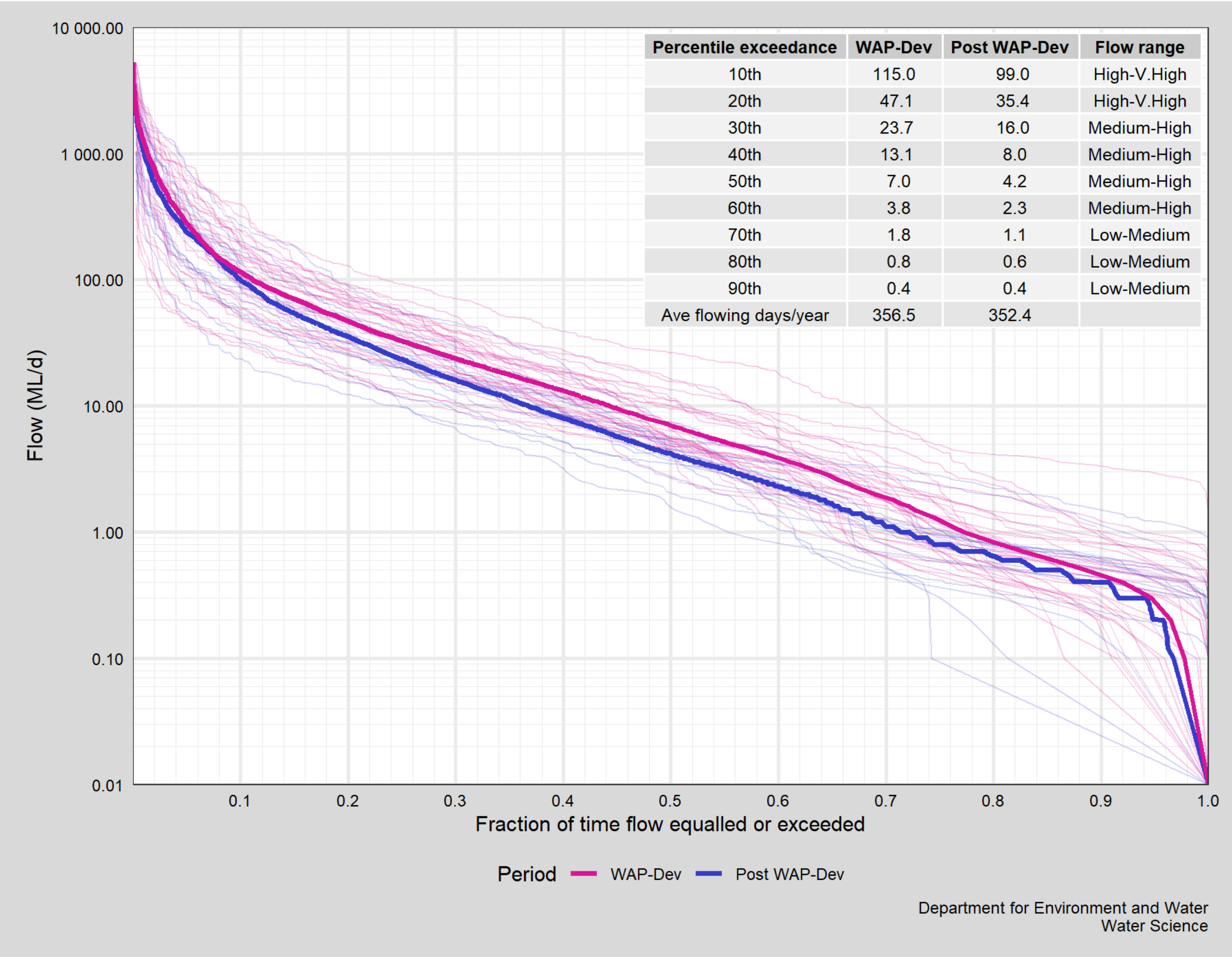


Figure 37. Flow duration curves for daily flow in Finniss River at Yundi (A4260504) for periods related to the WAP development periods

4.2 Bremer River

Streamflow records from the Bremer River near Hartley gauging station (A4260533) were analysed. The gauging station location covers more than 90% of the total area of the Bremer River catchment (Figure 33).

4.2.1 Data quality

The calculation of long-term flow statistics is compromised by missing flow data at this gauging station in recent years. In the 12-year period 2011 to 2022, daily flow data are missing on approximately 38% of days, with the annual proportions of missing days reaching a maximum of 60% of days in 2018.

Figure 38 shows the average number of missing flow days in each calendar month for periods either side of the Millennium drought. This shows that missing flow days were generally recorded in the period since the start of the Millennium drought, and importantly, recorded in lower-flow months outside the high flow periods. As a result, the missing flow days are expected to have had a minor impact on annual flow volumes and higher impacts on drier seasonal, monthly and daily flow data. For this reason, analysis results of monthly and daily flow data are not presented for this station.

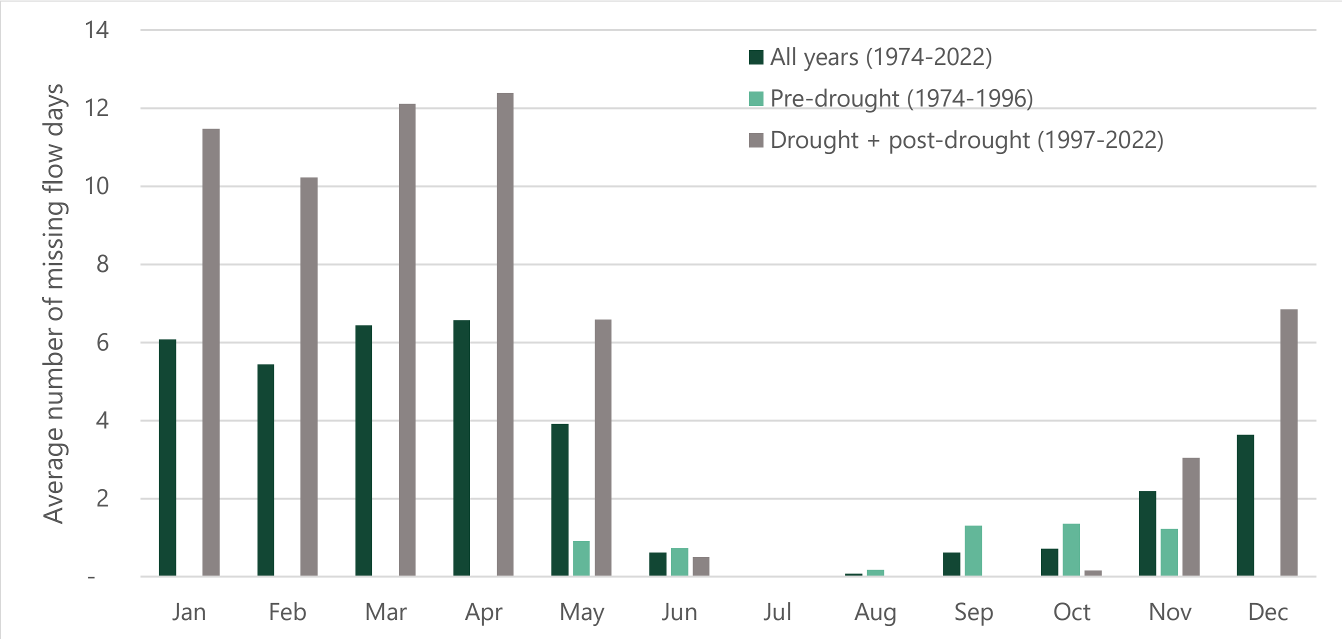


Figure 38. Average number of missing days in the daily flow record for Bremer River near Hartley (A4260533) for drought periods

4.2.2 Annual streamflows

Streamflow data for the reporting period reflects rainfall variability, reaching peak discharge volumes of 70,992 ML (1992) and a minimum annual discharge of 974 ML (1982), with the long-term annual median being 12,520 ML.

Figure 39 shows the distribution of annual streamflow at Hartley (A4260533) for the various pre-drought, drought and WAP-related periods as boxplots. Average annual flow is shown to have increased slightly in the post-drought period compared to the drought but remains lower than under the pre-drought period. Median annual flow in the post-WAP development period is lower than during the WAP development period.

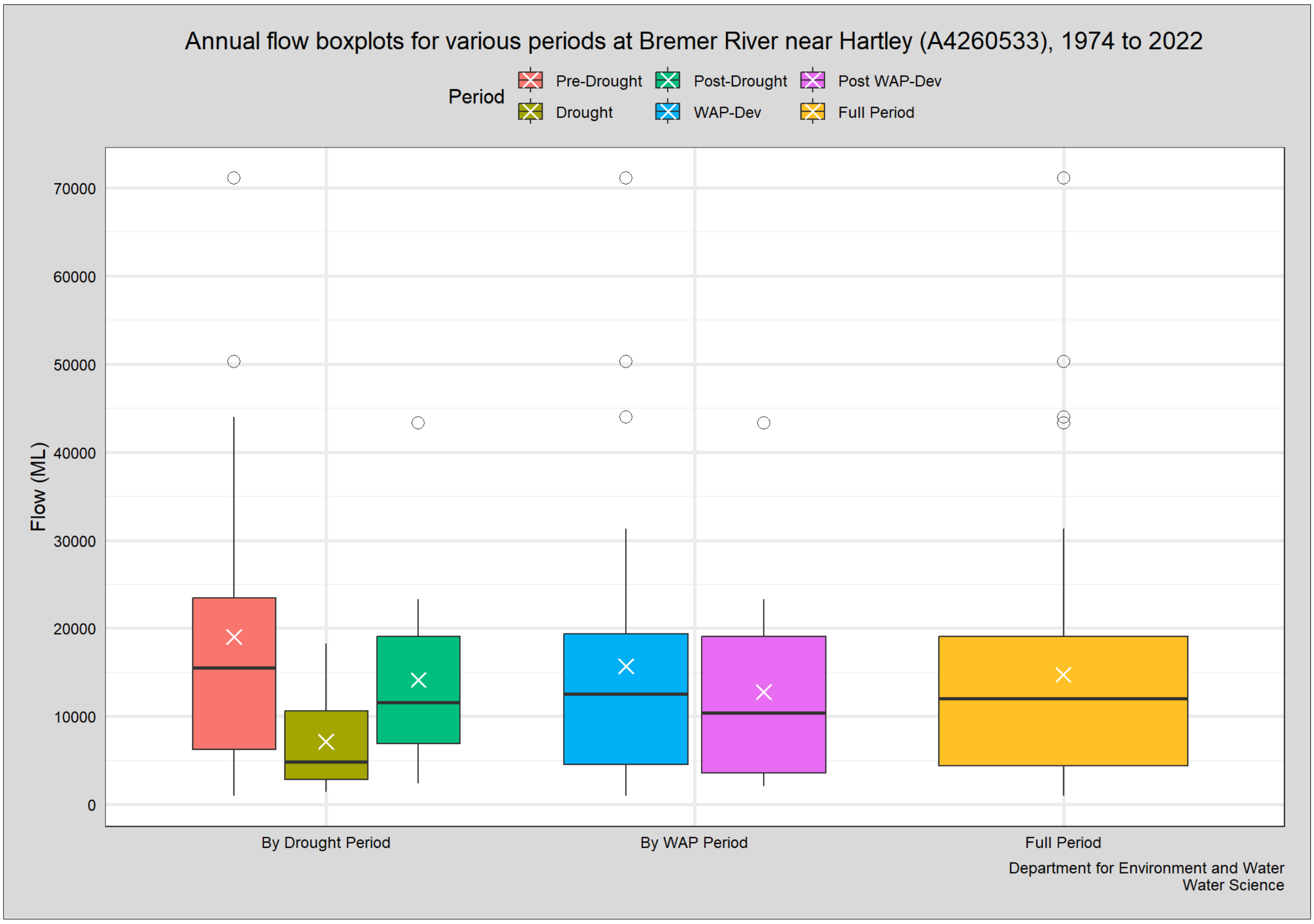


Figure 39. Distribution of annual streamflow totals for the Bremer River at Hartley (A4260533) for different periods during 1974 to 2022 (median (—), average (X), and outliers (O) shown)

Figure 40(a) shows a time series of annual streamflow totals for 1974 to 2022, with long-term average annual flow shown alongside a 10-year rolling average and long-term trend, both of which suggest a general decline in streamflow totals over the period of observation.

Figure 40(b) shows annual deviations from the long-term mean. Apart from a wet year in 2016, recent decades have shown a greater number of below-average streamflow years relative to above-average flow years compared to the pre-drought period (1974 to 1996).

Figure 40(c) shows annual streamflow with average annual flows displayed for pre-drought, drought, and post-drought periods as well as the full period average. It shows an almost 70% reduction in median annual streamflow during the drought period.

Figure 40(d) shows annual streamflow totals coloured by the drought phase, with average annual flows for the WAP development and Post WAP-development periods, showing a 17% reduction in median annual flow during the post-WAP development periods.

Figure 40. **(a) Annual streamflow totals for Bremer River near Hartley (A4260533) for 1974 to 2022, (b) Deviations in annual streamflow totals for Bremer River near Hartley (A4260533) from long-term median, (c) Annual streamflow totals for Bremer River near Hartley (A4260533) showing averages before and after the drought (1997 to 2009), (d) Annual streamflow totals for Bremer River near Hartley (A4260533) showing averages during WAP development (1974 to 2006) and during Post WAP-development**

4.2.3 Seasonal streamflows

The data shows there have been substantially lower flows recorded at the A4260533 station in each season since the start of the Millennium drought. Table 52 summarises the median seasonal streamflow for different periods relative to the Millennium drought, in addition to the changes in each seasonal average for periods either side of 1997. Data for Summer and Autumn seasons are not presented due to incomplete streamflow records during those seasons, which is further discussed in Section 4.2.1. Data from years with full records show that at least 90% of annual flow is recorded across winter and spring for each of the different periods analysed. Median flow in each of these two seasons reduced substantially during the drought period relative to the pre-drought period, before increasing again in the post-drought period, although not to the levels of the pre-drought period.

Table 52. Median annual and seasonal streamflow for Bremer River near Hartley (A4260533) across periods defined by the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1974 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (ML *(%)*)	Post-drought (ML *(%)*)
Summer	-*	-	-	-	-	-
Autumn	-	-	-	-	-	-
Winter	4,983	8,273	2,886	6,060	-5,387 (-65%)	-2,212 (-27%)
Spring	2,989	3,857	1,269	2,821	-2,588 (-67%)	-1,036 (-27%)
Annual	**12,022**	**15,522**	**4,823**	**11,601**	**-10,698 (-69%)**	**-3,920 (-25%)**

* Data not presented due to incomplete records, refer to section 4.2.1

Table 53 summarises seasonal average flow for periods defined by the development and implementation of the WAPs. Median seasonal flows reduce in each season from WAP development to post-WAP development periods, with the largest percentage reduction seen in spring and with increases observed in winter median flows. Winter and spring reductions were relatively lower, at 17% and 9%, respectively.

Table 53. Median annual and seasonal streamflow for Bremer River near Hartley (A4260533) across periods representing the WAP development and implementation

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1974 to 2022)	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Summer	-	-	-	-	-
Autumn	-	-	-	-	-
Winter	4,983	4,909	5,284	374	8%
Spring	2,989	3,701	2,495	-1,206	-33%
Annual	**12,022**	**12,520**	**10,382**	**-2,139**	**-17%**

4.3 Onkaparinga River

Streamflow records were reviewed for Scott Creek at Scott Bottom gauging station (A5030502). Scott Creek is a tributary of the Onkaparinga River, joining the Onkaparinga between Mount Bold Reservoir and Clarendon Reservoir. Streamflow data for the period 1974 to 2022 reflects rainfall variability, reaching peak discharge volumes of 8,998 ML (2016) and a minimum annual discharge of 619 ML (1982), with the long-term annual median being 2,979 ML.

4.3.1 Annual streamflows

Figure 41 shows the distribution of annual streamflow in Scott Creek (A5030502) for the various drought- and WAP-related periods as boxplots. Median annual flow dropped by 1,388 ML (35%) during the drought period. Annual flows increased marginally during the post-drought period but remain lower than the pre-drought period median by 33% (Table 54). Median annual flow in the post-WAP development period was lower by 1,090 ML (30%) than during the WAP development period (Table 55).

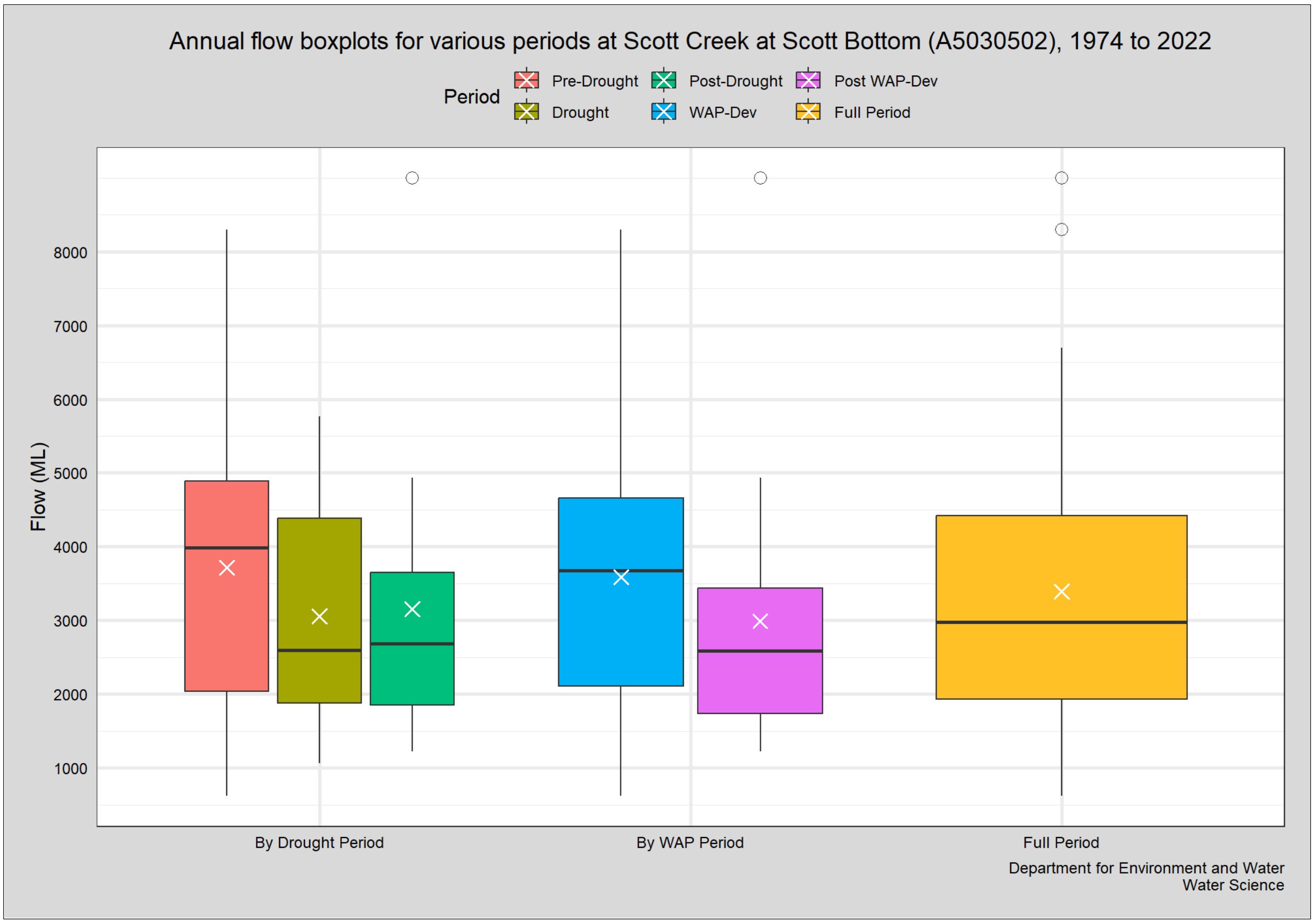


Figure 41. Distribution of annual streamflow totals for Scott Creek (A5030502) for different periods during 1974 to 2022 (median (—), average (X), and outliers (O) shown)

Figure 42 (a) shows a time series of annual streamflow totals for 1974 to 2022, with long-term median annual flow shown alongside a 10-year rolling average and long-term trend, both of which suggest a general decline in streamflow totals over the period of observation.

Figure 42 (c) shows annual deviations from the long-term median, and apart from 2016 (wettest) and 2002 (above-median), recent decades have experienced a greater number, and higher frequency, of drier (below-median streamflow) years.

Figure 42 (d) shows annual streamflow totals coloured by drought phase, with median annual flows for the WAP development and post-WAP development periods also shown. These reveal a 30% (1,089 ML) reduction in median annual flow in the period following WAP development (that is, from 2007 onwards).

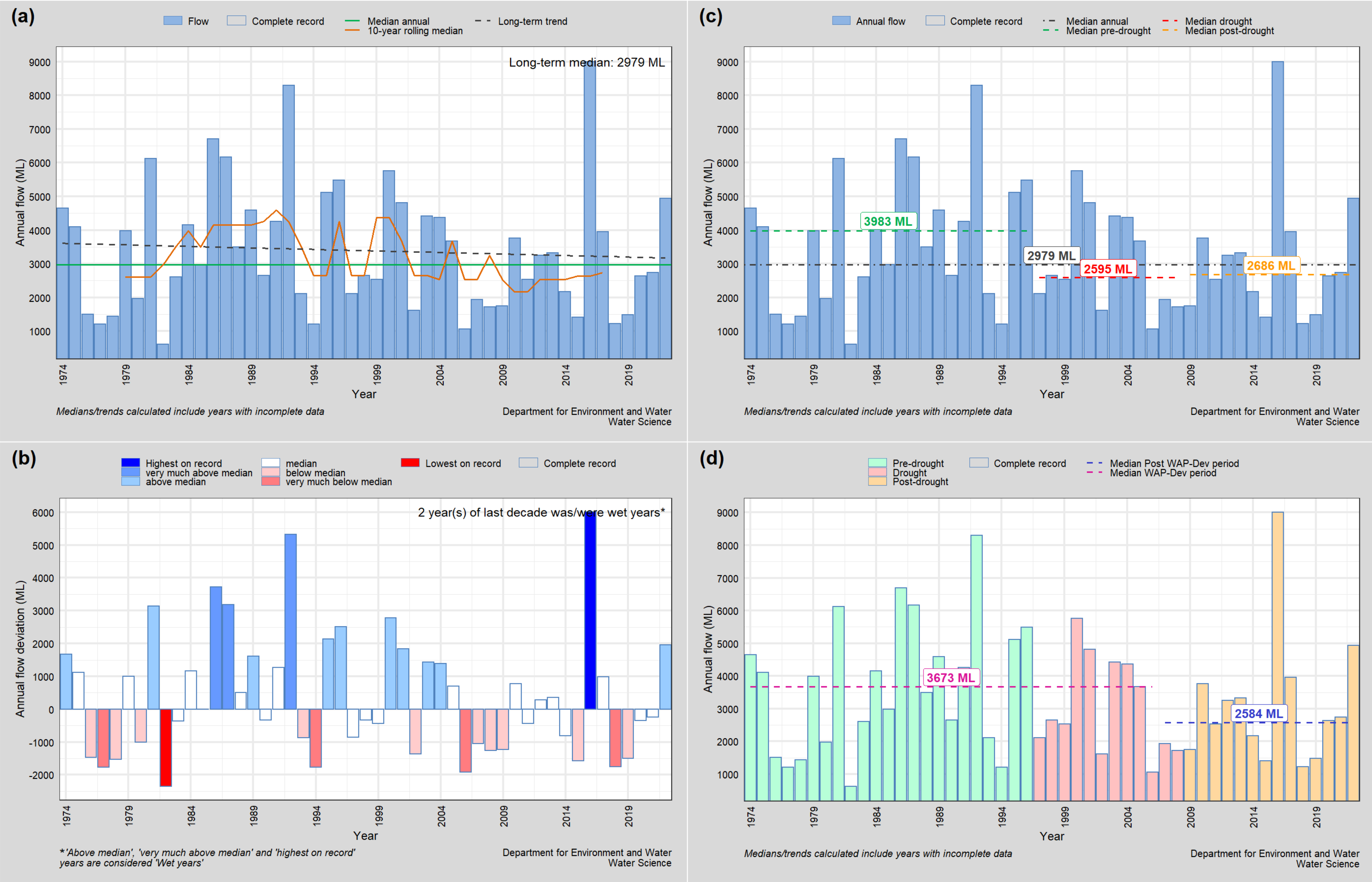


Figure 42. (a) Annual streamflow totals for Scott Creek, Onkaparinga (A5030502) for 1974 to 2022, (b) Deviations in annual streamflow totals for Scott Creek, Onkaparinga (A5030502) from long-term median, (c) Annual streamflow totals for Scott Creek, Onkaparinga (A5030502) showing medians before and after the drought (1997 to 2009), (d) Annual streamflow totals for Scott Creek, Onkaparinga (A5030502) showing averages during WAP development (1974 to 2006) and during Post WAP-development

4.3.2 Seasonal streamflows

The data shows there have been lower flows recorded at the A5030502 station in each season since the start of the Millennium drought, except during the post-drought winter period, which was the wettest amongst the 3 comparison periods. Table 54 summarises the median seasonal streamflow for different periods relative to the Millennium drought, in addition to the changes in each seasonal median for periods either side of 1997. These statistics show that majority of annual flow is recorded across winter and spring for each of the different periods analysed. While flows during autumn and summer are only a small proportion of the annual totals, they are critical in keeping the stream beds wet and maintaining in-stream ecosystem functionality.

Median flow in the 3 seasons (autumn excluded) reduced substantially during the drought period relative to the pre-drought period. Flows during winter season recovered substantially in the post-drought period and were the highest (wettest) amongst the comparison periods. Conversely, median seasonal flows during the other 3 seasons decreased further during the post-drought periods, making them the driest amongst the comparison periods. A 38% reduction is spring, 48% reduction in autumn and 34% reduction in summer median seasonal flows have been observed since the beginning of the Millennium drought.

Table 54. Median annual and seasonal streamflow for Scott Creek, Onkaparinga (A5030502) across periods defined by the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1974 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (ML *(%)*)	Post-Drought (ML *(%)*)
Summer	42	52	42	34	-10 (-19%)	-18 (-34%)
Autumn	123	134	152	86	17 (13%)	-48 (-36%)
Winter	1,783	1,813	1,532	1,919	-281 (-16%)	106 (6%)
Spring	730	911	678	567	-233 (-26%)	-344 (-38%)
Annual	**2,979**	**3,983**	**2,595**	**2,686**	**-1388 (-35%)**	**-1297 (-33%)**

Table 55 summarises seasonal median flow for WAP development and post-WAP development periods. Median seasonal flows reduced substantially (>35%) in each season, from WAP development to post-WAP development periods, except during winter (3% increase).

Table 55. Median annual and seasonal streamflow for Scott Creek, Onkaparinga (A5030502) across periods representing the WAP development and Post-WAP development

Season	WAP development	Post-WAP development	Change (WAP dev to Post-WAP dev.)	
	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Summer	49	32	-17	-35%
Autumn	144	89	-56	-38%
Winter	1,779	1,838	59	3%
Spring	911	517	-394	-43%
Annual	**3,673**	**2,584**	**-1,088**	**-30%**

Annual and seasonal streamflow responses during drought and WAP development-related comparison periods reflect the long-term annual and seasonal trends in rainfall records at the Cherry Gardens (23709) station, as presented in Appendix 7.4. The site at Cherry Gardens (23709) is the closest rainfall site that meets the site selection criteria discussed in Section 2.2.

4.3.3 Monthly streamflows

The distribution of flow across each calendar month, with monthly totals aggregated to various drought- and WAP-related periods are summarised in Table 56 and Table 57 respectively. The monthly data show median flow in each calendar month, except for June, was lower in the post-drought period than during the pre-drought period (Yet to Recover).

Table 56. Median monthly streamflow for Scott Creek, Onkaparinga (A5030502) for drought periods

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Jan	8	12	6	5	-5 (-46%)	-7 (-58%)
Feb	7	7	7	6	0 (-6%)	-1 (-16%)
Mar	11	13	15	8	2 (17%)	-5 (-40%)
Apr	31	32	36	26	5 (14%)	-5 (-16%)
May	76	81	94	57	13 (16%)	-24 (-30%)
Jun	174	170	341	186	171 (100%)	16 (9%)
Jul	545	627	622	479	-5 (-1%)	-148 (-24%)
Aug	845	1052	646	783	-406 (-39%)	-269 (-26%)
Sep	386	386	393	351	8 (2%)	-35 (-9%)
Oct	197	229	170	126	-59 (-26%)	-103 (-45%)
Nov	64	69	92	52	23 (33%)	-18 (-26%)
Dec	22	23	23	20	1 (4%)	-2 (-10%)
Annual	**2,979**	**3,983**	**2,595**	**2,686**	**-1,388 (-35%)**	**-1,297 (-33%)**

In the WAP-related period context, only June shows an increase in median flow in the post-WAP development period, while all other months show a decrease relative to the WAP development period.

Table 57. Median monthly streamflow for Scott Creek, Onkaparinga (A5030502) for WAP periods

Month	All years (1974 to 2022)	WAP development (1974 to 2006)	Post-WAP development (2007 to 2022)	Change (WAP dev. to Post-WAP dev.) (ML)	(%)
Jan	8	10	5	-5	-52%
Feb	7	8	3	-4	-57%
Mar	11	13	6	-7	-56%
Apr	31	35	26	-8	-24%
May	76	83	59	-24	-29%
Jun	174	173	186	13	8%
Jul	545	627	479	-148	-24%
Aug	845	899	783	-117	-13%
Sep	386	407	286	-121	-30%
Oct	197	229	122	-107	-47%
Nov	64	81	49	-32	-40%
Dec	22	24	19	-5	-19%
Annual	**2,979**	**3,673**	**2,584**	**-1,088**	**-30%**

4.3.4 Daily streamflows

Further investigation of flow records at a daily time step was undertaken to evaluate the impacts of changing rainfall on daily flow patterns. The plots and data in the inset table in Figure 43 show:

- Daily flows in the Very high to High range (10^{th} and 20^{th} percentiles) reduced in the post-drought relative to the pre-drought period. All other flow ranges show no or minimal change between those 2 periods.
- The daily flow range of median (50^{th} percentile) and higher daily flows reduced in the post-drought period and were the lowest amongst the 3 comparison periods. Daily flow lower than the median have remined the same during the drought and post-drought periods.
- The average number of flowing days in a year has progressively decreased (marginally) through the 3 comparison periods.

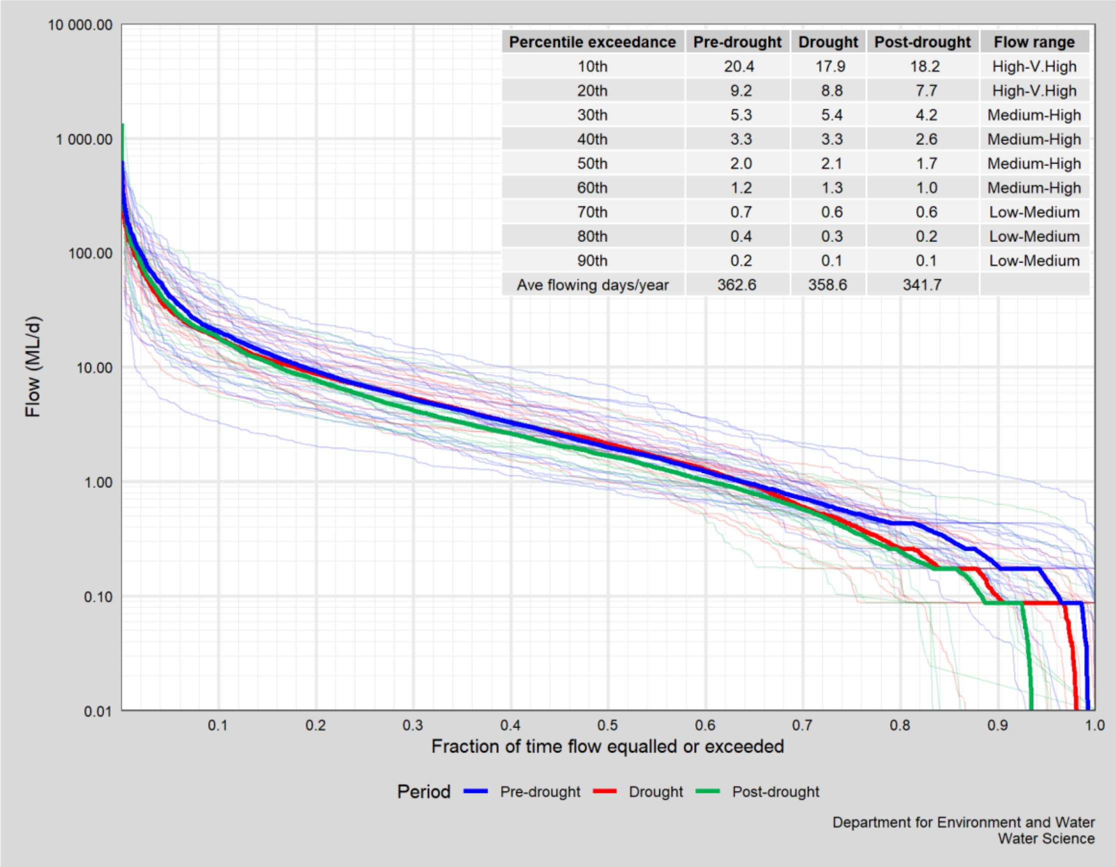
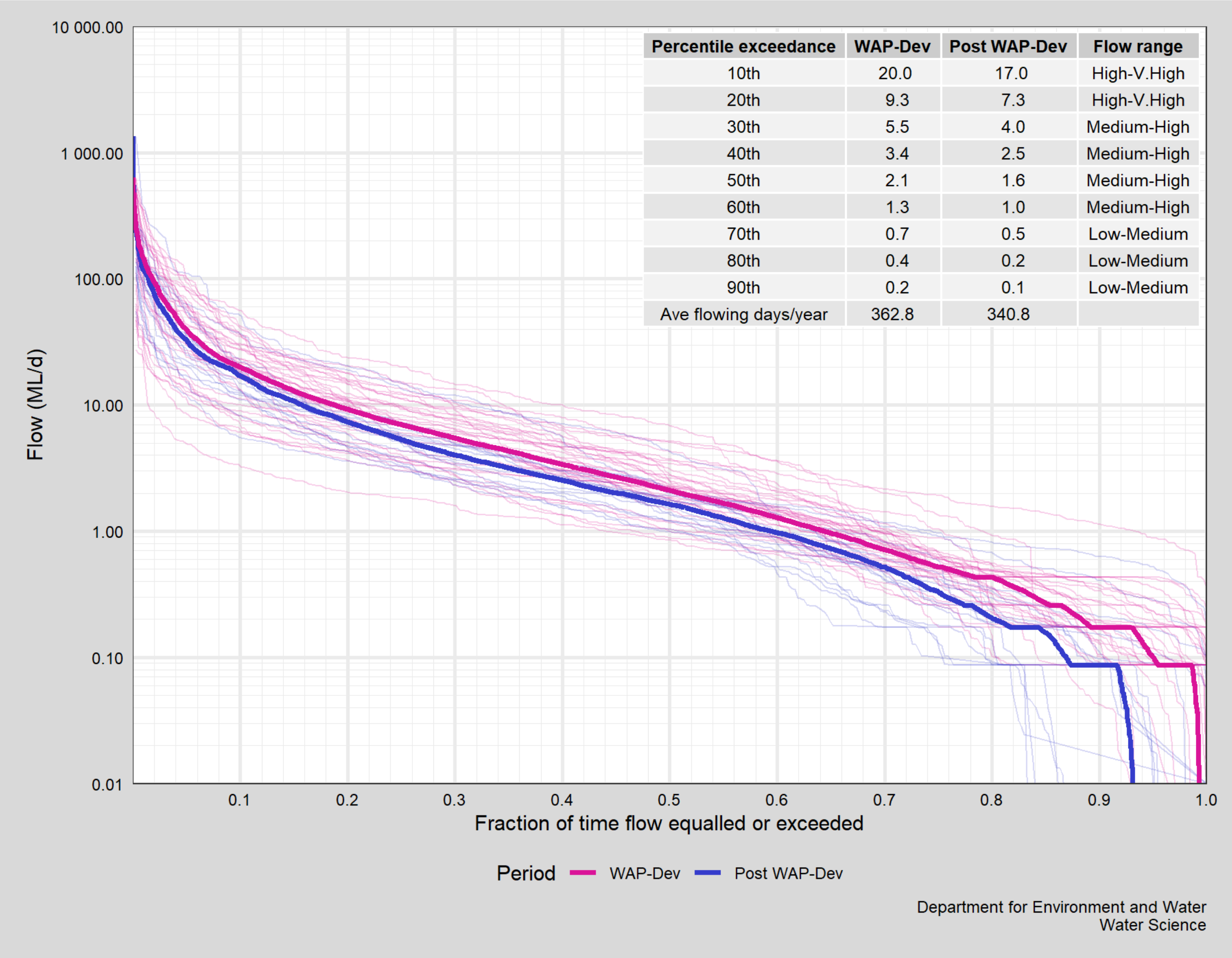


Figure 43. Flow duration curves for daily flow in Scott Creek, Onkaparinga (A5030502) for periods related to the drought

Figure 44 shows the distribution of daily flow for the WAP development and post-WAP development periods, with both distributions summarised in the inset table. The results indicate the entire flow regime was different during the 2 comparison periods.



Percentile exceedance	WAP-Dev	Post WAP-Dev	Flow range
10th	20.0	17.0	High-V.High
20th	9.3	7.3	High-V.High
30th	5.5	4.0	Medium-High
40th	3.4	2.5	Medium-High
50th	2.1	1.6	Medium-High
60th	1.3	1.0	Medium-High
70th	0.7	0.5	Low-Medium
80th	0.4	0.2	Low-Medium
90th	0.2	0.1	Low-Medium
Ave flowing days/year	362.8	340.8	

Figure 44. Flow duration curves for daily flow in Scott Creek, Onkaparinga (A5030502) for WAP development and Post-WAP Development

The number of flowing days per year and the low, medium, and high flow ranges are some of the key metrics that characterise the flow regime of a catchment. These metrics also form part of the environmental water requirement metrics that used to assess eco-system flow requirements in the WAPs. The results presented provide evidence of alteration of the flow regime since the beginning of the drought and during post-WAP development period.

4.4 Torrens River

Streamflow records were reviewed for the Torrens River at Mount Pleasant gauging station (A5040512) for the period 1974 to 2022. The station is located at the outlet of a small headwater sub-catchment in the Torrens River. This series has peak discharge volumes of 8,811 ML (1992) and a minimum annual discharge of 28 ML (1982), with the long-term annual median being 1,341 ML.

4.4.1 Annual streamflows

Figure 45 shows the distribution of annual streamflow in the Torrens River (A5040512) for the various drought- and WAP-related periods as boxplots. Median annual flow dropped by ≈80% during the drought period. Annual flows increased during the post-drought period but were still lower than pre-drought period median by 54% (Table 58). Median annual flow in the post-WAP development period was lower by 1,151 ML (62%) than during the WAP development period (Table 59).

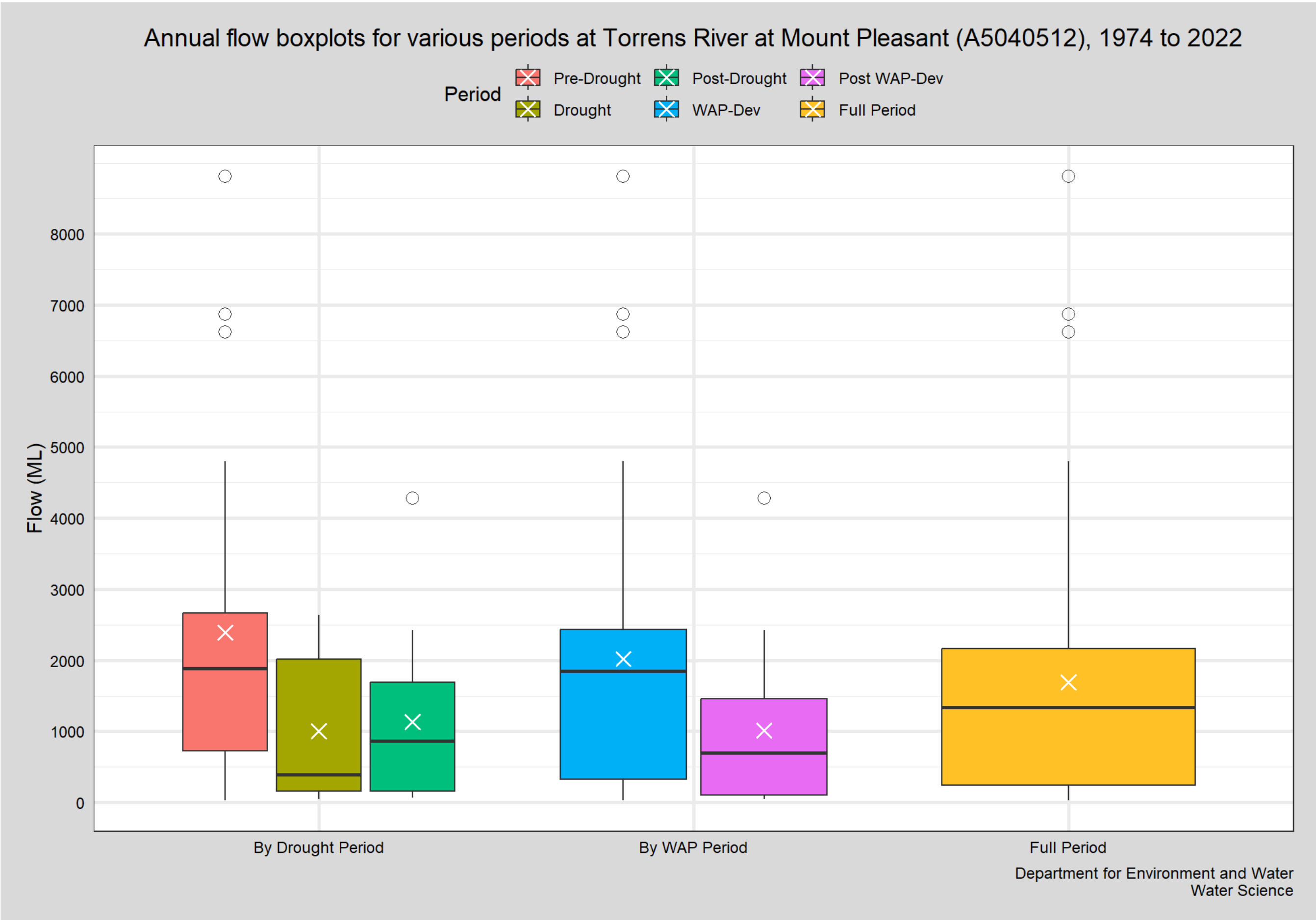


Figure 45. Distribution of annual streamflow totals for Torrens River at Mount Pleasant (A5040512) for different periods during 1974 to 2022 (median (—), average (X), and outliers (O) shown)

Figure 46 (a) shows a time series of annual streamflow totals for 1974 to 2022, with long-term median annual flow shown alongside a 10-year rolling average and long-term trend, both of which suggest a substantial decline in streamflow totals over the period of observation.

Figure 46 (b) shows deviations of annual streamflow from the long-term median. Apart from a wet year in 2016, recent decades have shown a greater number, and higher frequency, of below-median streamflow years relative to above-median flow years, compared to the pre-drought period (1974 to 1996).

Figure 46 (c) shows annual streamflow with median annual flows displayed for pre-drought, drought, and post-drought periods as well as the full period median. These results, and results in Table 58, show that the median annual streamflow during the drought period was 1,500 ML (80%) less than that for the pre-drought period. The median annual flow subsequently increased by almost 500 ML in the post-drought period but remained below the pre-drought median by 1,014 ML (54%).

Figure 46 (d) shows annual streamflow totals coloured by the drought phase, with median annual flows for the WAP development and post-WAP development periods also shown. These reveal a substantial reduction in median annual flow in the period following the WAP development (that is, from 2007 onwards), by over 1,151 ML (62%).

Figure 46. (a) Annual streamflow totals for Torrens River at Mount Pleasant (A5040512) for 1974 to 2022, (b) Deviations in annual streamflow totals for Torrens River at Mount Pleasant (A5040512) from long-term median, (c) Annual streamflow totals for Torrens River at Mount Pleasant (A5040512) showing medians before and after the drought (1997 to 2009), (d) Annual streamflow totals for Torrens River at Mount Pleasant (A5040512) showing medians during WAP development (1974 to 2006) and during Post WAP-development

4.4.2 Seasonal streamflows

The data shows that substantially lower flows were recorded at the A5040512 station in each season since the start of the Millennium drought. Table 58 summarises the median seasonal streamflow for different periods relative to the Millennium drought, in addition to the changes in each seasonal median for periods either side of the drought. These statistics show that majority of annual flow is recorded across winter and spring for each of the different periods analysed. While flows during autumn and summer are only a small proportion of the annual totals, they are critical in keeping stream beds wet and maintaining in-stream ecosystem functionality.

Summer and autumn flows constitute a minor proportion of annual totals, and very little change in the magnitude of flows were observed during the three comparison periods. Median flows in winter and spring seasons reduced substantially during the drought period relative to the pre-drought period. Further decrease in median seasonal flows was observed during spring and autumn in the post-drought period. A 71% reduction in spring and autumn median seasonal flows was observed since the commencement of the Millennium drought. Flows increased during winter in the post-drought period but was still lower than pre-drought median by 47%.

Table 58. Median annual and seasonal streamflow for Torrens River at Mount Pleasant (A5040512) across periods defined by the drought

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1974 to 1996)	(1997 to 2009)	(2010 to 2022)	Drought (ML (%))	Post-drought (ML (%))
Summer	2	2	0	2	-1 (-87%)	0 (26%)
Autumn	6	8	4	2	-5 (-56%)	-6 (-71%)
Winter	636	888	280	472	-608 (-69%)	-416 (-47%)
Spring	182	317	150	93	-167 (-53%)	-224 (-71%)
Annual	**1341**	**1,888**	**388**	**869**	**-1,501 (-79%)**	**-1,019 (-54%)**

Table 59 summarises seasonal average flow for WAP development and post-WAP development. Median seasonal flows reduced in each season during the post-WAP development, with the largest reduction observed in spring (82%), followed by autumn (59%), winter (51%) and summer (16%).

Table 59. Median annual and seasonal streamflow for Torrens River at Mount Pleasant (A5040512) for WAP development and Post-WAP development periods

Season	WAP development	Post-WAP development	Change (WAP dev. to Post-WAP dev.)	
	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Summer	2	1	0	-16%
Autumn	6	2	-4	-59%
Winter	751	368	-383	-51%
Spring	314	56	-258	-82%
Annual	**1,851**	**700**	**-1,151**	**-62%**

4.4.3 Monthly streamflows

The distribution of flow across each calendar month, with monthly totals aggregated to various drought- and WAP-related periods are summarised in Table 60 and Table 61 respectively. The monthly data show median flow in each flowing calendar month has a significant reduction from the commencement of the drought period, except for November and December. At least 75% of average annual flow in each period is recorded across a 3-month period from July to September, and the large reductions in flow during these months impact annual flows.

Table 60. Median monthly streamflow for Torrens River at Mount Pleasant (A5040512) for drought periods

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1900 to 1996)	(1997 to 2008)	(2009-2022)	Drought (mm (%))	Post-drought (mm (%))
Jan	0	0	0	0	0 (0%)	0 (0%)
Feb	0	0	0	0	0 (0%)	0 (0%)
Mar	0	0	0	0	0 (-100%)	0 (-100%)
Apr	1	2	0	0	-2 (-100%)	-2 (-100%)
May	4	4	4	1	-1 (-12%)	-3 (-80%)
Jun	12	16	12	9	-5 (-28%)	-7 (-42%)
Jul	87	185	66	65	-119 (-64%)	-121 (-65%)
Aug	297	442	89	291	-353 (-80%)	-151 (-34%)
Sep	142	198	77	65	-121 (-61%)	-133 (-67%)
Oct	25	31	34	22	3 (10%)	-8 (-27%)
Nov	7	6	8	8	2 (34%)	2 (32%)
Dec	1	1	0	1	-1 (-91%)	0 (-42%)
Annual	**1,341**	**1,888**	**388**	**869**	**-1,501 (-79%)**	**-1,019 (-54%)**

In the WAP-related period context, all sites with a non-zero median showed a decrease in monthly median flow in the post-WAP development period relative to the WAP development period.

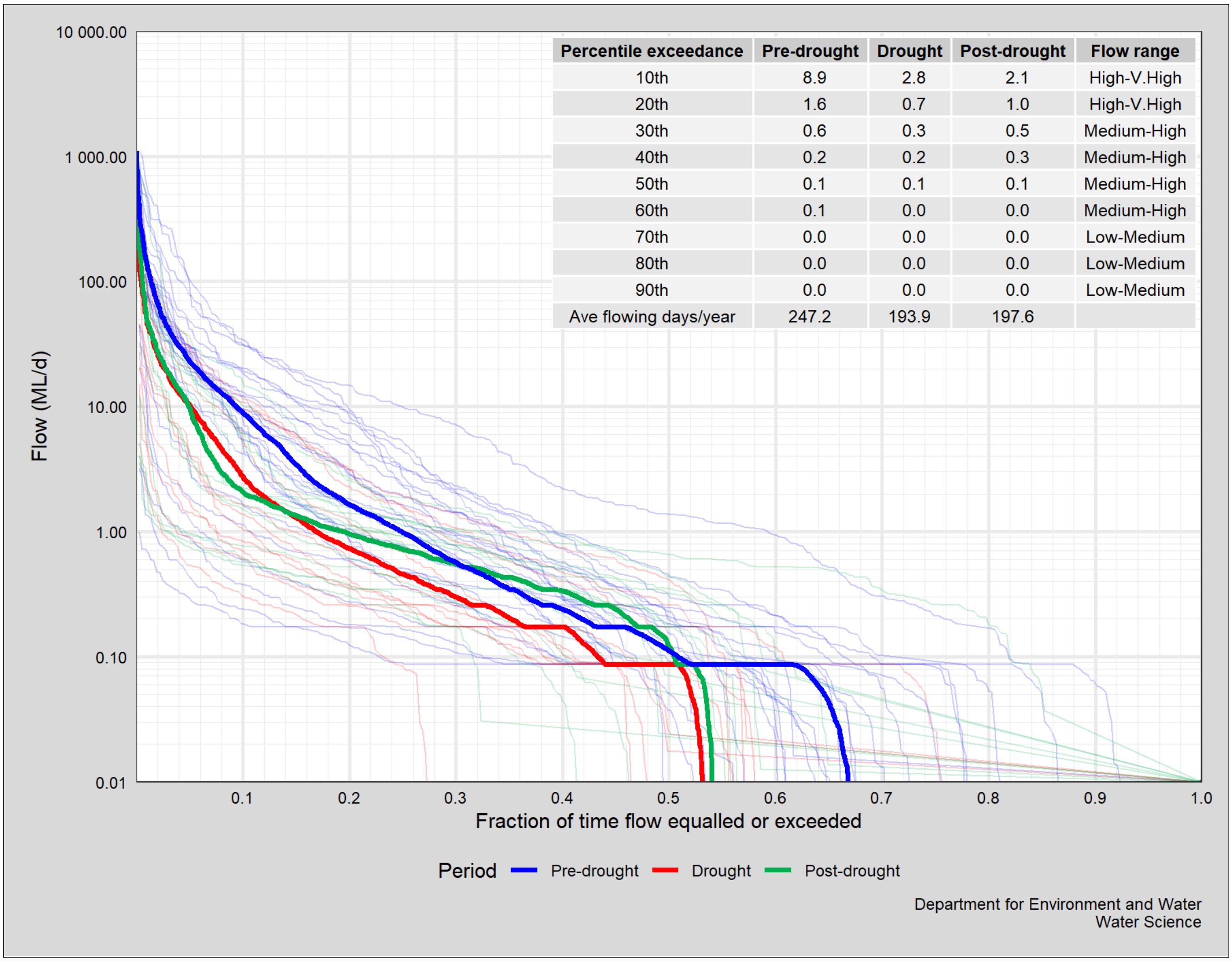
Table 61. Median monthly streamflow for Torrens River at Mount Pleasant (A5040512) for WAP periods

Month	All years (1974 to 2022)	WAP development (1974 to 2006)	Post-WAP development (2007 to 2022)	Change (WAP dev. to post-WAP dev.) (ML)	(%)
Jan	0	0	0	0	0%
Feb	0	0	0	0	0%
Mar	0	0	0	0	0%
Apr	1	1	0	-1	-100%
May	4	4	1	-3	-80%
Jun	12	14	9	-5	-35%
Jul	87	87	65	-22	-26%
Aug	297	396	205	-191	-48%
Sep	142	198	29	-169	-85%
Oct	25	35	19	-16	-45%
Nov	7	8	6	-2	-30%
Dec	1	1	1	0	-34%
Annual	**1,341**	**1851**	**700**	**-1,151**	**-62%**

4.4.4 Daily streamflows

Further investigation of flow records at a daily time step was undertaken to evaluate the impacts of changing rainfall on daily flow patterns. The plots and data in the inset table in Figure 47 shows:

- All flow ranges have been affected since the beginning of the drought.
- The medium–high flows have been impacted the most since the drought and are yet to return to pre-drought conditions.
- The average annual number of flowing days in the pre-drought period was 247 days (70%). This reduced to around 195 days (53%) during the drought and increased marginally (by 2 days) during the post-drought period.
- A similar difference in behaviour of the flow regime is also observed between the WAP development and post-WAP development periods as shown in Figure 48.



Percentile exceedance	Pre-drought	Drought	Post-drought	Flow range
10th	8.9	2.8	2.1	High-V.High
20th	1.6	0.7	1.0	High-V.High
30th	0.6	0.3	0.5	Medium-High
40th	0.2	0.2	0.3	Medium-High
50th	0.1	0.1	0.1	Medium-High
60th	0.1	0.0	0.0	Medium-High
70th	0.0	0.0	0.0	Low-Medium
80th	0.0	0.0	0.0	Low-Medium
90th	0.0	0.0	0.0	Low-Medium
Ave flowing days/year	247.2	193.9	197.6	

Figure 47. Flow duration curves for daily flow in Torrens River at Mount Pleasant (A5040512) for periods related to the drought

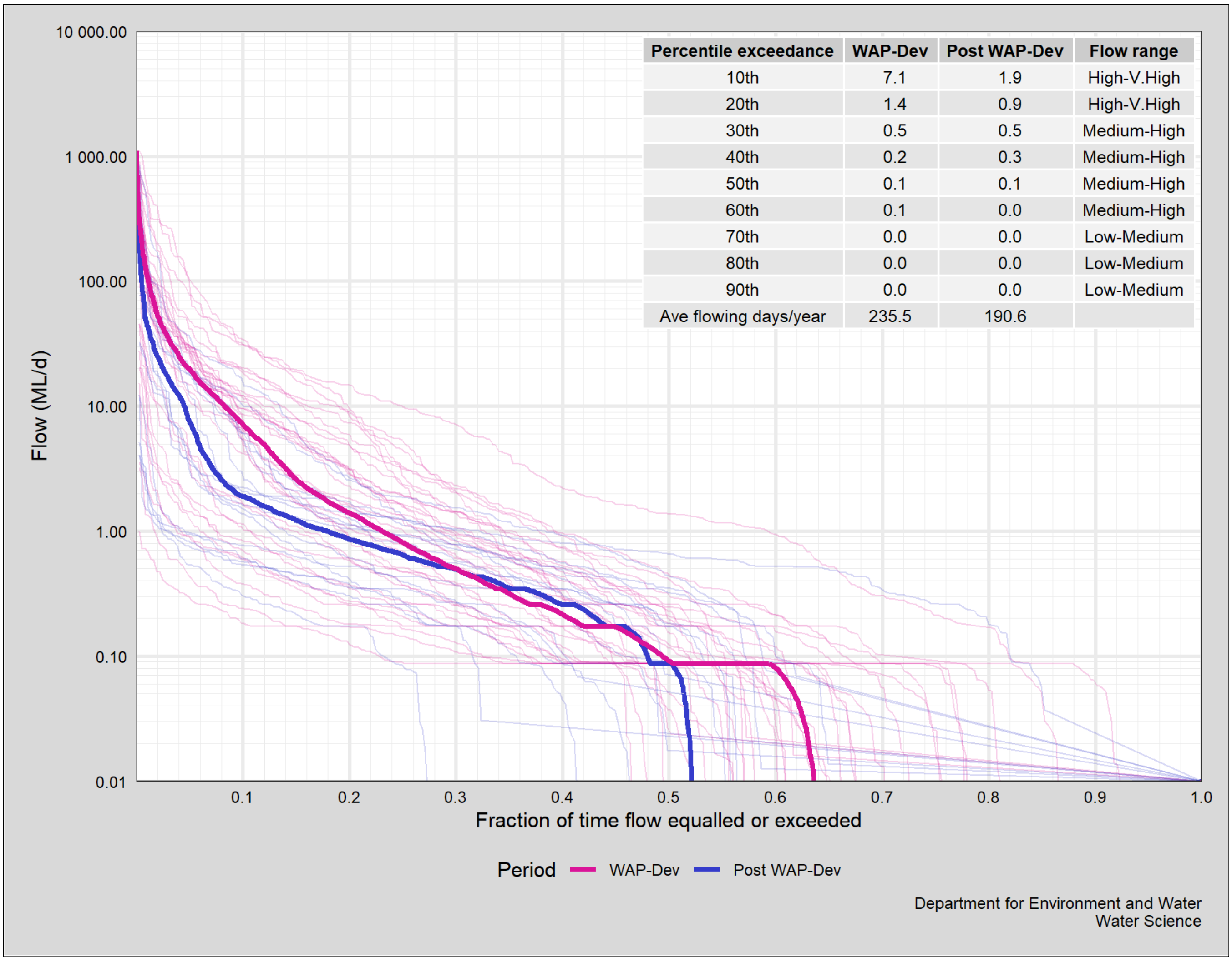


Figure 48. Flow duration curves for daily flow in Torrens River at Mount Pleasant (A5040512) for periods related to the development and implementation of the WAP

The number of flowing days per year and the low, medium, and high flow ranges are some of the key metrics that characterise the flow regime of a catchment. These metrics also form part of the environmental water requirement metrics that used to assess eco-system flow requirements in the WAPs. The results presented provide evidence of alteration of the flow regime since the beginning of the drought and during the post-WAP development period.

4.5 Myponga River

Streamflow records were reviewed for the Myponga River (A5020502) for the period 1978 to 2022. The gauging station is located upstream of the Myponga reservoir and covers a large proportion of the entire catchment (Figure 33). This series has missing data for January 1974 to April 1978, and has 72 and 57 missing days in 1991 and 1998 respectively. It is to be noted that the results presented here include data from years with partial records. This series has peak discharge volumes of 18,920 ML (1992) and a minimum annual discharge of 2,503 ML (1982), with the long-term median of 7,203 ML.

4.5.1 Annual streamflows

Figure 49 shows the distribution of annual streamflow in the Myponga River (A5020502) for the various drought- and WAP-related periods as boxplots. Median (and mean) annual flow is shown to have increased in the post-drought period compared to the drought but remains lower than under the pre-drought period. Median (and mean) annual flow in the post-WAP development period is lower than during the WAP development period.

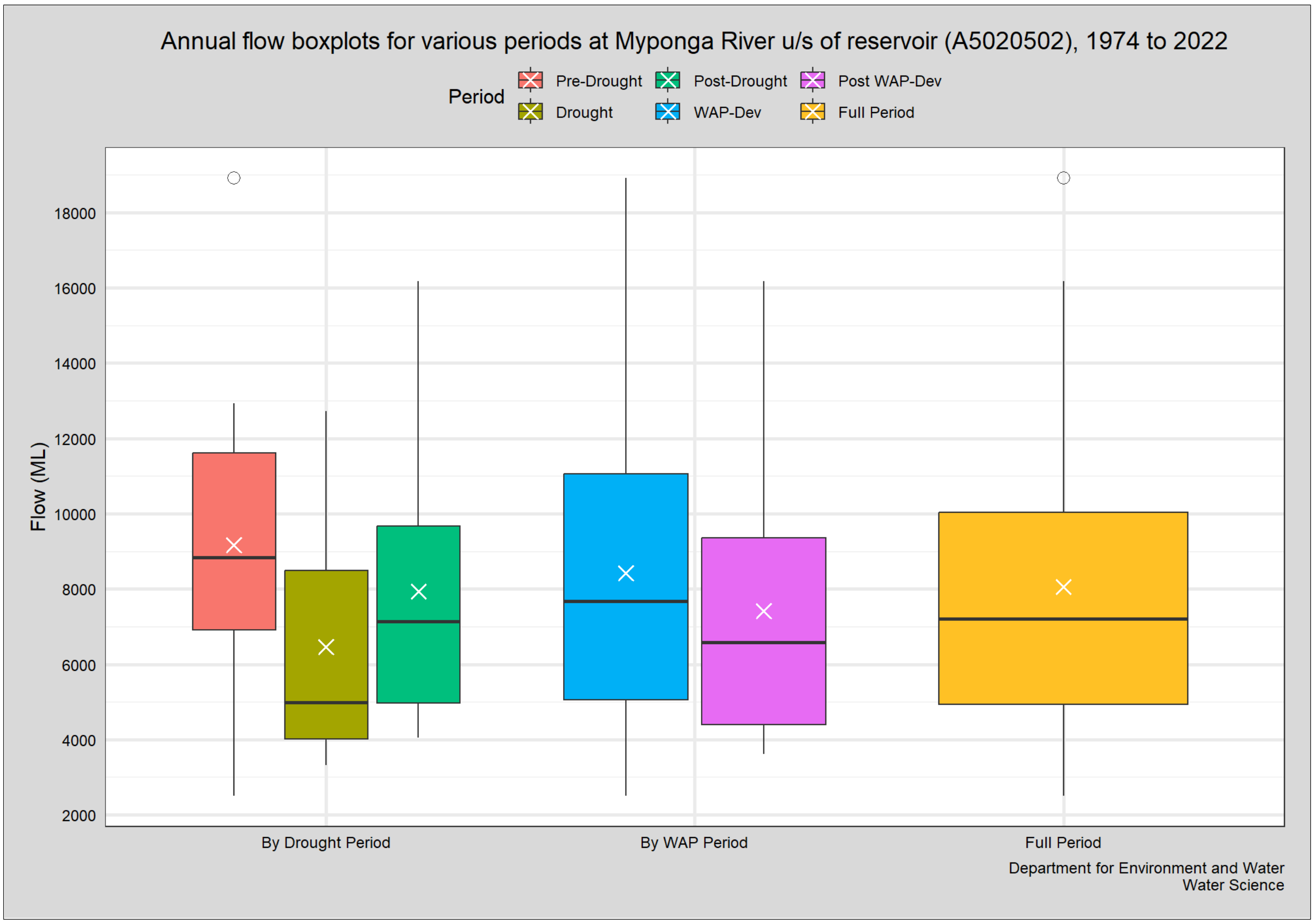


Figure 49. Distribution of annual streamflow totals for Myponga River (A5020502) for different periods during 1974 to 2022 (median (—), average (X), and outliers (O) shown)

Figure 50 (a) shows a time series of annual streamflow totals for 1974 to 2022, with long-term median annual flow shown alongside a 10-year rolling average and long-term trend, both of which suggest minor decline in streamflow totals over the period of observation.

Figure 50 (b) shows annual deviations from the long-term median, and in the last 2 decades, only 3 years (2016, 2021 and 2022) were 'wet' years. The number and frequency of 'dry' and 'very dry' years is much higher in the recent decades.

Figure 50 (c) shows annual streamflow with median annual flows displayed for pre-drought, drought, and post-drought periods as well as for the full period. These results, and results in Table 62, show that the median annual streamflow during the drought period was 3,850 ML (44%) less than that for the pre-drought period. The median annual flow subsequently increased in the post-drought period but remained below the pre-drought median by 1,698 ML (19%).

Figure 50 (d) shows annual streamflow totals coloured by the drought phase, with median annual flows for the WAP development and post-WAP development periods also shown. These reveal a reduction in median annual flow in the period following the WAP development (that is, from 2007 onwards), by over 1,098 ML (14%) (Table 63).

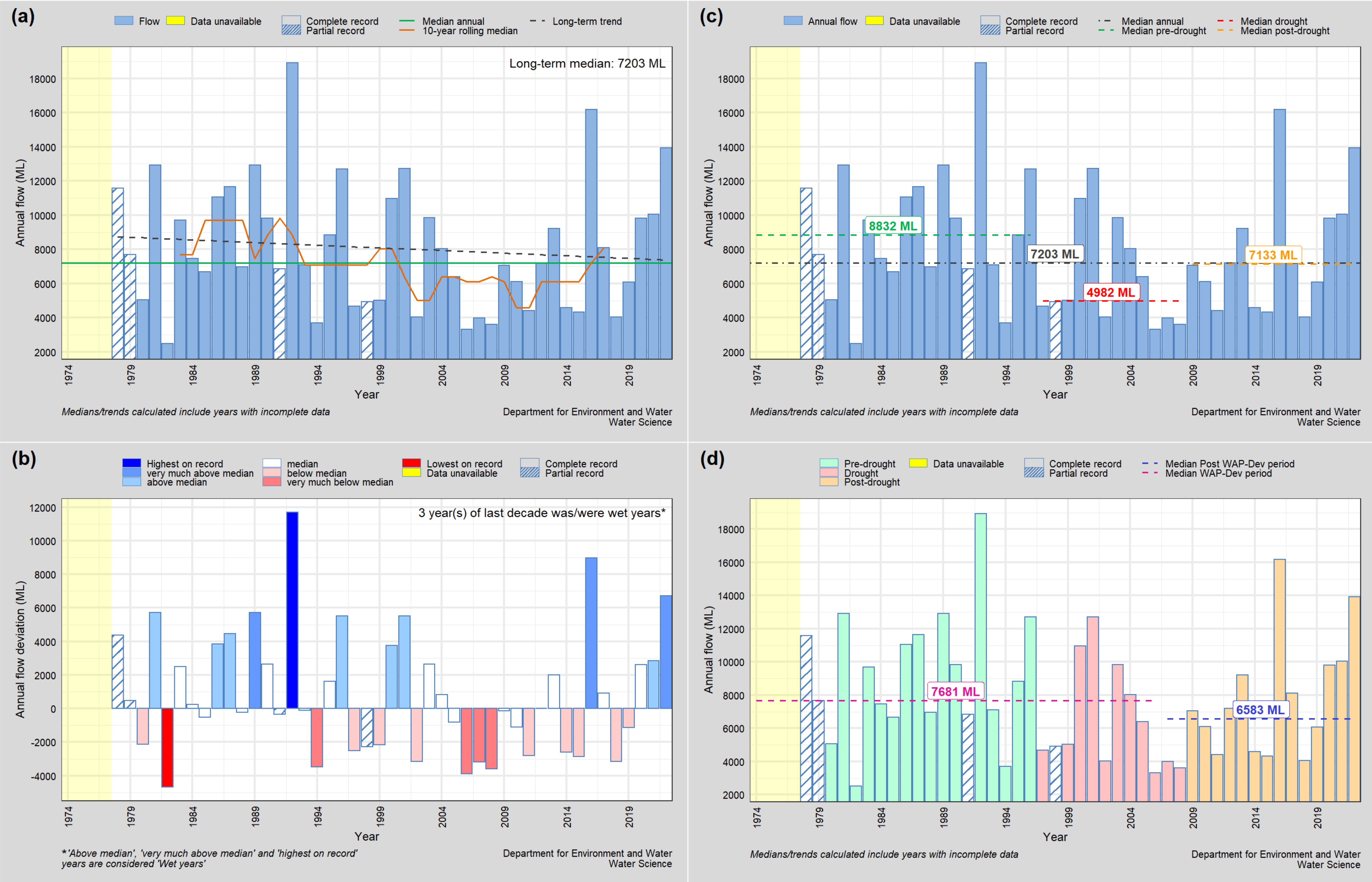


Figure 50. **(a) Annual streamflow totals for Myponga River (A5020502) for 1974 to 2022, (b) Deviations in annual streamflow totals for Myponga River (A5020502) from long-term median, (c) Annual streamflow totals for Myponga River (A5020502) showing medians before and after the drought (1997 to 2009), (d) Annual streamflow totals for Myponga River (A5020502) showing medians during WAP development (1974 to 2006) and during Post WAP-development**

4.5.2 Seasonal streamflows

Results of analysis of streamflow records at the A5020502 station at seasonal time steps are presented in this section. Table 62 summarises the median seasonal streamflow for different periods relative to the Millennium drought. These statistics show that the majority of annual flow is recorded across winter and spring seasons.

Winter season median flows decreased during the drought period, subsequently increasing during the post-drought period but were still lower than the pre-drought medians (Partial recovered). Autumn and spring season median flows decreased during drought but increased to higher than pre-drought medians in the post-drought period (Fully Recovered and wettest). Unlike other sub-catchments investigated, summer season median flows progressively increased through the 3 drought-related periods, appearing to have no impact from the drought. Autumn, spring and summer seasons were the wettest in the post-drought period.

Table 62. Median annual and seasonal streamflow for Myponga River (A5020502) across drought-related periods

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-Drought	
	(1974 to 2022)	(1974 to 1996)	(1997 to2009)	(2010 o2022)	Drought (ML *(%)*)	Post-Drought (ML *(%)*)
Summer	81	66	80	169	14 (21%)	103 (157%)
Autumn	454	451	427	469	-24 (-5%)	18 (4%)
Winter	5037	6605	2966	4929	-3640 (-55%)	-1676 (-25%)
Spring	1662	1689	1485	1711	-204 (-12%)	22 (1%)
Annual	**7,203**	**8,832**	**4,982**	**7,133**	**-3,850 (-44%)**	**-1,698 (-19%)**

Table 63 summarises seasonal flow for WAP development and post-WAP development periods. Median seasonal flows during all seasons except summer were lower during the post-WAP development period.

Table 63. Median annual and seasonal streamflow for Myponga River (A5020502) across WAP development and Post-WAP development periods

Season	WAP development	Post-WAP development	Change (WAP dev. to post-WAP dev.)	
	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Summer	71	138	67	94%
Autumn	454	452	-1	0%
Winter	5,823	4,652	-1171	-20%
Spring	1,689	1,347	-342	-20%
Annual	**7,681**	**6,583**	**-1,098**	**-14%**

4.5.3 Monthly streamflows

The distribution of flow across each calendar month, with monthly totals aggregated to various drought- and WAP-related periods are summarised in Table 64and Table 65 respectively. The monthly data shows median flow in the months of January, April, July to October, and December experienced a decrease in median monthly flows during the drought period, while the remaining months experienced an increase over the same period. Of the months that experienced a decrease during the drought, only January and December showed a recovery in the post-drought period, increasing above the pre-drought median, while April, July and August demonstrated only a partial recovery. September and October remained at or decreased further below the drought period median, suggesting no recovery yet. At all remaining sites the post-drought median remained above the pre-drought median.

Table 64. Median monthly streamflow for Myponga River (A5020502) for drought periods

Month	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2022)	(1974 to1996)	(1997 to2008)	(2009 to 2022)	Drought (mm (%))	Post-drought (mm (%))
Jan	14	12	10	32	-1 (-10%)	20 (175%)
Feb	12	5	22	33	16 (294%)	27 (498%)
Mar	33	17	46	47	29 (171%)	30 (174%)
Apr	105	112	99	103	-13 (-11%)	-9 (-8%)
May	301	279	329	291	50 (18%)	12 (4%)
Jun	755	689	1,009	738	320 (46%)	49 (7%)
Jul	1,731	2,523	1,406	1,783	-1,117 (-44%)	-740 (-29%)
Aug	1,960	2,870	1,336	1,978	-1,535 (-53%)	-892 (-31%)
Sep	953	1,338	777	780	-561 (-42%)	-558 (-42%)
Oct	404	502	403	290	-98 (-20%)	-212 (-42%)
Nov	152	128	182	131	54 (42%)	3 (2%)
Dec	48	39	29	99	-10 (-25%)	60 (155%)
Annual	**7,203**	**8,832**	**4,982**	**7,133**	**-3,850 (-44%)**	**-1,698 (-19%)**

Table 65. Median monthly streamflow for Myponga River (A5020502) for WAP periods

Month	All years	WAP development	Post WAP-development	Change (WAP dev. to Post WAP-dev.)	
	(1974 to 2022)	(1974 to 2006)	(2007 to 2022)	(ML)	(%)
Jan	14	11	27	16	142%
Feb	12	7	19	12	174%
Mar	33	35	30	-5	-13%
Apr	105	111	103	-8	-7%
May	301	311	280	-31	-10%
Jun	755	775	687	-88	-11%
Jul	1,731	1,990	1,667	-323	-16%
Aug	1,960	1,950	1,978	28	1%
Sep	953	1,083	686	-396	-37%
Oct	404	414	285	-129	-31%
Nov	152	154	131	-23	-15%
Dec	48	39	75	36	94%
Annual	**7,203**	**7,681**	**6,583**	**-1,098**	**-14%**

In the context of WAP-related periods, all months except the summer months (December to February) and August demonstrated a decrease in median flow over the post-WAP development period relative to the WAP development period.

4.5.4 Daily streamflows

Figure 51 plots the range of daily flows (on a logarithmic scale) as probability of exceedance curves, for the pre-drought, drought, and post-drought periods. Unlike catchments reported in the earlier sections, there is no clear separation between the distribution of daily flows for the 3 comparison periods. A key observation from these results is that all flow ranges during the post-drought period, except for daily flows in the high–very high flow range (10th and 20th percentiles), are similar to, or higher than, during the pre-drought period.

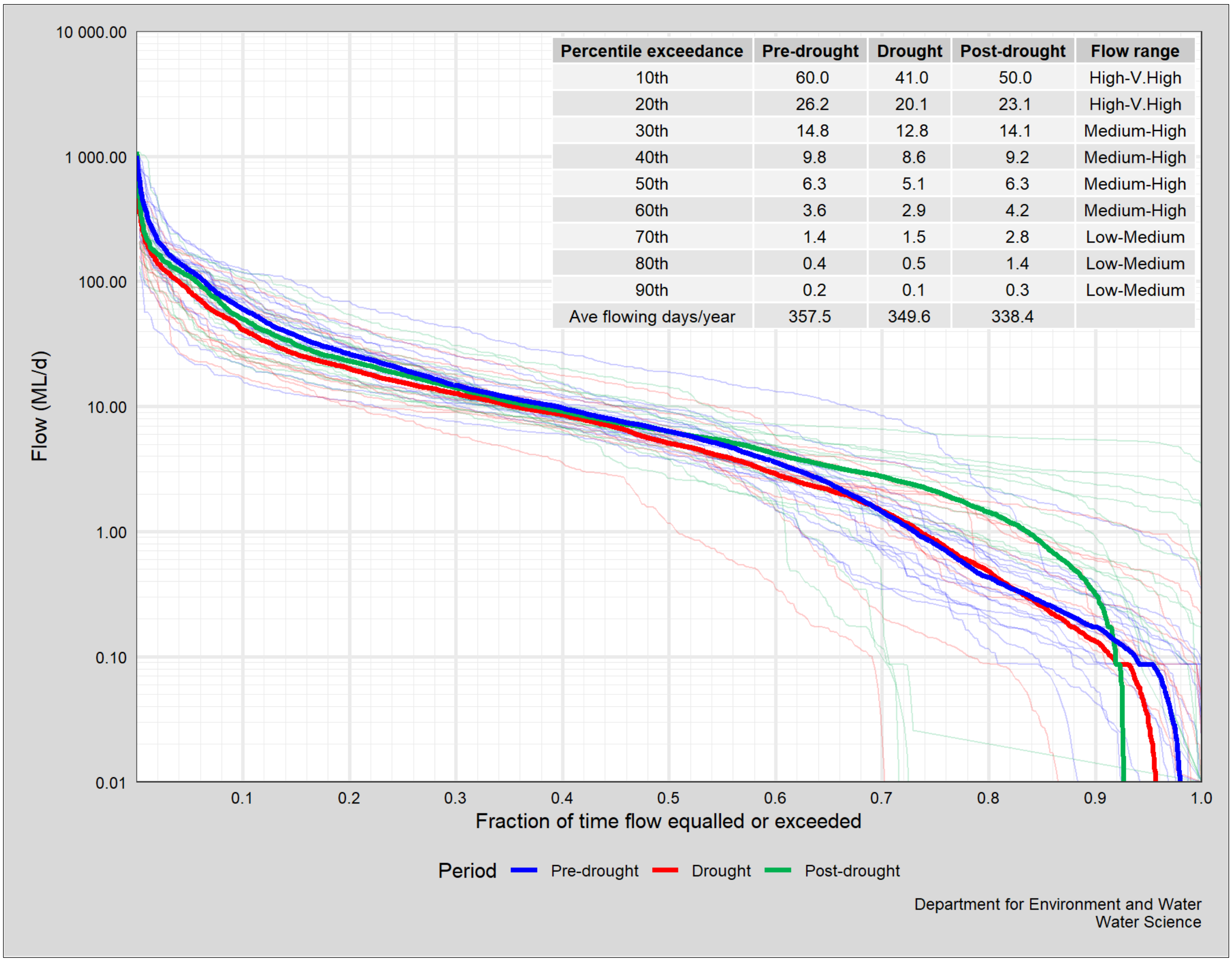


Figure 51. Flow duration curves for daily flow in Myponga River (A5020502) for periods related to the drought

Figure 52 shows the distribution of daily flow for the WAP development period, and for the post-WAP development period since 2007, with both distributions summarised. The results indicate a small reduction to flows above-median daily flow and an increase in flows below median daily flow during the post-WAP development periods.

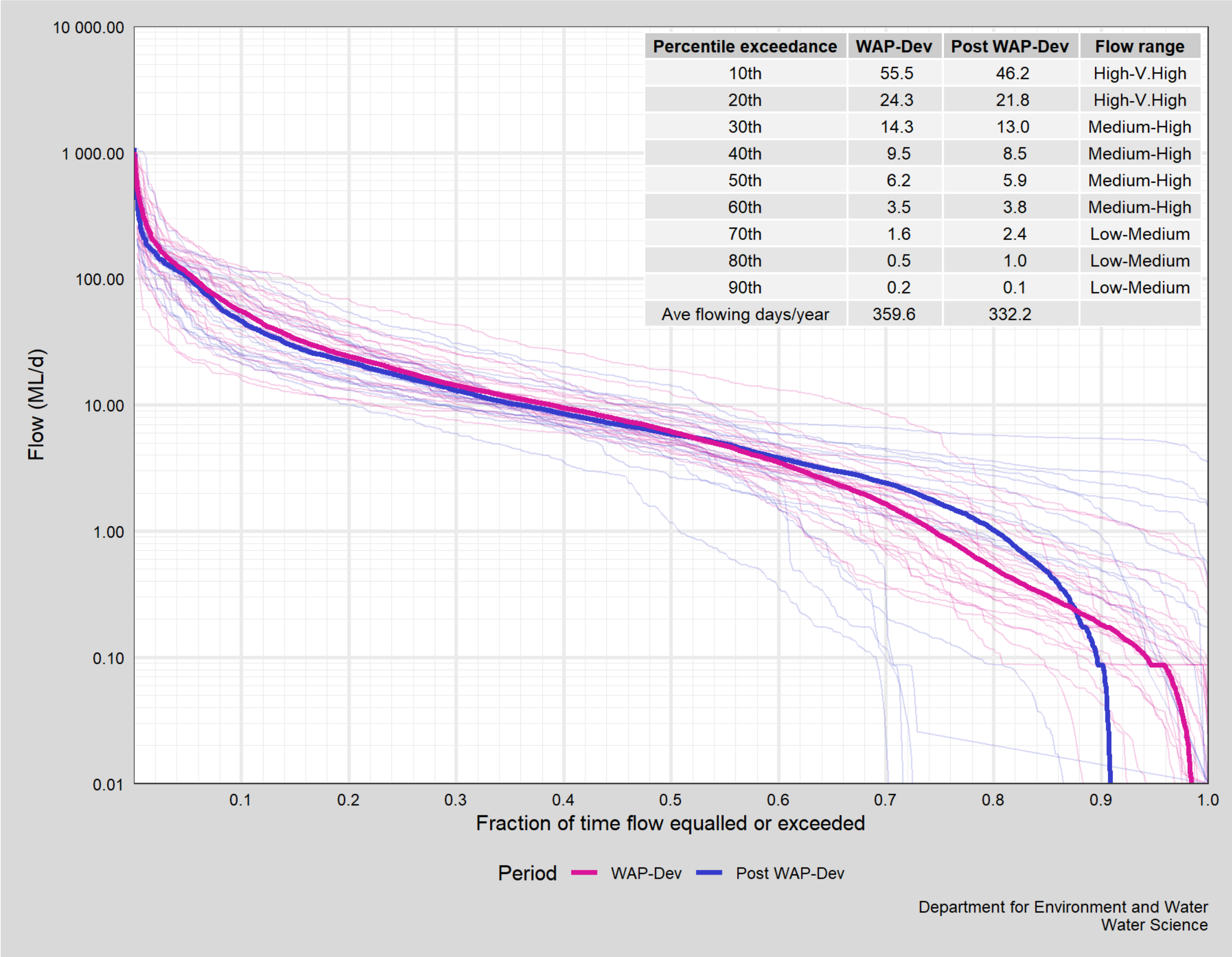


Figure 52. Flow duration curves for daily flow in Myponga River (A5020502) for periods related to the WAP development and post WAP-dev. periods.

4.6 Streamflow summary

4.6.1 Streamflow recovery – drought related period medians

Annual and seasonal median streamflow data for the 3 drought comparison periods for each sub-catchment were presented in earlier sections. To obtain a PWRAs-scale picture of the 'recovery' status of streamflow during the post-drought period (2009 to 2022), the stations were grouped into the 3 categories by comparing the post-drought median to drought and pre-drought period medians, as defined in Section 2.5, and summarised below.

Table 66 summarises the changes to seasonal and annual flows during the post-drought period (2009 to 2022) in comparison to the pre-drought (1974 to 1996) and drought (1997 to 2008) periods. Some of the key observations from reviewing the data are:

- Myponga is different to the other catchments with regards to seasonal streamflow behaviour, as spring, autumn and summer seasons experienced the highest median seasonal flows during the post-drought period (Fully Recovered and wettest). Only winter median flow remained below the pre-drought median, although increased above the drought median (Partially Recovered).
- In all the non-Myponga sub-catchments, autumn has been the driest (Yet to Recover) season in the post-drought period. Spring has been the next most impacted season, with none of the stations reaching Fully Recovered status in the post-drought period.
- Annual streamflow volumes in the post-drought period increased from drought period medians in all sub-catchments but were still lower than pre-drought medians (Partially Recovered). This is attributed primarily to winter flows having either Partially or Fully Recovered in the post-drought period.
- The results also demonstrate the seasonal variability of streamflow across the sub-catchments and, on a large scale, across the 2 PWRAs.

Table 66. Summary of streamflow recovery in the post-drought period

	Finniss	Bremer	Torrens	Onkaparinga	Myponga
Winter	Partially Recovered	Partially Recovered	Partially Recovered	Fully Recovered	Partially Recovered
Spring	Partially Recovered	Partially Recovered	Yet to Recover	Yet to Recover	Fully Recovered
Autumn	Yet to Recover	-*	Yet to Recover	Yet to Recover	Fully Recovered
Summer	Partially Recovered	-	Fully Recovered	Yet to Recover	Fully Recovered
Annual	Partially Recovered	Partially Recovered	Partially Recovered	Partially Recovered	Partially Recovered

* Data not presented due to incomplete records, refer to Section 4.2.1.

4.6.2 Streamflow recovery – WAP development related period medians

Results of comparison between WAP development and post-WAP development median seasonal flow show:

- Finniss (Meadows Creek sub-catchment): All seasons experienced reduced flows in the post-WAP development period (Table 49).
- Onkaparinga (Scott Creek sub-catchment): All seasons except winter experienced reduced flows in the post-WAP development period (Table 55).

- Torrens (Mt Pleasant sub-catchment): All seasons expect summer experienced reduced flows in the post-WAP development period (Table 59).
- Common statistic for the 3 catchments above: Autumn and spring flows were lower in the post-WAP development period.
- Myponga (u/s of reservoir): All seasons except summer experienced decreased flows in the post-WAP development period (Table 63)

4.6.3 Monthly flow recovery summary

Finniss sub-catchment: Flows recovered in all months in the post-drought period in comparison to the drought period medians but were still lower (except in February) than pre-drought medians (Partially Recovered). It was a similar case for the post-WAP development period with flows Yet to Recover to WAP development period medians.

Onkaparinga sub-catchment: All months (except June) in the post-drought period experienced the lowest monthly flows amongst the 3 drought related periods (Yet to Recover and driest). It was a similar case for the post-WAP development period when compared to WAP development monthly flows.

Torrens sub-catchments: The majority of the annual flow occurs in the period between June to October and all these months had reduced flow in the post-drought in comparison to the pre-drought period (Partial recovery). Flows during the June to October months were lower in the post-WAP development period compared to the WAP development period.

Myponga sub-catchment: The months of January, April, July to October, and December experienced a decrease in median monthly flows during the drought period, while the remaining months experienced an increase over the same period. Median flow in September and October remained at or decreased further in the post-drought period (Yet to Recover). All other months were either Partially Recovered or Fully Recovered in the post-drought period.

4.6.4 Daily flow (flow regime) recovery

Since the beginning of the Millennium drought, daily flows (flow regime) have been altered to varying extents in 4 of the 5 sub-catchments (except Myponga), and the average number of flowing days per year has reduced in all catchments except in the Finniss. The results are similar for the post-WAP development period in comparison to the WAP development period daily flows.

The number of flowing days per year and the low, medium, and high flow ranges are some of the key metrics that characterise the flow regime of a catchment. These metrics also form part of the environmental water requirement metrics that were used to assess eco-system flow requirements in the WAPs. The results presented provide evidence of alteration of the flow regime since the beginning of the drought and during post-WAP development period in most of the non-Myponga sub-catchments.

5 Rainfall–runoff response

The rainfall–runoff relationship for a given catchment is stable ('stationarity') when a certain amount of runoff could be expected for a given amount of annual rainfall. A change to (or shift in) climatic conditions from historically established conditions, such as a shift in rainfall patterns, or significant changes to factors such as land use, land management, and capture, diversion and extraction of surface and ground water resources – which may alter a catchment's 'initial loss–continuing loss' characteristic – will result in a change to this relationship ('hydrologic non-stationarity') (Chiew et al. 2014).

New capture, diversion and extraction of surface and ground water resources in the MLR is expected to have ceased since the resources were prescribed in 2005. Hence, this factor is not considered to have impacted the rainfall–runoff response in the post-drought period (that is from 2009). Preliminary investigations indicate no large-scale changes to land use and land management practices during the post-drought period, but further detailed investigation is warranted. Given these factors, it would be reasonable to assume the amount of annual runoff for a given amount of annual rainfall to be consistent with earlier periods, unless there has been a shift in climate, in particular the rainfall pattern at a given location.

Possible shifts in rainfall patterns across different drought and WAP development-related periods are discussed in the previous sections. An additional investigation into the effects of shift in rainfall patterns on catchment rainfall–runoff response is provided in this section.

Runoff response to annual rainfall totals for catchment areas upstream of the streamflow gauging stations (sub-catchments) that were used in the streamflow section are presented here. Figure 53 and Figure 54 show rainfall-runoff plots for the five sub-catchments investigated. Each plot presents a series of data points, each representing observed rainfall–runoff values for a given year, noting that runoff is converted from megalitres to millimetres (refer to Section 2.6 for further details). The full 49-year period of record from 1974 to 2022, where available, is included along with a generalised relationship between these variables shown by a TanH curve fitted to these data. Annual values are presented in different colours based on the period of their association, either pre-drought (blue), drought (red) or post-drought (green). The TanH curve representing the full reporting period is coloured in black.

Data presented in the plots for the individual sub-catchments is discussed below:

- Finniss, Meadows Creek sub-catchment: Streamflow records from Yundi (A4260504) gauging station and rainfall records from Meadows (23730) rainfall site were used in the analysis. Inspection of the plot (Figure 53) indicates a clear difference in runoff response during different drought-related periods. The annual runoff observed for a given rainfall amount is generally the highest for pre-drought (blue) years, lowest for drought (red) years, with the post-drought (green) years generally falling between the two. Data points on either ends of the curve – representing very low (≈<650mm) and very high (≈>1000mm) rainfall years – are considered outliers from a rainfall-runoff response perspective.

  As an example, for the eight years that received annual rainfall of 820 mm (data points in the oval in the plot):

  - Runoffs during the 3 pre-drought period years were around 145, 130 and 120 mm, with an average of 132 mm.
  - Runoff during the 2 drought period years were around 50 and 70 mm, with an average of 60 mm. This represents a ≈50% reduction in runoff in comparison to pre-drought period average runoff.
  - Runoff during 3 post-drought period years were 100, 110 and 120 mm, with an average 110 mm. This represents an increase when compared to the drought period but remains lower than the pre-drought average.

  In the example above, 820 mm rainfall was chosen as it is the closest to the median (and mean) annual rainfall of 817mm for the full analysis period. However, similar results are observed for other data points in the medium to high annual rainfall range. This provides evidence to suggest that the underlying rainfall–runoff response of Meadows Creek sub-catchment has potentially changed in the period since the Millennium drought. Another key point to consider is that the median annual rainfall for the post-drought period is below the rainfall used in this example, at 783 mm, which results in a comparatively lower median runoff over the post-drought period than the 110 mm in the example.

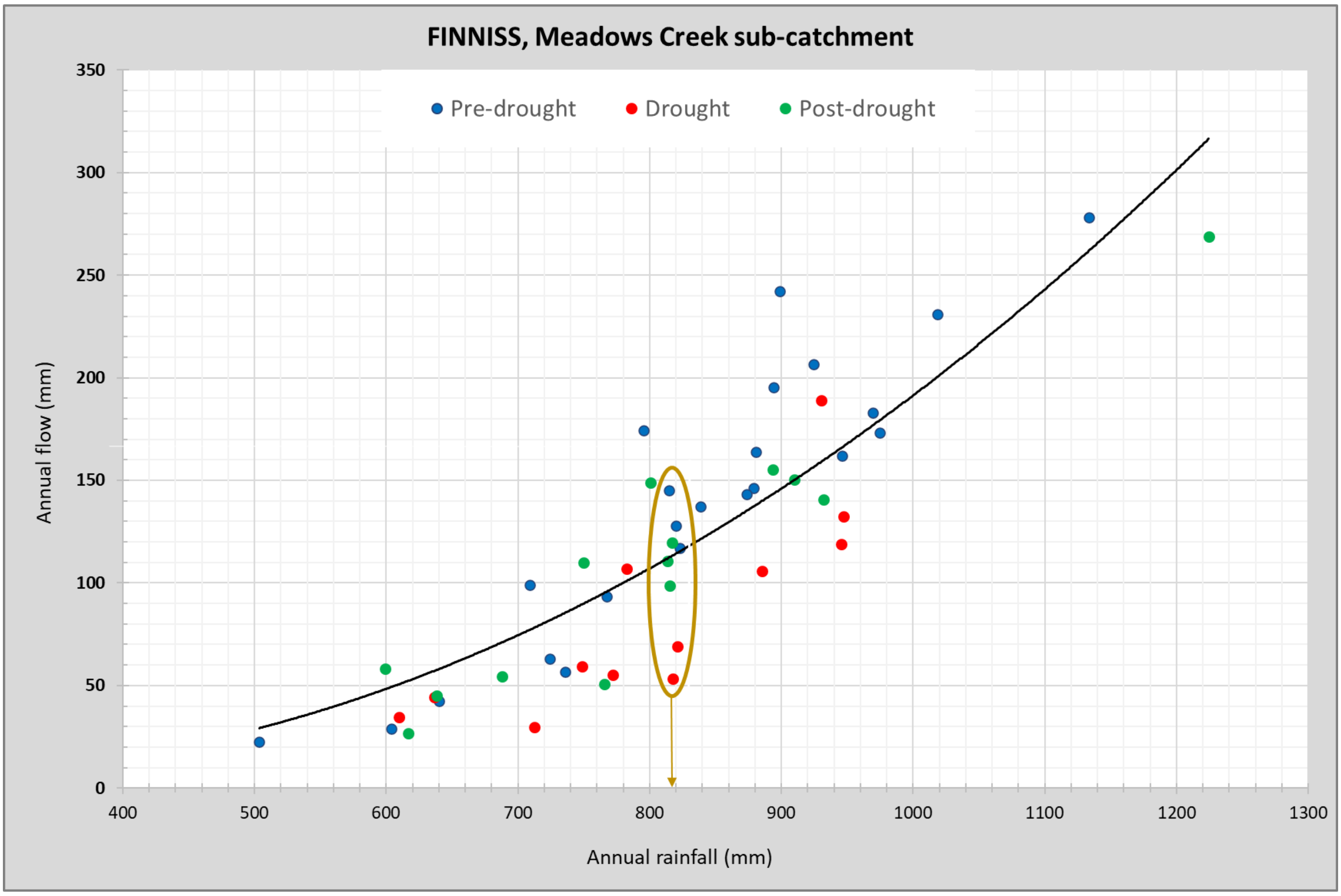


Figure 53. Rainfall-runoff plot for Meadows Creek sub-catchment, Finniss

- Bremer River at Hartley (Figure 54): As discussed in the streamflow section, a large proportion of the post-drought year had incomplete records. The chart presented here includes data only from years with complete records.
- Scott Creek, Onkaparinga: Streamflow records from Scott Creek (A5030502) gauging station and rainfall records, averaged from Cherry Gardens (23709) and Longwood (23727) rainfall sites, were used in the analysis. Inspection of the plot (Figure 54) shows that the annual rainfall–runoff points during the 3 drought-related periods are distributed evenly, in general, across the entire rainfall range. Pre-drought years show higher variability of rainfall–runoff response when compared to the 2 later periods.
- Mt Pleasant sub-catchment, Torrens: Streamflow records from Torrens River at Mount Pleasant gauging station (A5040512) and rainfall records from Mt Pleasant (23737) rainfall site were used in the analysis. Inspection of the plot (Figure 54) shows:
  - Both annual rainfall and rainfall-runoff response is shown to be highly variable in nature across the analysis period.
  - The rainfall-runoff data points representing all 3 comparison periods are mostly spread equally across the rainfall range, indicating post-drought annual rainfall totals are closer to pre-drought annual totals.

- A clear difference between the data points in pre-drought years and the post-drought years is apparent for years with rainfall >500mm, indicating difference in the rainfall–runoff response between the 2 periods.
- A majority of the data points in the post-drought period are lower in runoff than the data points in the drought period, indicating annual runoff generated for a given amount of rainfall was lower during the post-drought years than during the drought period.

This analysis provides evidence to suggest that the underlying rainfall–runoff response of Mt Pleasant sub-catchment has potentially changed in the period since the Millennium drought.

- Myponga sub-catchment upstream of reservoir: Streamflow records from Myponga River u/s of Reservoir station (A5020502) and rainfall records from Myponga (23738) rainfall site for the period from 1980 to 2021 were used in the analysis. Data for the years 1991 and 1998 were excluded due to data quality issues. Inspection of the plot (Figure 54) shows:
  - Unlike other areas in the MLR, the 4 wettest years during this period were during the drought (3) and post-drought (one) periods and the bottom 3 rainfall totals were during the pre-drought period.
  - The variability of rainfall across the Fleurieu region differs to the rest of the WMLR PWRA and is discussed in Section 3.5.

In summary, there is evidence to suggest that the underlying rainfall–runoff responses of Meadows Creek sub-catchment in the Finniss catchment and Mt Pleasant sub-catchment in the Torrens have potentially changed (or shifted) in the period since the Millennium drought. In the case of the Bremer sub-catchment, while there are indications of a shift during the drought period, the results are inconclusive due to the incompleteness of the streamflow records during the post-drought period. The evidence to suggest a shift in the rainfall-runoff response has occurred in the Onkaparinga or Myponga River sub-catchments is inconclusive.

It is uncertain, at this time, if this observed shift in seasonal rainfall and rainfall-runoff response is permanent or temporary-and-prolonged. It is also acknowledged that (a) this likely shift in observed rainfall-runoff response may be caused by multiple drivers, not all of which are the result of changing climate and (b) for changes attributed to changing climate, future trends may not continue at the same rate or in the same manner as historical trends (DCCEEW, 2023). Future investigations could include review of changes to water resource development, land cover and land management during the different comparison periods, streamflow generation mechanism and their influences, for example trends in groundwater levels influencing persistent baseflow or changes in estimates of actual evapotranspiration.

The surface water models used in development of the WAPs were generally calibrated to streamflow records for the period 1974 – 2006, with one rainfall-runoff relationship developed for the entire period used in deriving resource capacities in the WAPs. Given the shift in rainfall-runoff identified since the start of the drought in this investigation for some of the sub-catchments, recalibration of the models to include recent streamflow data (to include this shift (or non-stationarity)) is recommended for future use of the models, including while amending the WAPs. To evaluate the impacts of future climate on rainfall-runoff response, the recalibrated models would have to be run with climate projection data sets.

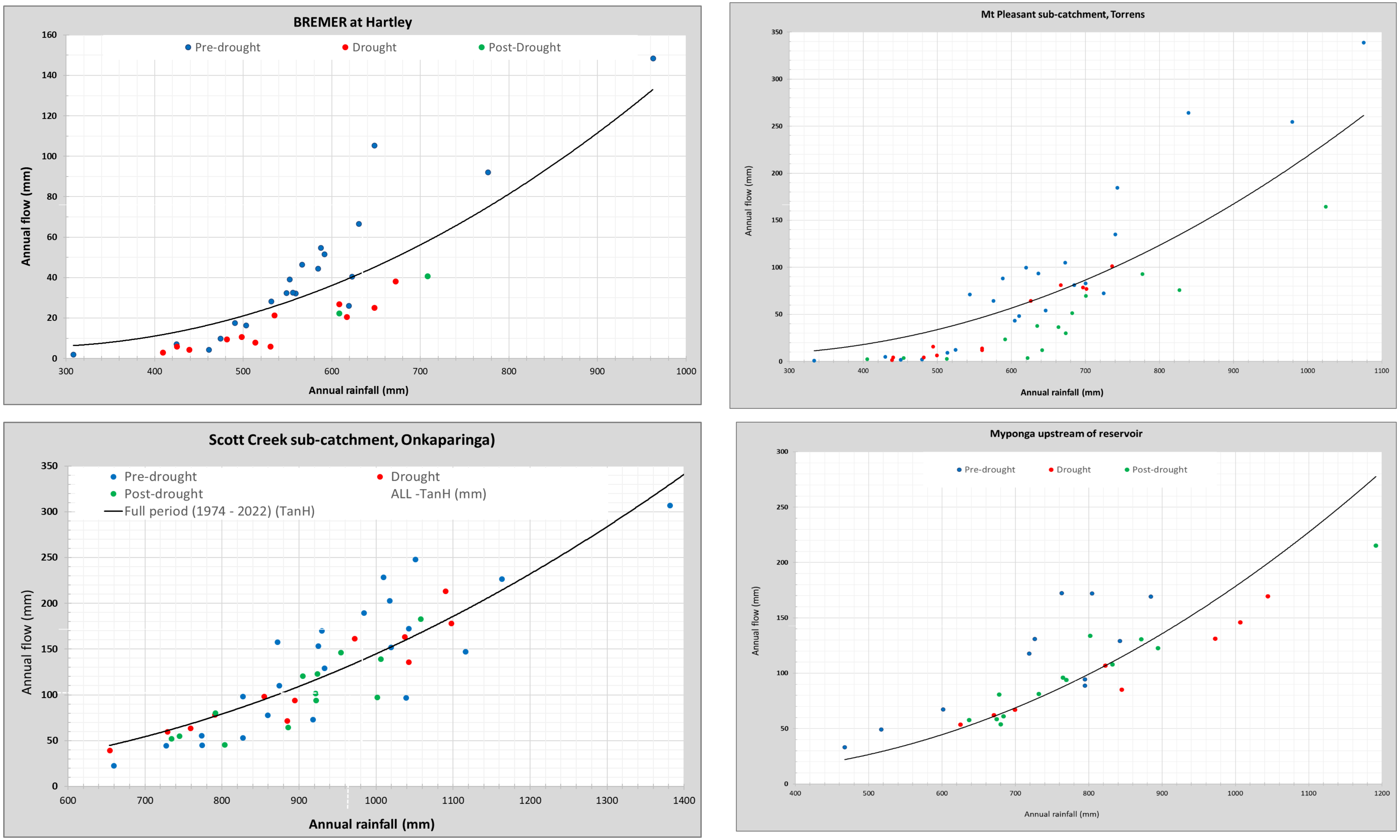


Figure 54. Rainfall-runoff–response curves for 4 sub-catchments

6 Conclusions and discussion

6.1 Rainfall

Rainfall records from 24 BoM stations across the MLR were analysed using different methods to investigate long-term trends, periodic shifts within long-term data and the impacts of the drought on rainfall totals and seasonality. Overall, they demonstrate the variability (spatial and temporal) of historical rainfall across the MLR, with the impacts of the drought also being variable (but with some similarities) across the MLR. Some of the key results of the analyses observed are summarised below.

- Long-term trends and shifts in long-term data (*Mann-Kendall test and Wilcoxon Rank Sum and Welch's t-tests*): Annual rainfall has generally shown evidence of significant change since the start of the Millennium drought at 50% of the stations investigated. Stations with no evidence of declining trend are located in the Bremer (lower elevation sections) and in certain sections of the Onkaparinga and Fleurieu catchments. Most of the statistically significant changes detected in the analysis across the comparison periods have been related to seasonal and/or monthly periods.

  Spring rainfall has shown mostly strong indications of a reducing trend following the onset of the Millennium drought, indicating a potential shift in rainfall has occurred at all catchments. October is the key month linked to this shift, showing a significant decrease at most rainfall stations. The largest effects of the impacts on spring rainfall have been mostly observed in the post-drought period, with the reducing trend commencing from early- to mid-2000s.

  Autumn rainfall has shown indications of a negative shift occurring since the onset of drought, with the most significant impact occurring during the drought period. In general, though, autumn rainfall showed signs of recovery in the post-drought rainfall period.

  Statistically significant long-term increasing trends were observed in summer rainfall at 3 stations, and in January rainfall at 5 stations. All these stations are located either in the Bremer's lower elevation sections or across the Fleurieu catchments.

- Rainfall recovery (comparison of drought and WAP-development related periodic medians): To obtain an MLR-scale picture of the recovery status of rainfall since the start of the drought, post-drought period (2009 to 2022) medians were compared to drought and pre-drought period medians, with the key results being: (a) Annually, 91% of stations have Fully Recovered or Partially Recovered. This is due to winter season recovery, with 83% of stations either Fully or Partially Recovered; (b)spring is the most impacted season with 80% of stations Yet to Recover; and (c) autumn is the next most impacted season, with 50% of stations Yet to Recover. (Recovery' definitions are provided Section 2.5)

Some of the catchment-specific results include:

- Finniss: rainfall at Meadows (23730) showed indications that rainfall had not recovered in the post-drought period, suggesting a shift occurred in median rainfall from pre-drought conditions. In contrast, the comparison station at Macclesfield (23728) indicated a recovery in median annual rainfall – although in both cases the rainfall distribution tended towards a negative skewness, a greater proportion of rainfall events in the lower quartile. Under WAP-related periods, both stations again showed a significant negative skewness in the post-WAP development period, with Meadows having a similar median to the WAP development period while for Macclesfield there was a significant increase in median.

- Bremer: recovery of rainfall to pre-drought conditions on an annual basis was observed in the majority of stations across the catchment, with both post-drought and post-WAP development periods showing rainfall to be equivalent to or greater than the pre-drought and WAP development periods, respectively. However, the data shows a shift of rainfall towards the winter and summer months at some stations in the catchment, suggesting that the high rainfall period has compressed to the winter months at the expense of spring and autumn rainfall.

- Onkaparinga: spring has shown an increase in rainfall variability since the mid-2000s, while the other seasons have shown a decrease in variability over the past 2 to 3 decades. However, rainfall in the warmer months (November to March) and also in July has shown some significant jumps at certain times in the post-drought period, suggesting an increase in extreme events during these months in particular. Some stations appear to show recovery of rainfall post-drought (for example, Uraidla, Echunga and Cherry Gardens) while others (for example, Hahndorf) indicate a shift in rainfall has occurred, with decreased median rainfall post-drought. Under WAP-related periods, some stations show consistent distributions between post-WAP development and WAP development periods, while others suggest a decrease (for example, Bridgewater and Lobethal) or an increase (Uraidla and Echunga).

- Torrens: summer rainfall showed an increase in rainfall in the post-drought period at 3 of the 4 stations in the catchment, coinciding with indications of extreme rainfall events occurring during some of the warmer months over the same period, in particular February, March and December. Winter rainfall, however, has shown a reduced variability over the last 2 decades. Recovery of rainfall in the post-drought period is suggested at 2 of the stations (Mount Pleasant and Gumeracha) but does not appear to have recovered at the other two stations (Birdwood and Cudlee Creek). From a WAP development perspective, only Cudlee Creek shows reduced rainfall in the post-WAP development period, while the others have similar or greater rainfall (Gumeracha) relative to WAP development.

- Fleurieu region: unlike the other catchments, evidence was weaker for a reduction in spring rainfall in this region, with the strongest indications of change at 2 of the mid-range rainfall stations at Willunga (23753) and Yankalilla (23754). Despite this difference to other catchments, October rainfall was still shown to be strongly impacted in the post-drought period for the majority of stations throughout the region. In contrast, summer, winter and autumn rainfall appear to remain largely consistent with pre-drought rainfall. In general, overall recovery of rainfall in the post-drought period is indicated at all stations but Yankalilla, which shows a similar reduction in annual median to that of the drought period. Similar results are also seen with the WAP-related periods, with only Yankalilla showing a decreased median in the post-WAP development period.

Overall, seasonal rainfall during spring (predominantly in October) and autumn to a lesser degree (in April) has undergone a statistically significant decrease since the start of the drought. There is also evidence of decline in long-term annual rainfall, particularly in the higher elevation areas of the MLR. A long-term upward trend was observed in summer rainfall at 3 stations, and in January rainfall at 5 stations. All these stations are located either in the Bremer catchment (lower elevation sections) or in the Fleurieu catchment. Investigation using a larger sample of lower elevation stations across the MLR is required to confirm if the impacts of climate change and/or the drought were primarily in the higher elevation sections of the MLR.

6.2 Streamflow

Analysis of streamflow records from 5 streamflow gauging stations across the two PWRAs has highlighted the variable nature of streamflow behaviour in catchments. The results also clearly indicate that the Myponga catchment is different to the other 4 catchments with regards to streamflow patterns. Comparison of seasonal flows for the 3 drought-related periods provides valuable insight into the extent of catchment recovery since the beginning of the Millennium drought. Some of the key observations from reviewing the data are:

- Finniss catchment has experienced a reduction in median flows in all four seasons during the post-drought period in comparison to the pre-drought period (Yet to Recover).

- Bremer and Torrens catchments experienced the highest summer flows (wettest) and lower flows for the other three seasons (Yet to Recover) during the post-drought period in comparison to the pre-drought period.

- Onkaparinga catchment experienced higher winter flows and lower flows in the other 3 seasons during the post-drought period in comparison to the pre-drought period.
- A statistic common to all sub-catchments except Myponga was that autumn and spring season median flows were lower during the post-drought than the pre-drought period (Yet to Recover).
- Myponga experienced the largest reduction in median flows in the winter season during the drought (driest), with flows increasing in the post-drought period but remaining below the pre-drought median (partial recovery). Autumn and spring median flows both decreased during the drought before increasing to values similar to the pre-drought period (Fully Recovered), while summer median rainfall showed the largest increase in the post-drought period (wettest).

Since the beginning of the Millennium drought, daily flows have been altered considerably, to varying extents, in 4 of the 5 sub-catchments (except Myponga), and the average number of flowing days per year has reduced in all catchments except in the Finniss.

A common statistic from the comparison between WAP development and post-WAP development median seasonal flows was that autumn and spring flows were lower in the post-WAP development period (Yet to Recover).

In contrast to other catchments, the post-drought period was the wettest among the comparison periods in the Myponga catchment upstream of the reservoir. Further investigations into the weather systems that influence long-term rainfall patterns and how the Millennium drought interfaced with those weather systems, along with the implementation of more streamflow monitoring sites in the Fleurieu region, is recommended to improve understanding of, and/or for effective future investigations and management of, water resources in the Fleurieu region.

6.3 Rainfall-runoff response

Results of rainfall-runoff response analysis show that there is evidence to suggest that the underlying rainfall–runoff responses of Meadows Creek sub-catchment in the Finniss River and Mt Pleasant sub-catchment in the Torrens River have potentially changed (or shifted) in the period since the Millennium drought. In the case of the Bremer sub-catchment, while there are indications of a change during the drought period, the results are inconclusive due to the incompleteness of the streamflow records during the post-drought period. The evidence to suggest that a shift in the rainfall–runoff response has occurred in the Onkaparinga or Myponga River sub-catchments is inconclusive.

It is uncertain whether the observed changes (or shifts) are permanent or temporary-and-prolonged. This non-stationarity in observed rainfall–runoff response may be caused by multiple drivers, not all of which are the result of climate change. For changes attributed to climate change, future trends may not continue at the same rate or in the same manner as historical trends (Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2023).

A change to (or shift in) climatic conditions from historical, such as a shift in rainfall patterns, or significant changes to factors such as land use, land management, and capture, diversion and extraction of surface and ground water resources – which may alter a catchment's interception, storage and soil moisture deficit characteristics – will result in a change to this relationship, bringing non-stationarity to rainfall–runoff response. New capture, diversion and extraction of surface and ground water resources in the MLR is expected to have ceased since the resources were prescribed in 2005. Hence, these factors are not considered to have impacted the rainfall–runoff response in the post-drought period from 2009. Preliminary investigations indicate no large-scale changes to land use and land management practices during the post-drought period, but further detailed investigation is warranted, particularly in the catchments that have demonstrated a change in the rainfall–runoff relationship. Future investigations could include a review of streamflow generation mechanisms and their influences, for example trends in groundwater levels influencing persistent baseflow or actual evapotranspiration.

Overall, the data presented in this report provide evidence for a possible shift in rainfall–runoff response since the beginning of the drought. Stronger evidence is available for 2 sub-catchments (Finniss and Torrens), marginal evidence for one (in the Bremer catchment), and insufficient evidence for the other 2 sub-catchments (Onkaparinga and Myponga). Consequently, the use of a rainfall–runoff relationship developed from long-term (including pre-drought) hydrological data for amending WAPs is expected to result in an overestimation of the resource capacity. In addition, this would ignore evidence that the climate, along with rainfall–runoff responses of catchments and their flow regime, is changing.

The hydrological models used in development of the WAPs were generally calibrated to streamflow records for the period 1974 to 2006, with one rainfall-runoff relationship developed for the entire period and used in deriving resource capacities in the WAPs. Given the shift in rainfall–runoff identified since the start of the drought in this investigation for some of the sub-catchments, recalibration of the models to include recent streamflow data (to include this shift or non-stationarity) is recommended for future use of the models, including while amending the WAPs. To evaluate the impacts of future climate on rainfall–runoff response, the recalibrated models would have to be run with climate projection data sets.

6.4 Implications for water planning

Research into the rainfall-runoff responses of catchments pre- and post-drought have shown that in some areas, the ability of a catchment to generate runoff from a given amount of rainfall post-drought had returned to pre-drought conditions, while in others it either had not returned, or the generation of runoff was suppressed (DELWP 2020). In the case of the MLR, whether this recently observed shift/change in rainfall patterns (and the implied change to rainfall–runoff response) is temporary or reflective of the near-future[2] climate is critical while amending the WAPs, as the recent climate is only relevant if it is reflective of the near-future climate. While long-term future climate is expected to be highly variable, modelling using climate projections for the MLR similar to the work undertaken for the Barossa PWRA (DEW 2022) is likely to provide further insight into whether the new-future climate is expected to be similar to recent climate.

Overall, the historical practice, in general, of using the longest available hydrological data sets in developing rainfall–runoff relationships, quantifying resource capacities, defining environmentally sensitive flow regimes and establishing sustainable extraction limits, requires careful consideration in future. It is common knowledge that climate has been variable in the past and is expected to be highly variable and uncertain in future with the impacts of climate change. This investigation acknowledges both and has attempted to identify possible shift(s) in rainfall in the recent past due to changing climate (and the drought), and its implications for catchment rainfall–runoff responses, to inform future water planning when amending the WAPs.

[2] For the life of the amended WAPs (10 years)

7 Appendices

7.1 Median annual and seasonal rainfall for drought related periods and post-drought recovery status – all reporting sites

Median annual rainfall for drought-related periods and post-drought recovery status – All reporting sites

Station name	Station numbers	Catchment	PWRA	Period median			Change from Pre-drought median				Post-drought recovery status
				Pre-	Drought	Post-	Drought		Post-		
				(mm)	(mm)	(mm)	(mm)	(%)	(mm)	(%)	
MT BARKER	23733	Bremer	EMLR	729	699	782	-30	-4	53	7	Fully Recovered
NAIRNE	23739	Bremer	EMLR	664	587	643	-77	-12	-21	-3	Partially Recovered
HARROGATE	23722	Bremer	EMLR	567	544	616	-23	-4	50	9	Fully Recovered
KANMANTOO	23724	Bremer	EMLR	472	420	492	-53	-11	20	4	Fully Recovered
LANGHORNE CK	24515	Bremer	EMLR	384	343	407	-41	-11	23	6	Fully Recovered
CALLINGTON	24508	Bremer	EMLR	370	380	416	10	3	46	12	Fully Recovered
MACCLESFIELD	23728	Angas	EMLR	721	627	739	-94	-13	18	3	Fully Recovered
MEADOWS	23730	Finniss	EMLR	874	800	800	-74	-8	-73	-8	Fully Recovered
CUDLEE CREEK	23731	Torrens	WMLR	864	879	799	15	2	-65	-7	Yet to Recover
GUMERACHA	23719	Torrens	WMLR	796	739	808	-57	-7	13	2	Fully Recovered
BIRDWOOD	23705	Torrens	WMLR	734	671	686	-63	-9	-48	-6	Partially Recovered
Mt PLEASANT	23737	Torrens	WMLR	655	560	652	-95	-14	-3	0	Partially Recovered
URAIDLA	23750	Onkaparinga	WMLR	1,042	1,072	1,103	30	3	61	6	Fully Recovered
BRIDGEWATER PO	23707	Onkaparinga	WMLR	1,018	1,011	950	-7	-1	-68	-7	Yet to Recover
CHERRY GARDENS	23709	Onkaparinga	WMLR	933	854	919	-79	-8	-13	-1	Partially Recovered
LOBETHAL	23726	Onkaparinga	WMLR	891	831	845	-60	-7	-46	-5	Partially Recovered
HAHNDORF PO	23720	Onkaparinga	WMLR	846	726	812	-120	-14	-34	-4	Partially Recovered
ECHUNGA GC	23713	Onkaparinga	WMLR	785	746	798	-39	-5	12	2	Fully Recovered
VICTOR HARBOR	23743	Fleurieu	WMLR	706	624	701	-82	-12	-5	-1	Partially Recovered
WILLUNGA	23753	Fleurieu	WMLR	639	606	636	-33	-5	-3	0	Partially Recovered
SECOND VALLEY	23744	Fleurieu	WMLR	576	624	640	48	8	64	11	Fully Recovered
YANKALILLA	23754	Fleurieu	WMLR	598	530	530	-69	-11	-68	-11	Fully Recovered
NORMANVILLE	23741	Fleurieu	WMLR	511	512	529	1	0	18	4	Fully Recovered
PORT ELLIOT C.P.	23742	Fleurieu	WMLR	495	470	510	-25	-5	15	3	Fully Recovered

Median winter rainfall for drought-related periods and post-drought recovery status – All reporting sites

Station name	Station numbers	Catchment	PWRA	Period median			Change from Pre-drought median				Post-drought recovery status
				Pre-	Drought	Post-	Drought		Post-		
				(mm)	(mm)	(mm)	(mm)	(%)	(mm)	(%)	
MT BARKER	23733	Bremer	EMLR	295	278	345	-17	-6%	50	17%	Fully Recovered
NAIRNE	23739	Bremer	EMLR	256	231	294	-25	-10%	38	15%	Fully Recovered
HARROGATE	23722	Bremer	EMLR	214	228	256	14	7%	42	20%	Fully Recovered
KANMANTOO	23724	Bremer	EMLR	166	154	191	-12	-7%	25	15%	Fully Recovered
LANGHORNE CK	24515	Bremer	EMLR	124	112	126	-12	-10%	2	2%	Fully Recovered
CALLINGTON	24508	Bremer	EMLR	117	123	143	6	5%	26	22%	Fully Recovered
MACCLESFIELD	23728	Angas	EMLR	285	258	336	-27	-9%	51	18%	Fully Recovered
MEADOWS	23730	Finniss	EMLR	334	352	304	18	5%	-30	-9%	Yet to Recover
CUDLEE CREEK	23731	Torrens	WMLR	345	333	328	-12	-3%	-17	-5%	Yet to Recover
GUMERACHA	23719	Torrens	WMLR	321	308	386	-13	-4%	65	20%	Fully Recovered
BIRDWOOD	23705	Torrens	WMLR	291	273	284	-18	-6%	-7	-2%	Partially Recovered
Mt PLEASANT	23737	Torrens	WMLR	268	243	268	-25	-9%	0	0%	Fully Recovered
URAIDLA	23750	Onkaparinga	WMLR	437	429	527	-8	-2%	90	21%	Fully Recovered
BRIDGEWATER PO	23707	Onkaparinga	WMLR	417	430	473	13	3%	56	13%	Fully Recovered
CHERRY GARDENS	23709	Onkaparinga	WMLR	371	347	381	-24	-6%	10	3%	Fully Recovered
LOBETHAL	23726	Onkaparinga	WMLR	357	373	409	16	4%	52	15%	Fully Recovered
HAHNDORF PO	23720	Onkaparinga	WMLR	342	315	349	-27	-8%	7	2%	Fully Recovered
ECHUNGA GC	23713	Onkaparinga	WMLR	311	309	361	-2	-1%	50	16%	Fully Recovered
VICTOR HARBOR	23743	Fleurieu	WMLR	288	247	325	-41	-14%	37	13%	Fully Recovered
WILLUNGA	23753	Fleurieu	WMLR	259	220	254	-39	-15%	-5	-2%	Partially Recovered
SECOND VALLEY	23744	Fleurieu	WMLR	245	256	239	11	4%	-6	-2%	Yet to Recover
YANKALILLA	23754	Fleurieu	WMLR	235	219	236	-16	-7%	1	0%	Fully Recovered
NORMANVILLE	23741	Fleurieu	WMLR	220	219	232	-1	0%	12	5%	Fully Recovered
PORT ELLIOT C.P.	23742	Fleurieu	WMLR	193	203	187	10	5%	-6	-3%	Yet to Recover

Median spring rainfall for drought-related periods and post-drought recovery status – All sites

Station name	Station numbers	Catchment	PWRA	Period median			Change from Pre-drought median				Post-drought recovery status
				Pre-	**Drought**	**Post-**	**Drought**		**Post-**		
				(mm)	(mm)	(mm)	(mm)	(%)	(mm)	(%)	
MT BARKER	23733	Bremer	EMLR	190	174	166	-16	-8%	-24	-13%	Yet to Recover
NAIRNE	23739	Bremer	EMLR	169	141	143	-28	-17%	-26	-15%	Partially Recovered
HARROGATE	23722	Bremer	EMLR	145	146	125	1	1%	-20	-14%	Yet to Recover
KANMANTOO	23724	Bremer	EMLR	122	113	107	-9	-7%	-15	-12%	Yet to Recover
LANGHORNE CK	24515	Bremer	EMLR	97	93	94	-4	-4%	-3	-3%	Partially Recovered
CALLINGTON	24508	Bremer	EMLR	97	91	92	-6	-6%	-5	-5%	Partially Recovered
MACCLESFIELD	23728	Angas	EMLR	189	149	140	-40	-21%	-49	-26%	Yet to Recover
MEADOWS	23730	Finniss	EMLR	211	201	178	-10	-5%	-33	-16%	Yet to Recover
CUDLEE CREEK	23731	Torrens	WMLR	204	216	168	12	6%	-36	-18%	Yet to Recover
GUMERACHA	23719	Torrens	WMLR	203	193	145	-10	-5%	-58	-29%	Yet to Recover
BIRDWOOD	23705	Torrens	WMLR	192	168	158	-24	-13%	-34	-18%	Yet to Recover
Mt PLEASANT	23737	Torrens	WMLR	174	135	132	-39	-22%	-42	-24%	Yet to Recover
URAIDLA	23750	Onkaparinga	WMLR	250	248	220	-2	-1%	-30	-12%	Yet to Recover
BRIDGEWATER PO	23707	Onkaparinga	WMLR	247	236	199	-11	-4%	-48	-19%	Yet to Recover
CHERRY GARDENS	23709	Onkaparinga	WMLR	220	206	190	-14	-6%	-30	-14%	Yet to Recover
LOBETHAL	23726	Onkaparinga	WMLR	220	200	166	-20	-9%	-54	-25%	Yet to Recover
HAHNDORF PO	23720	Onkaparinga	WMLR	210	172	190	-38	-18%	-20	-10%	Partially Recovered
ECHUNGA GC	23713	Onkaparinga	WMLR	197	183	159	-14	-7%	-38	-19%	Yet to Recover
VICTOR HARBOR	23743	Fleurieu	WMLR	160	155	138	-5	-3%	-22	-14%	Yet to Recover
WILLUNGA	23753	Fleurieu	WMLR	151	126	128	-25	-17%	-23	-15%	Partially Recovered
SECOND VALLEY	23744	Fleurieu	WMLR	129	154	105	25	19%	-24	-19%	Yet to Recover
YANKALILLA	23754	Fleurieu	WMLR	132	139	103	7	5%	-29	-22%	Yet to Recover
NORMANVILLE	23741	Fleurieu	WMLR	119	124	101	5	4%	-18	-15%	Yet to Recover
PORT ELLIOT C.P.	23742	Fleurieu	WMLR	121	134	94	13	11%	-27	-22%	Yet to Recover

Median autumn rainfall for drought-related periods and post-drought recovery status – All reporting sites

Station name	Station numbers	Catchment	PWRA	Period median			Change from Pre-drought median				Post-drought recovery status
				Pre-	Drought	Post-	Drought		Post-		
				(mm)	(mm)	(mm)	(mm)	(%)	(mm)	(%)	
MT BARKER	23733	Bremer	EMLR	174	162	150	-12	-7%	-24	-14%	Yet to Recover
NAIRNE	23739	Bremer	EMLR	150	138	121	-12	-8%	-29	-19%	Yet to Recover
HARROGATE	23722	Bremer	EMLR	121	114	121	-7	-6%	0	0%	Fully Recovered
KANMANTOO	23724	Bremer	EMLR	97	90	91	-7	-7%	-6	-6%	Partially Recovered
LANGHORNE CK	24515	Bremer	EMLR	91	78	83	-13	-14%	-8	-9%	Partially Recovered
CALLINGTON	24508	Bremer	EMLR	82	72	78	-10	-12%	-4	-5%	Partially Recovered
MACCLESFIELD	23728	Angas	EMLR	167	147	163	-20	-12%	-4	-2%	Partially Recovered
MEADOWS	23730	Finniss	EMLR	199	171	178	-28	-14%	-21	-11%	Partially Recovered
CUDLEE CREEK	23731	Torrens	WMLR	199	175	172	-24	-12%	-27	-14%	Yet to Recover
GUMERACHA	23719	Torrens	WMLR	173	163	166	-10	-6%	-7	-4%	Partially Recovered
BIRDWOOD	23705	Torrens	WMLR	146	142	141	-4	-3%	-5	-3%	Yet to Recover
Mt PLEASANT	23737	Torrens	WMLR	135	115	136	-20	-15%	1	1%	Fully Recovered
URAIDLA	23750	Onkaparinga	WMLR	250	272	230	22	9%	-20	-8%	Yet to Recover
BRIDGEWATER PO	23707	Onkaparinga	WMLR	240	252	203	12	5%	-37	-15%	Yet to Recover
CHERRY GARDENS	23709	Onkaparinga	WMLR	210	224	221	14	7%	11	5%	Fully Recovered
LOBETHAL	23726	Onkaparinga	WMLR	192	188	150	-4	-2%	-42	-22%	Yet to Recover
HAHNDORF PO	23720	Onkaparinga	WMLR	185	172	166	-13	-7%	-19	-10%	Yet to Recover
ECHUNGA GC	23713	Onkaparinga	WMLR	188	174	192	-14	-7%	4	2%	Fully Recovered
VICTOR HARBOR	23743	Fleurieu	WMLR	152	148	145	-4	-3%	-7	-5%	Yet to Recover
WILLUNGA	23753	Fleurieu	WMLR	157	144	133	-13	-8%	-24	-15%	Yet to Recover
SECOND VALLEY	23744	Fleurieu	WMLR	140	146	152	6	4%	12	9%	Fully Recovered
YANKALILLA	23754	Fleurieu	WMLR	133	118	117	-15	-11%	-16	-12%	Yet to Recover
NORMANVILLE	23741	Fleurieu	WMLR	119	122	121	3	3%	2	2%	Fully Recovered
PORT ELLIOT C.P.	23742	Fleurieu	WMLR	110	111	103	1	1%	-7	-6%	Yet to Recover

Median summer rainfall for drought-related periods and post-drought recovery – All reporting sites

Station name	Station numbers	Catchment	PWRA	Period median			Change from Pre-drought median				Post-drought recovery status
				Pre-	**Drought**	**Post-**	**Drought**		**Post-**		
				(mm)	(mm)	(mm)	(mm)	(%)	(mm)	(%)	
MT BARKER	23733	Bremer	EMLR	73	74	78	1	1%	5	7%	Fully Recovered
NAIRNE	23739	Bremer	EMLR	67	65	66	-2	-3%	-1	-1%	Partially Recovered
HARROGATE	23722	Bremer	EMLR	55	62	69	7	13%	14	25%	Fully Recovered
KANMANTOO	23724	Bremer	EMLR	60	56	59	-4	-7%	-1	-2%	Partially Recovered
LANGHORNE CK	24515	Bremer	EMLR	56	52	51	-4	-7%	-5	-9%	Yet to Recover
CALLINGTON	24508	Bremer	EMLR	54	53	50	-1	-2%	-4	-7%	Yet to Recover
MACCLESFIELD	23728	Angas	EMLR	79	79	83	0	0%	4	5%	Fully Recovered
MEADOWS	23730	Finniss	EMLR	81	78	90	-3	-4%	9	11%	Fully Recovered
CUDLEE CREEK	23731	Torrens	WMLR	80	82	69	2	3%	-11	-14%	Yet to Recover
GUMERACHA	23719	Torrens	WMLR	68	56	61	-12	-18%	-7	-10%	Partially Recovered
BIRDWOOD	23705	Torrens	WMLR	67	61	66	-6	-9%	-1	-1%	Partially Recovered
Mt PLEASANT	23737	Torrens	WMLR	65	64	68	-1	-2%	3	5%	Fully Recovered
URAIDLA	23750	Onkaparinga	WMLR	98	81	111	-17	-17%	13	13%	Fully Recovered
BRIDGEWATER PO	23707	Onkaparinga	WMLR	91	86	73	-5	-5%	-18	-20%	Yet to Recover
CHERRY GARDENS	23709	Onkaparinga	WMLR	94	79	81	-15	-16%	-13	-14%	Partially Recovered
LOBETHAL	23726	Onkaparinga	WMLR	75	64	73	-11	-15%	-2	-3%	Partially Recovered
HAHNDORF PO	23720	Onkaparinga	WMLR	76	65	78	-11	-14%	2	3%	Fully Recovered
ECHUNGA GC	23713	Onkaparinga	WMLR	83	67	74	-16	-19%	-9	-11%	Partially Recovered
VICTOR HARBOR	23743	Fleurieu	WMLR	72	69	72	-3	-4%	0	0%	Fully Recovered
WILLUNGA	23753	Fleurieu	WMLR	58	78	57	20	34%	-1	-2%	Yet to Recover
SECOND VALLEY	23744	Fleurieu	WMLR	52	67	67	15	29%	15	29%	Fully Recovered
YANKALILLA	23754	Fleurieu	WMLR	56	52	55	-4	-7%	-1	-2%	Partially Fully Recovered
NORMANVILLE	23741	Fleurieu	WMLR	43	47	56	4	9%	13	30%	Fully Recovered
PORT ELLIOT C.P.	23742	Fleurieu	WMLR	51	51	65	0	0%	14	27%	Fully Recovered

7.2 Mann-Kendall test results

Mann-Kendall test results for rainfall sites in Eastern MLR PWRA (1900 to 2022)

	Finniss catchment		Angas catchment		Bremer River catchment									
Period	**Meadows (23730)**		**Macclesfield (23728)**		**Mt Barker (23733)**		**Nairne (23739)**		**Harrogate (23722)**		**Callington (24508)**		**Langhorne Creek (24515)**	
	tau	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**
Annual	-0.179	0.003	-0.141	0.021	-0.122	0.046	-0.120	0.050	0.070	0.253	0.100	0.102	0.025	0.684
Summer	0.019	0.761	0.030	0.620	0.019	0.760	0.027	0.656	0.124	0.043	0.122	0.046	*0.113*	*0.063*
Autumn	-0.170	0.005	-0.126	0.039	*-0.118*	*0.054*	*-0.117*	*0.055*	-0.006	0.920	-0.011	0.865	-0.040	0.518
Winter	-0.029	0.635	-0.022	0.718	-0.001	0.993	0.002	0.977	*0.105*	*0.085*	0.067	0.272	0.020	0.740
Spring	-0.171	0.005	-0.179	0.003	-0.152	0.013	-0.148	0.015	-0.066	0.283	-0.025	0.678	-0.030	0.623
Jan	0.084	0.171	0.084	0.170	0.037	0.542	0.049	0.419	0.124	0.044	0.097	0.112	0.131	0.032
Feb	-0.013	0.832	-0.005	0.930	-0.001	0.984	-0.019	0.755	0.058	0.343	0.088	0.150	0.068	0.270
Mar	-0.052	0.393	-0.061	0.320	-0.046	0.455	-0.046	0.452	-0.013	0.834	-0.019	0.761	-0.052	0.396
Apr	-0.121	0.048	-0.072	0.240	-0.062	0.313	-0.069	0.259	0.020	0.745	0.055	0.368	0.027	0.665
May	-0.055	0.364	-0.034	0.580	-0.031	0.615	-0.045	0.460	0.024	0.700	-0.017	0.786	-0.037	0.548
Jun	-0.058	0.343	-0.066	0.281	-0.041	0.504	-0.033	0.594	0.022	0.720	-0.005	0.942	-0.030	0.624
Jul	0.010	0.875	0.028	0.643	0.044	0.469	0.031	0.615	*0.118*	*0.053*	0.076	0.211	0.060	0.327
Aug	-0.007	0.916	-0.003	0.960	0.005	0.932	-0.003	0.965	0.093	0.126	0.054	0.379	0.007	0.906
Sep	-0.131	0.032	-0.127	0.037	-0.080	0.193	*-0.109*	*0.075*	-0.041	0.506	-0.032	0.597	-0.050	0.412
Oct	*-0.117*	*0.054*	*-0.116*	*0.057*	*-0.101*	*0.098*	*-0.114*	*0.061*	-0.049	0.420	-0.025	0.678	-0.018	0.766
Nov	-0.041	0.504	-0.041	0.498	-0.020	0.750	0.020	0.743	0.048	0.431	0.047	0.440	0.008	0.894
Dec	-0.019	0.756	0.008	0.903	0.029	0.632	0.039	0.529	0.089	0.147	0.079	0.195	0.061	0.318

Mann-Kendall test results for rainfall sites in Western MLR PWRA (1900 to 2022)

	Torrens River catchment								Onkaparinga River catchment											
Period	**Mt Pleasant (23737)**		**Birdwood (23705)**		**Gumeracha (23719)**		**Cuddly Creek (23731)**		**Uraidla (23750)**		**Bridgewater (23707)**		**Cherry Gardens (23709)**		**Echunga Golf C. (23713)**		**Lobethal (23726)**		**Hahndorf PO (23720)**	
	tau	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**	**tau**	**p-val**
Annual	-0.090	0.142	-0.077	0.206	-0.132	0.031	*-0.110*	*0.072*	-0.054	0.375	-0.146	0.017	-0.049	0.425	-0.130	0.033	-0.066	0.278	-0.125	0.040
Summer	0.048	0.429	0.037	0.546	-0.052	0.395	-0.024	0.694	0.023	0.705	-0.005	0.932	0.021	0.731	0.021	0.890	0.002	0.972	0.020	0.743
Autumn	-0.055	0.369	-0.061	0.317	-0.092	0.131	-0.080	0.190	-0.060	0.330	-0.089	0.147	-0.024	0.694	-0.024	0.020	-0.076	0.214	-0.081	0.187
Winter	-0.046	0.449	-0.049	0.427	-0.047	0.444	-0.049	0.420	0.006	0.923	-0.068	0.269	0.004	0.946	0.004	0.632	0.010	0.871	-0.027	0.662
Spring	-0.139	0.023	*-0.107*	*0.080*	-0.142	0.020	-0.093	0.130	-0.099	0.105	-0.156	0.011	-0.057	0.351	*-0.057*	*0.007*	*-0.113*	*0.065*	*-0.159*	*0.009*
Jan	0.050	0.415	0.043	0.483	0.013	0.832	-0.014	0.815	0.032	0.604	0.026	0.671	0.069	0.257	0.030	0.621	0.057	0.355	0.035	0.573
Feb	-0.013	0.832	-0.034	0.583	-0.064	0.293	-0.034	0.583	-0.003	0.962	-0.015	0.801	0.020	0.740	-0.032	0.597	-0.032	0.606	0.003	0.967
Mar	-0.045	0.460	-0.028	0.651	-0.060	0.330	-0.049	0.420	-0.029	0.637	-0.029	0.638	-0.018	0.765	-0.062	0.311	-0.056	0.362	-0.027	0.657
Apr	-0.029	0.631	0.000	0.998	-0.039	0.525	-0.036	0.556	-0.050	0.416	-0.061	0.318	-0.013	0.837	-0.082	0.180	-0.031	0.615	-0.044	0.473
May	-0.003	0.956	-0.028	0.646	-0.026	0.667	-0.007	0.904	0.008	0.897	-0.017	0.785	0.026	0.673	-0.048	0.430	-0.013	0.837	-0.001	0.990
Jun	-0.098	0.108	-0.072	0.241	-0.082	0.180	-0.078	0.204	-0.046	0.452	-0.088	0.148	-0.034	0.582	-0.046	0.453	-0.058	0.346	-0.062	0.308
Jul	0.015	0.805	0.029	0.638	0.036	0.561	0.030	0.626	0.047	0.438	-0.003	0.962	0.066	0.278	0.093	0.128	0.058	0.342	0.010	0.871
Aug	-0.026	0.670	-0.012	0.844	-0.010	0.877	-0.009	0.878	0.024	0.697	-0.027	0.659	0.021	0.728	0.017	0.776	0.035	0.565	-0.006	0.918
Sep	-0.092	0.131	-0.062	0.307	-0.061	0.316	-0.025	0.679	-0.046	0.448	-0.057	0.354	-0.036	0.552	-0.081	0.185	-0.060	0.324	-0.080	0.190
Oct	-0.098	0.110	-0.087	0.153	*-0.114*	*0.063*	-0.081	0.182	-0.069	0.260	*-0.110*	*0.071*	-0.041	0.502	*-0.107*	*0.080*	-0.077	0.207	*-0.107*	*0.078*
Nov	-0.007	0.915	0.016	0.795	-0.036	0.555	-0.017	0.783	-0.012	0.846	-0.012	0.849	0.029	0.635	-0.048	0.436	-0.013	0.829	-0.003	0.962
Dec	0.023	0.712	0.043	0.479	-0.049	0.426	0.012	0.847	0.014	0.820	0.028	0.649	0.007	0.904	0.007	0.904	0.013	0.837	0.003	0.963

Mann-Kendall test results for rainfall sites in the Fleurieu region (1900 to 2022)

	Fleurieu											
Period	Victor Harbor (23743)		Willunga (23753)		Second Valley (23744)		Yankalilla (23754)		Normanville (23741)		Pt Elliott (23742)	
	tau	p-val	tau	p-val	tau	p-val	tau	p-val	tau	p-val	tau	p-val
Annual	*-0.105*	*0.085*	*-0.117*	*0.055*	0.019	0.756	-0.120	0.050	-0.030	0.627	-0.057	0.352
Summer	0.086	0.160	0.014	0.818	0.121	0.047	0.044	0.475	0.085	0.162	0.068	0.266
Autumn	-0.095	0.122	*-0.103*	*0.092*	-0.054	0.375	-0.093	0.126	-0.045	0.465	-0.086	0.158
Winter	-0.008	0.892	-0.032	0.604	0.038	0.533	-0.036	0.555	0.028	0.643	0.043	0.479
Spring	-0.130	0.033	*-0.166*	*0.007*	-0.011	0.865	*-0.119*	*0.052*	-0.071	0.247	-0.094	0.125
Jan	0.122	0.046	0.100	0.101	0.125	0.041	0.077	0.208	0.140	0.022	0.089	0.147
Feb	0.024	0.699	-0.023	0.705	0.044	0.476	0.016	0.795	0.034	0.580	0.016	0.798
Mar	-0.024	0.691	-0.068	0.265	-0.002	0.976	-0.063	0.300	-0.043	0.484	-0.083	0.176
Apr	-0.059	0.333	-0.037	0.545	-0.027	0.665	-0.049	0.424	-0.027	0.654	-0.018	0.775
May	-0.050	0.415	-0.015	0.802	0.007	0.915	-0.027	0.656	0.011	0.861	-0.055	0.364
Jun	-0.027	0.664	-0.064	0.298	-0.011	0.861	-0.056	0.363	-0.012	0.841	0.001	0.983
Jul	-0.006	0.922	0.046	0.448	0.037	0.540	0.003	0.969	0.032	0.606	0.029	0.641
Aug	0.060	0.325	0.016	0.800	0.088	0.150	0.020	0.750	0.046	0.456	0.071	0.245
Sep	*-0.109*	*0.074*	-0.096	0.117	-0.047	0.447	-0.099	0.106	-0.046	0.449	-0.071	0.242
Oct	-0.071	0.248	-0.096	0.118	0.013	0.839	-0.076	0.212	-0.055	0.370	-0.048	0.436
Nov	-0.018	0.766	-0.031	0.614	0.081	0.186	-0.032	0.606	0.016	0.796	0.000	0.998
Dec	0.035	0.573	0.008	0.897	0.083	0.176	-0.001	0.986	0.017	0.780	0.030	0.623

7.3 Wilcoxon Rank Sum and Welch's *t*-test results

Wilcoxon Rank Sum and Welch's *t*-test results for rainfall sites in Eastern MLR PWRA (1900 to 2022)

	Finniss catchment		Angas catchment		Bremer River catchment									
Period	**Meadows (23730)**		**Macclesfield (23728)**		**Mt Barker (23733)**		**Nairne (23739)**		**Harrogate (23722)**		**Callington (24508)**		**Langhorne Creek (24515)**	
	Wil.	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***
Annual	0.02	0.02	0.03	0.03	0.22	0.21	0.05	*0.06*	0.89	0.90	0.88	0.81	0.32	0.29
Summer	0.56	0.38	0.48	0.33	0.57	0.42	0.56	0.41	0.94	0.94	0.89	0.77	0.73	0.90
Autumn	0.01	0.01	*0.07*	0.04	*0.09*	0.02	0.05	0.01	0.44	0.44	0.48	0.45	0.19	0.23
Winter	0.59	0.50	0.53	0.51	0.83	0.80	0.66	0.56	0.96	0.96	0.88	0.86	0.44	0.97
Spring	0.02	0.03	0.01	0.02	0.11	0.24	*0.06*	0.11	0.35	0.35	0.38	0.58	0.32	0.51
Jan	0.83	0.56	0.76	0.44	0.67	0.27	0.65	0.15	0.88	0.55	0.75	0.36	0.75	0.28
Feb	0.51	0.43	0.58	0.52	0.67	0.55	0.63	0.55	0.93	0.86	0.91	0.76	0.81	0.71
Mar	0.43	0.16	0.33	0.21	0.62	0.26	0.55	0.24	0.59	0.37	0.63	0.39	0.48	0.25
Apr	0.01	0.01	0.03	*0.06*	*0.07*	0.03	0.03	0.02	0.31	0.21	0.48	0.63	0.18	0.37
May	0.48	0.23	0.59	0.27	0.61	0.22	0.38	0.11	0.76	0.48	0.46	0.35	0.42	0.29
Jun	0.68	0.56	0.69	0.64	0.85	0.77	0.80	0.73	0.94	0.91	0.79	0.78	0.54	0.62
Jul	0.51	0.53	0.54	0.53	0.78	0.74	0.50	0.51	0.76	0.79	0.86	0.86	0.50	0.50
Aug	0.41	0.40	0.29	0.33	0.58	0.49	0.38	0.34	0.88	0.85	0.56	0.46	0.14	0.16
Sep	*0.10*	*0.07*	0.05	*0.07*	0.41	0.36	0.11	0.10	0.48	0.57	0.50	0.62	0.34	0.62
Oct	0.03	0.02	0.03	0.02	*0.07*	*0.07*	*0.06*	0.05	0.15	0.21	0.24	0.36	0.24	0.34
Nov	0.26	0.28	0.23	0.21	0.64	0.64	0.75	0.70	0.86	0.82	0.84	0.74	0.63	0.54
Dec	0.362	0.28	0.28	0.22	0.51	0.45	0.51	0.53	0.84	0.81	0.82	0.72	0.56	0.40

Wilcoxon Rank Sum and Welch's t-test results for rainfall sites in Western MLR PWRA (1900 to 2022)

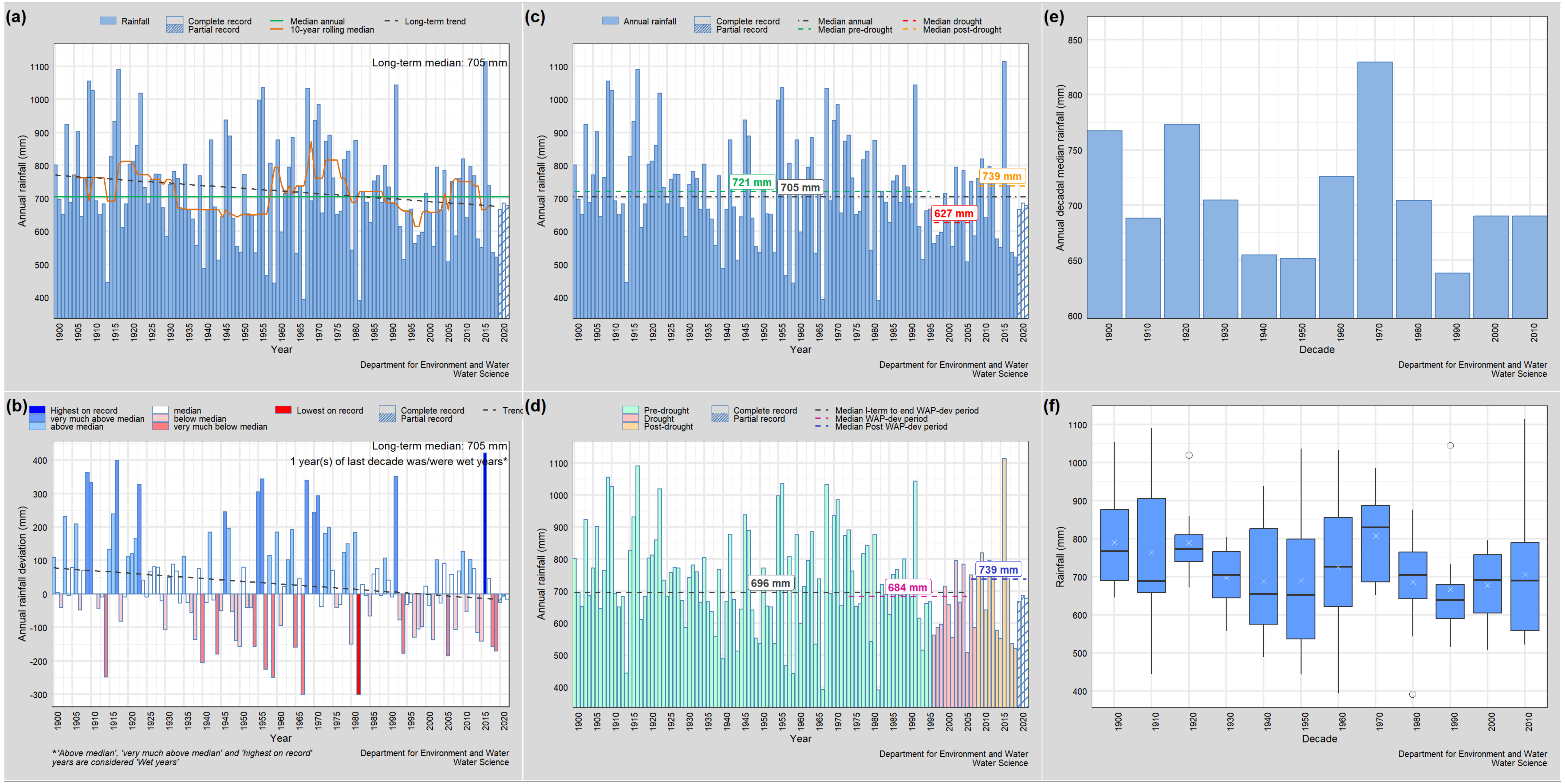
	Torrens River catchment								Onkaparinga River catchment											
Period	**Mt Pleasant (23737)**		**Birdwood (23705)**		**Gumeracha (23719)**		**Cuddly Creek (23731)**		**Uraidla (23750)**		**Bridgewater (23707)**		**Cherry Gardens (23709)**		**Echunga Golf C. (23713)**		**Lobethal (23726)**		**Hahndorf PO (23720)**	
	Wil.	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***
Annual	*0.07*	*0.06*	0.05	0.04	0.17	0.19	*0.06*	0.04	0.12	0.49	0.19	0.17	0.14	0.17	0.20	0.24	0.12	*0.10*	0.02	0.03
Summer	0.68	0.69	0.58	0.71	0.38	0.38	0.36	0.29	0.54	0.52	0.37	0.35	0.42	0.30	0.38	0.22	0.54	0.47	0.39	0.29
Autumn	0.18	*0.09*	0.15	0.04	0.31	0.18	0.23	0.12	*0.10*	0.35	0.39	0.22	0.51	0.37	0.13	0.05	0.10	0.04	0.10	0.02
Winter	0.22	*0.09*	0.11	0.05	0.47	0.44	0.25	0.14	0.56	0.70	0.63	0.43	0.53	0.42	0.93	0.90	0.56	0.46	0.40	0.30
Spring	*0.066*	0.14	*0.09*	0.15	0.11	0.25	*0.10*	0.20	*0.08*	0.37	*0.07*	0.19	0.08	0.16	0.05	0.17	*0.08*	0.15	0.01	0.07
Jan	0.60	0.41	0.59	0.49	0.47	0.27	0.33	0.12	0.58	0.48	0.56	0.34	0.63	0.48	0.55	0.20	0.77	0.44	0.59	0.27
Feb	0.50	0.64	0.41	0.59	0.40	0.53	0.57	0.48	0.61	0.56	0.45	0.33	0.65	0.38	0.45	0.30	0.43	0.50	0.54	0.50
Mar	0.39	0.49	0.49	0.40	0.43	0.36	0.59	0.46	0.77	0.56	0.67	0.58	0.75	0.59	0.56	0.30	0.38	0.26	0.56	0.27
Apr	0.17	0.18	0.26	0.21	0.26	0.20	0.21	0.16	0.19	0.18	0.13	*0.09*	0.19	0.17	0.08	0.06	0.12	*0.09*	*0.07*	0.03
May	0.55	0.12	0.38	0.06	0.71	0.39	0.66	0.25	0.83	0.59	0.73	0.47	0.84	0.62	0.56	0.29	0.48	0.16	0.57	0.18
Jun	0.34	0.24	0.39	0.19	0.49	0.34	0.42	0.23	0.78	0.60	0.65	0.39	0.76	0.62	0.83	0.76	0.60	0.50	0.59	0.45
Jul	0.17	0.15	0.19	0.14	0.57	0.54	0.20	0.14	0.43	0.59	0.47	0.40	0.30	0.30	0.89	0.86	0.50	0.43	0.23	0.33
Aug	0.30	0.25	0.27	0.18	0.61	0.52	0.50	0.43	0.74	0.69	0.67	0.60	0.57	0.41	0.71	0.65	0.60	0.51	0.46	0.37
Sep	0.15	0.15	0.23	0.22	0.37	0.40	0.50	0.44	0.47	0.50	0.48	0.34	0.33	0.24	0.38	0.41	0.30	0.21	0.15	0.15
Oct	0.05	0.05	0.05	0.04	*0.07*	*0.09*	*0.08*	*0.06*	0.17	0.18	*0.07*	*0.09*	*0.09*	0.11	0.04	*0.07*	*0.07*	*0.09*	0.03	0.02
Nov	0.64	0.69	0.77	0.70	0.42	0.56	0.37	0.42	0.48	0.57	0.43	0.45	0.53	0.44	0.32	0.30	0.38	0.50	0.42	0.45
Dec	0.57	0.71	0.59	0.72	0.31	0.40	0.46	0.44	0.52	0.45	0.55	0.51	0.31	0.24	0.39	0.39	0.49	0.46	0.25	0.28

Wilcoxon Rank Sum and Welch's t-test results for rainfall sites in the Fleurieu (1900 to 2022)

	Fleurieu											
Period	**Victor Harbor (23743)**		**Willunga (23753)**		**Second Valley (23744)**		**Yankalilla (23754)**		**Normanville (23741)**		**Pt Elliott (23742)**	
	Wil.	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***	***Wil.***	***Wel.***
Annual	*0.10*	*0.10*	*0.10*	0.05	0.95	0.96	0.03	0.02	0.48	0.44	0.26	0.24
Summer	0.84	0.47	0.64	0.48	0.98	0.87	0.78	0.51	0.90	0.70	0.78	0.37
Autumn	*0.07*	0.03	0.16	*0.08*	0.70	0.55	0.11	0.02	0.49	0.23	0.19	0.08
Winter	0.33	0.33	0.26	0.26	0.90	0.93	*0.07*	0.04	0.51	0.42	0.58	0.52
Spring	0.19	0.30	0.07	0.11	0.82	0.87	0.25	0.32	0.38	0.58	0.33	0.48
Jan	0.93	0.57	0.91	0.84	0.91	0.73	0.84	0.69	0.95	0.78	0.87	0.52
Feb	0.83	0.56	0.53	0.30	0.91	0.63	0.77	0.59	0.89	0.76	0.84	0.51
Mar	0.62	0.18	0.52	0.20	0.90	0.65	0.53	0.17	0.63	0.28	0.44	0.15
Apr	0.03	0.02	0.15	0.25	0.20	0.14	*0.07*	0.05	0.17	0.15	*0.09*	*0.08*
May	0.49	0.34	0.48	0.21	0.91	0.82	0.51	0.18	0.82	0.63	0.54	0.50
Jun	0.70	0.58	0.49	0.50	0.88	0.87	0.40	0.29	0.81	0.73	0.85	0.84
Jul	0.12	0.16	0.19	0.22	0.71	0.68	0.05	0.04	0.22	0.20	0.18	0.14
Aug	0.47	0.49	0.41	0.35	0.86	0.88	0.17	0.16	0.39	0.42	0.49	0.50
Sep	0.12	0.21	0.20	0.14	0.44	0.57	0.29	0.32	0.54	0.57	0.41	0.59
Oct	0.27	0.25	*0.08*	0.11	0.78	0.85	0.13	0.16	0.17	0.22	0.13	0.16
Nov	0.71	0.72	0.43	0.39	0.96	0.93	0.67	0.71	0.83	0.82	0.81	0.75
Dec	0.36	0.24	0.44	0.22	0.87	0.83	0.23	0.12	0.28	0.14	0.43	0.19

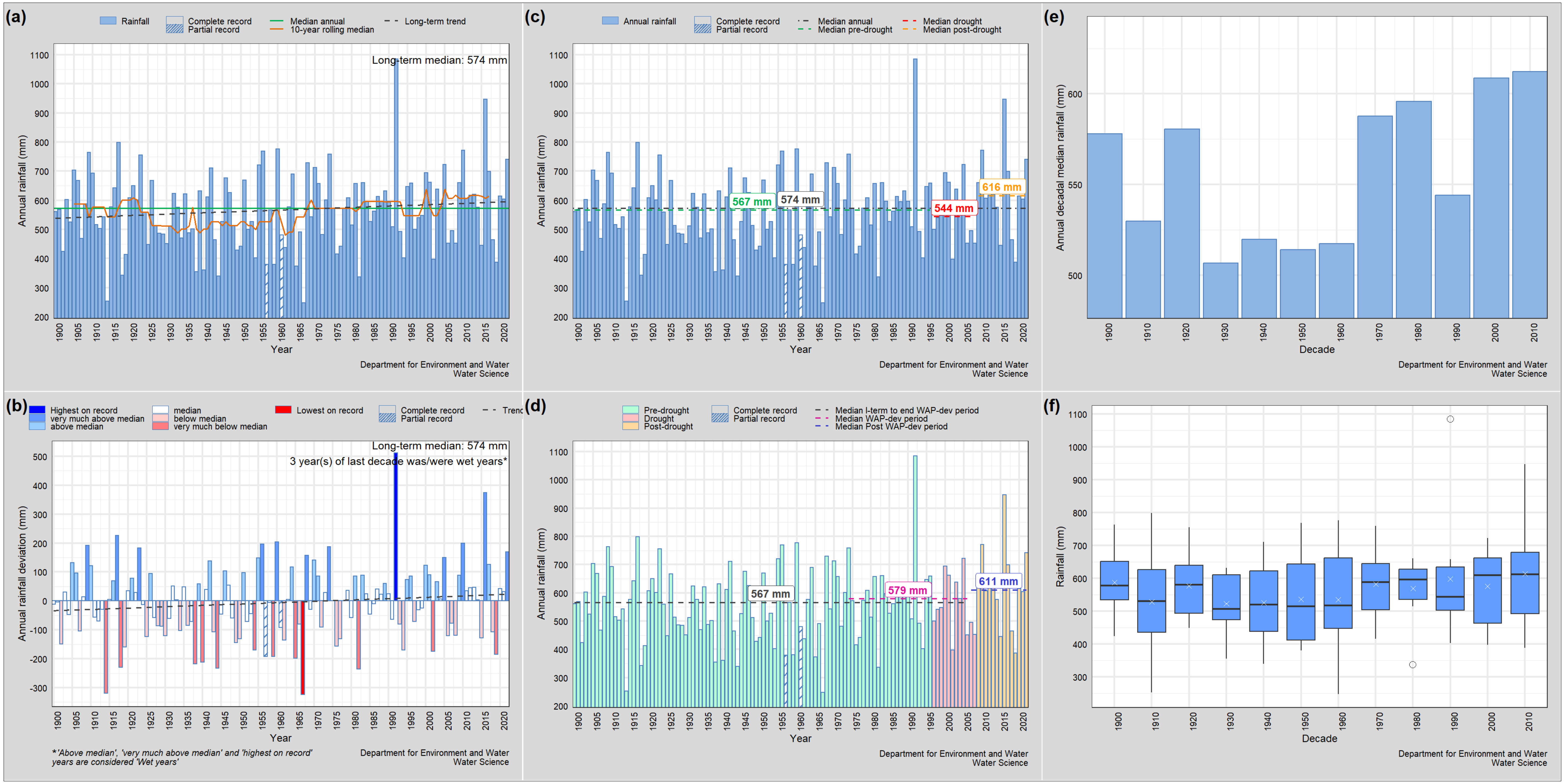
7.4 Annual and decadal rainfall plots for individual sites

Annual and decadal rainfall plots – Macclesfield (23728)

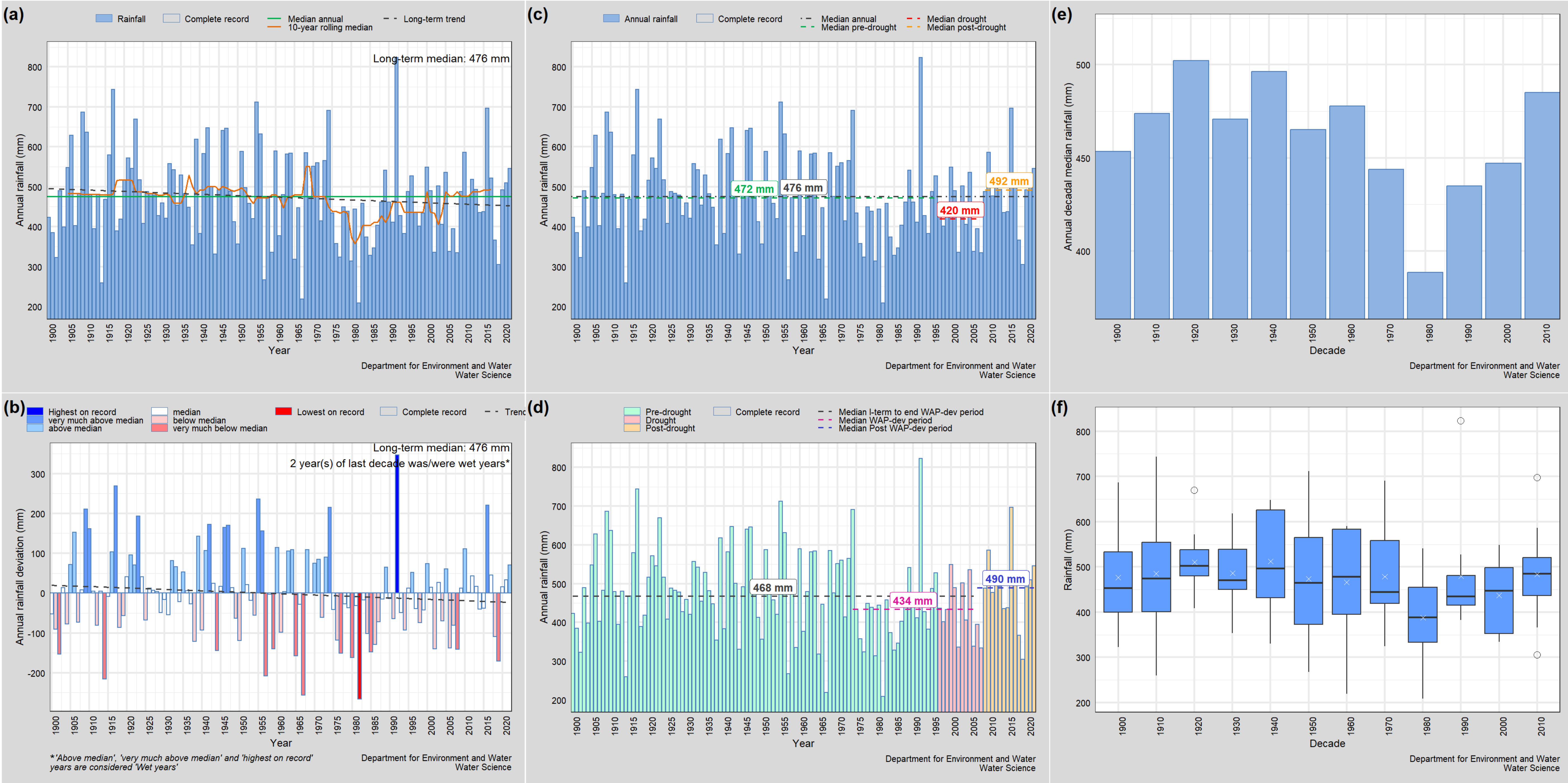


Annual and decadal rainfall plots – Mt Barker (23733), Bremer catchment

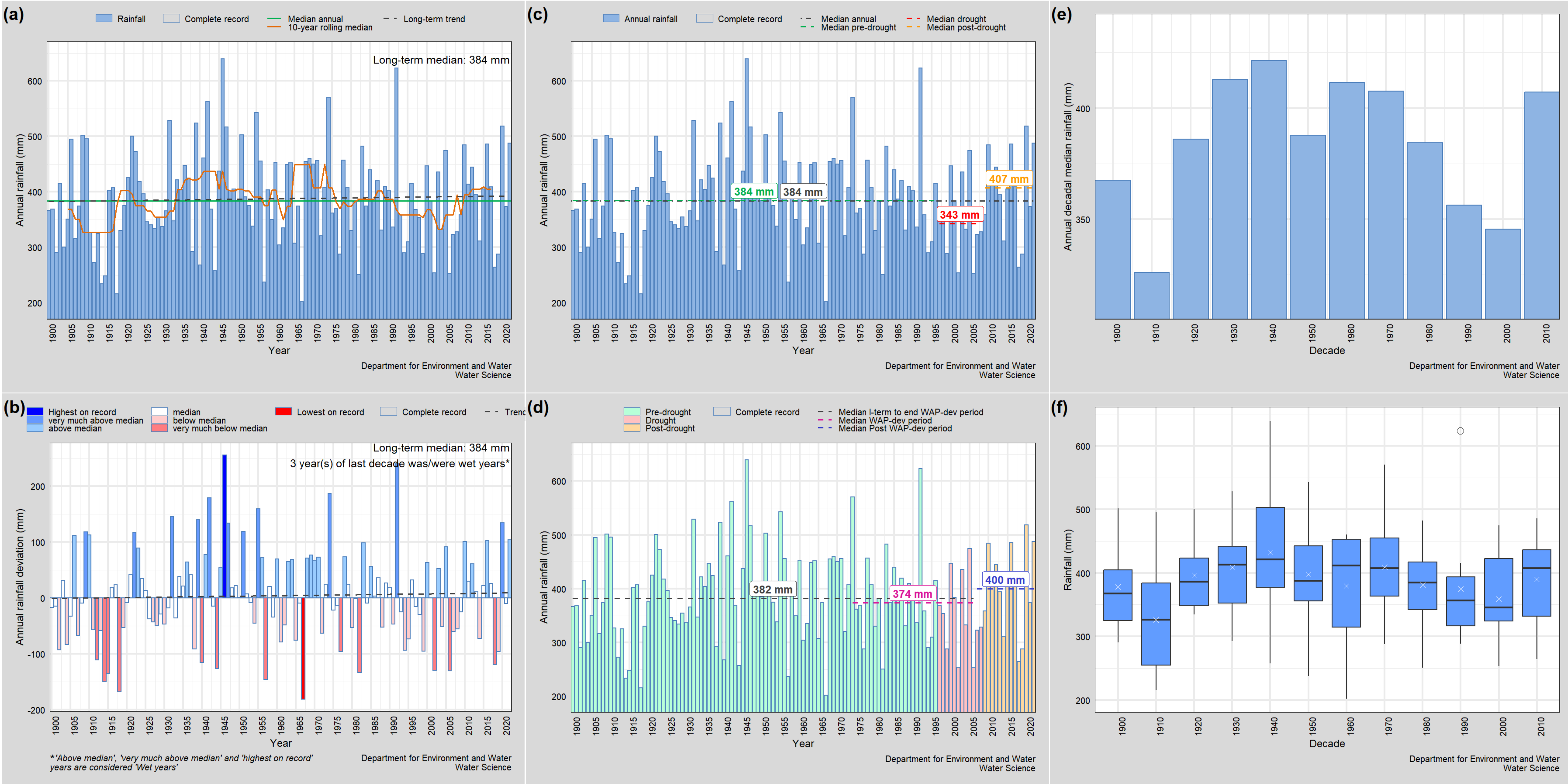
Annual and decadal rainfall plots – Harrogate (23722), Bremer catchment



Annual and decadal rainfall plots – Kanmantoo (23724), Bremer catchment

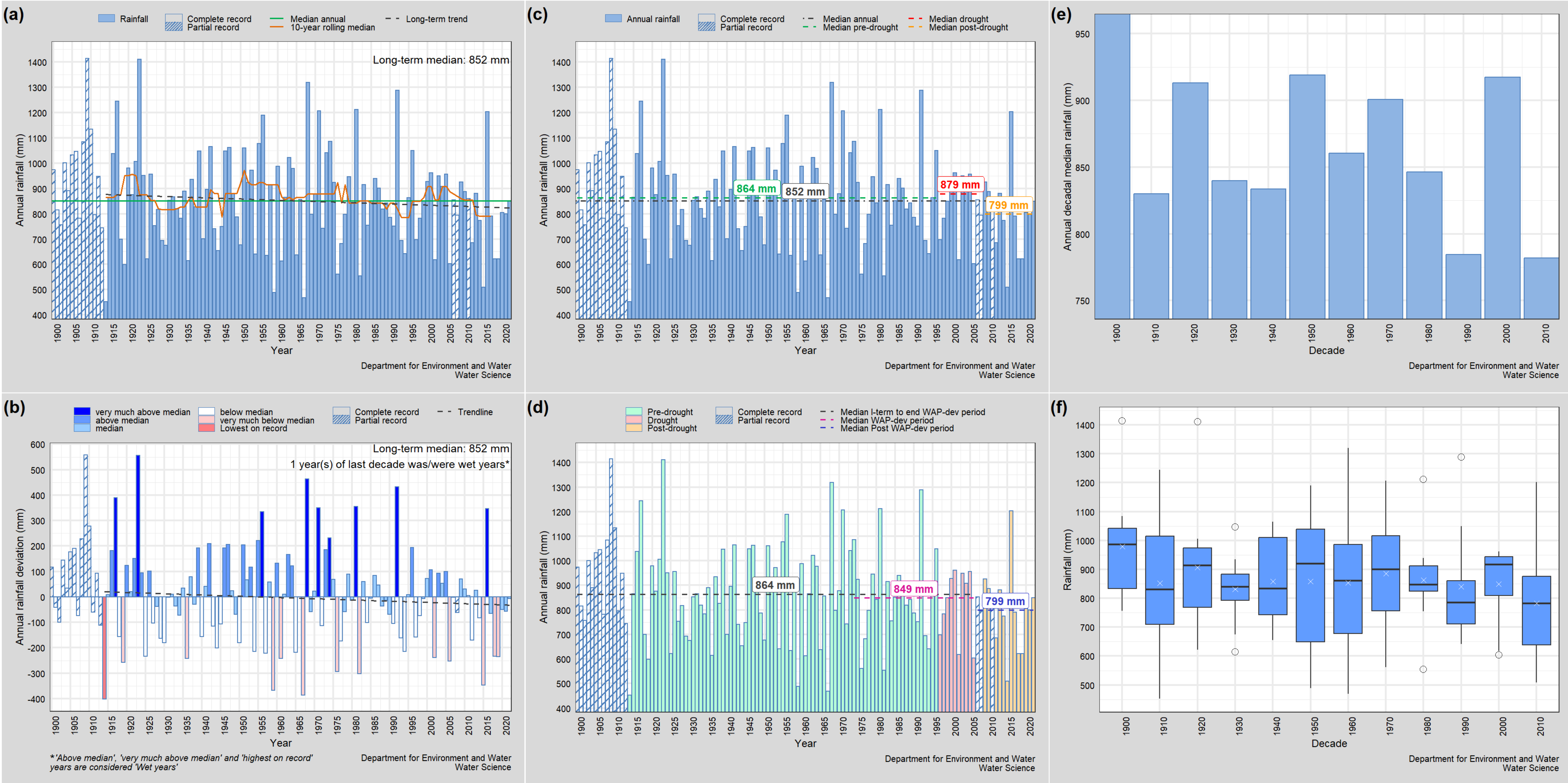


Annual and decadal rainfall plots – Langhorne Creek (24515), Bremer catchment

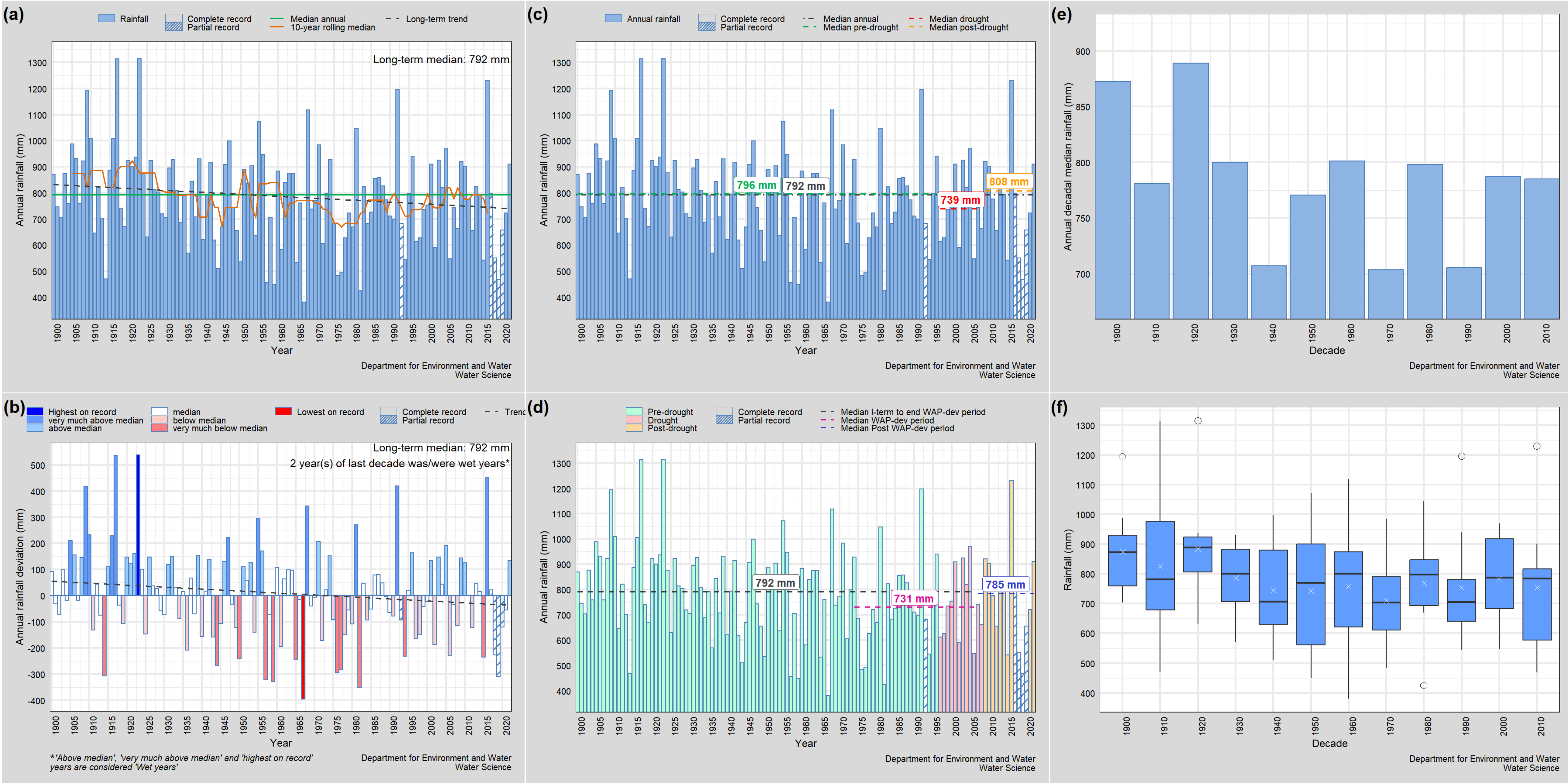


Annual and decadal rainfall plots – Callington (24508), Bremer catchment

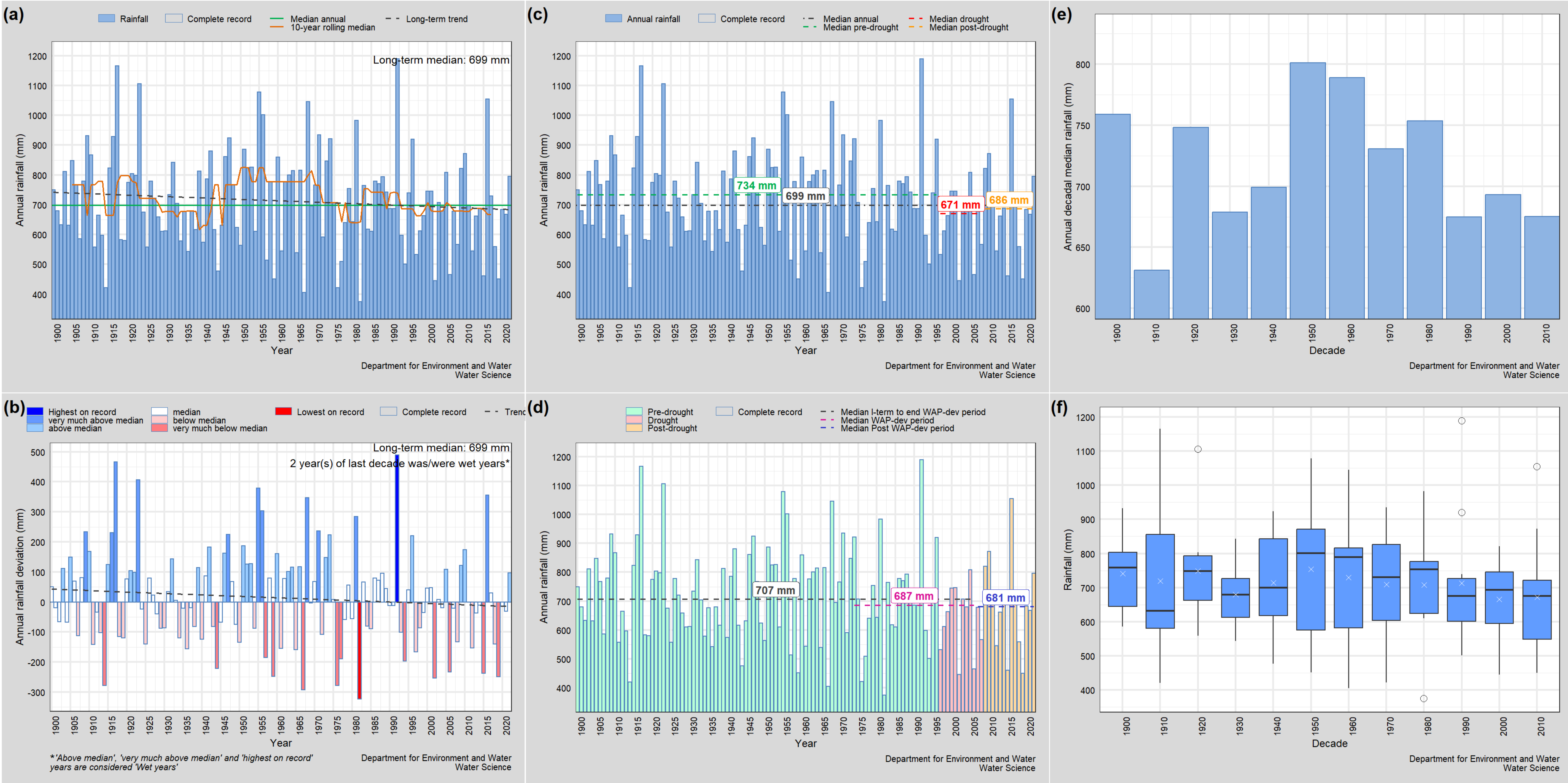
Annual and decadal rainfall plots – Cuddlee Creek (23731), Torrens catchment



Annual and decadal rainfall plots – Gumeracha (23719), Torrens catchment



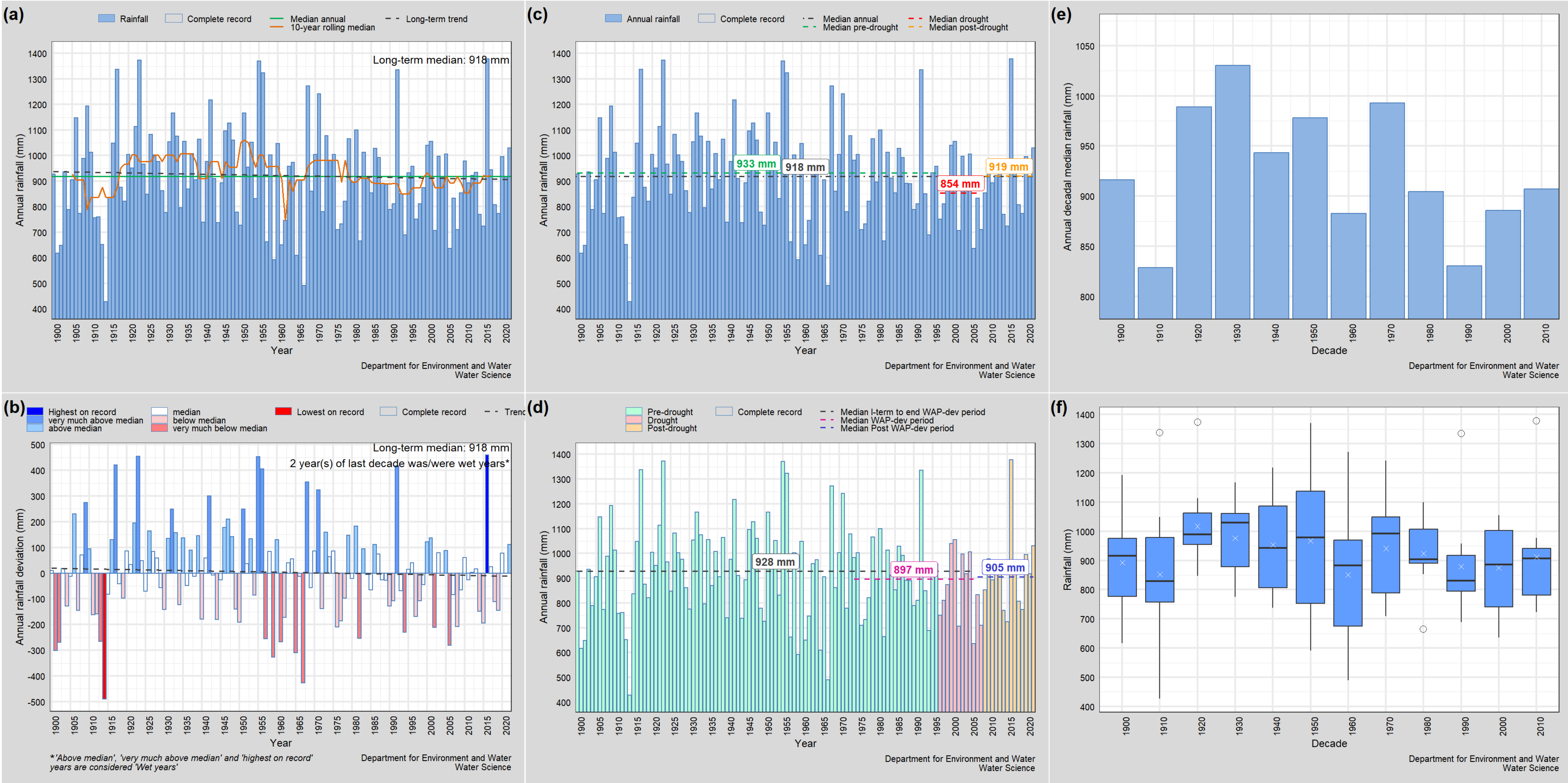
Annual and decadal rainfall plots – Birdwood (23705), Torrens catchment



Annual and decadal rainfall plots – Uraidla (23750), Onkaparinga catchment

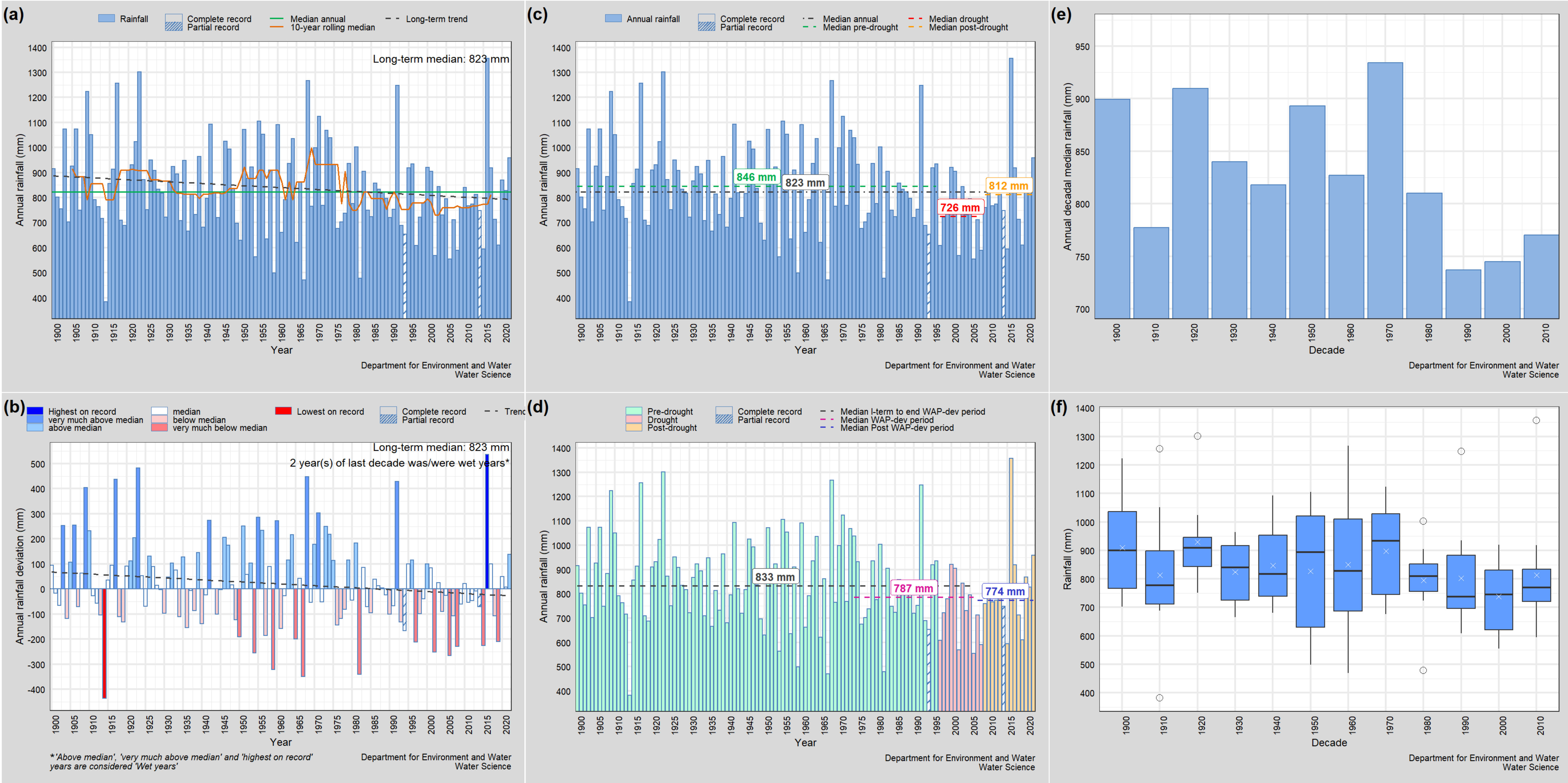
Annual and decadal rainfall plots – Bridgewater PO (23707), Onkaparinga catchment

Annual and decadal rainfall plots – Cherry Gardens (23709), Onkaparinga catchment

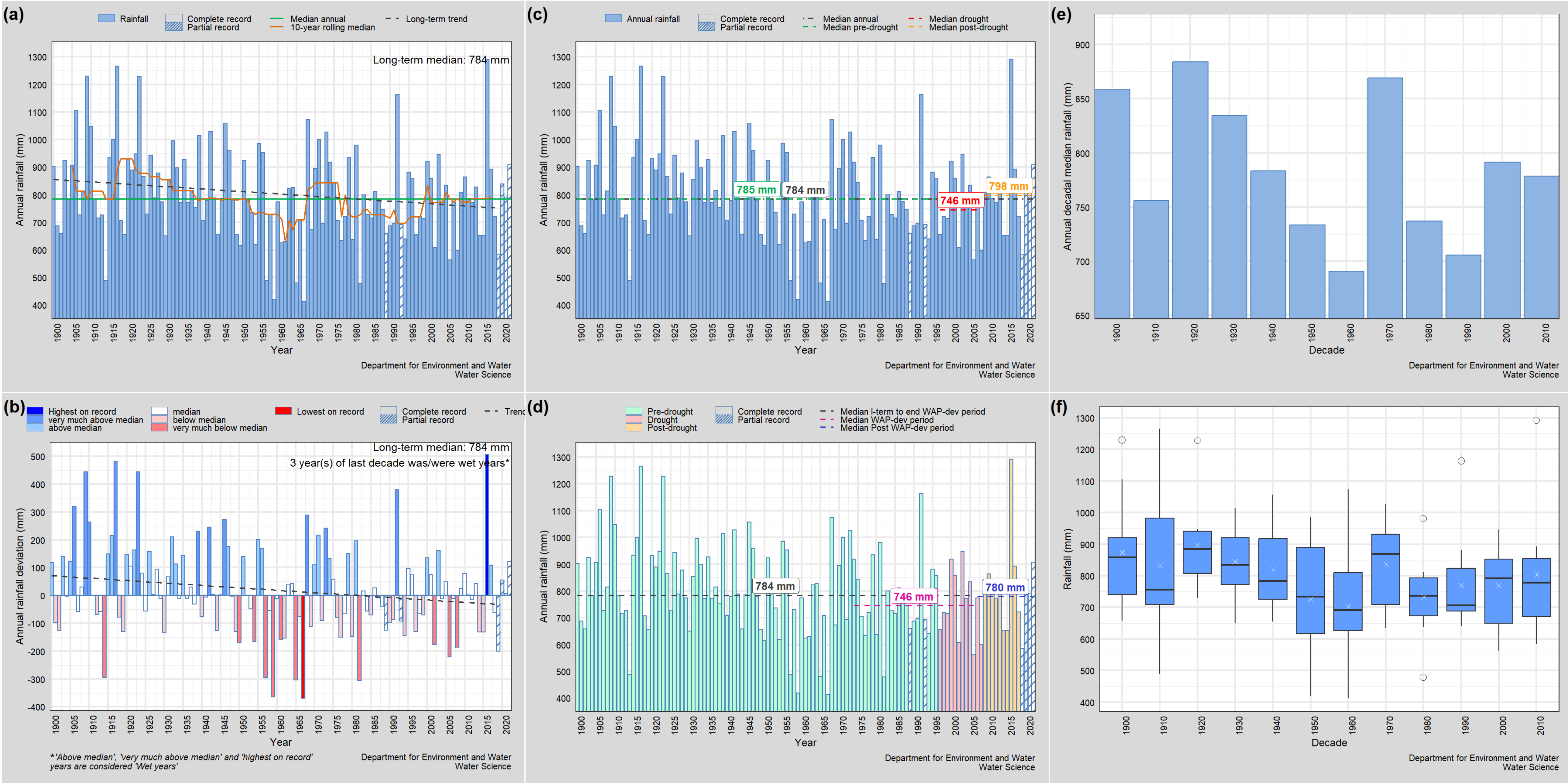


Annual and decadal rainfall plots – Lobethal (23726), Onkaparinga catchment

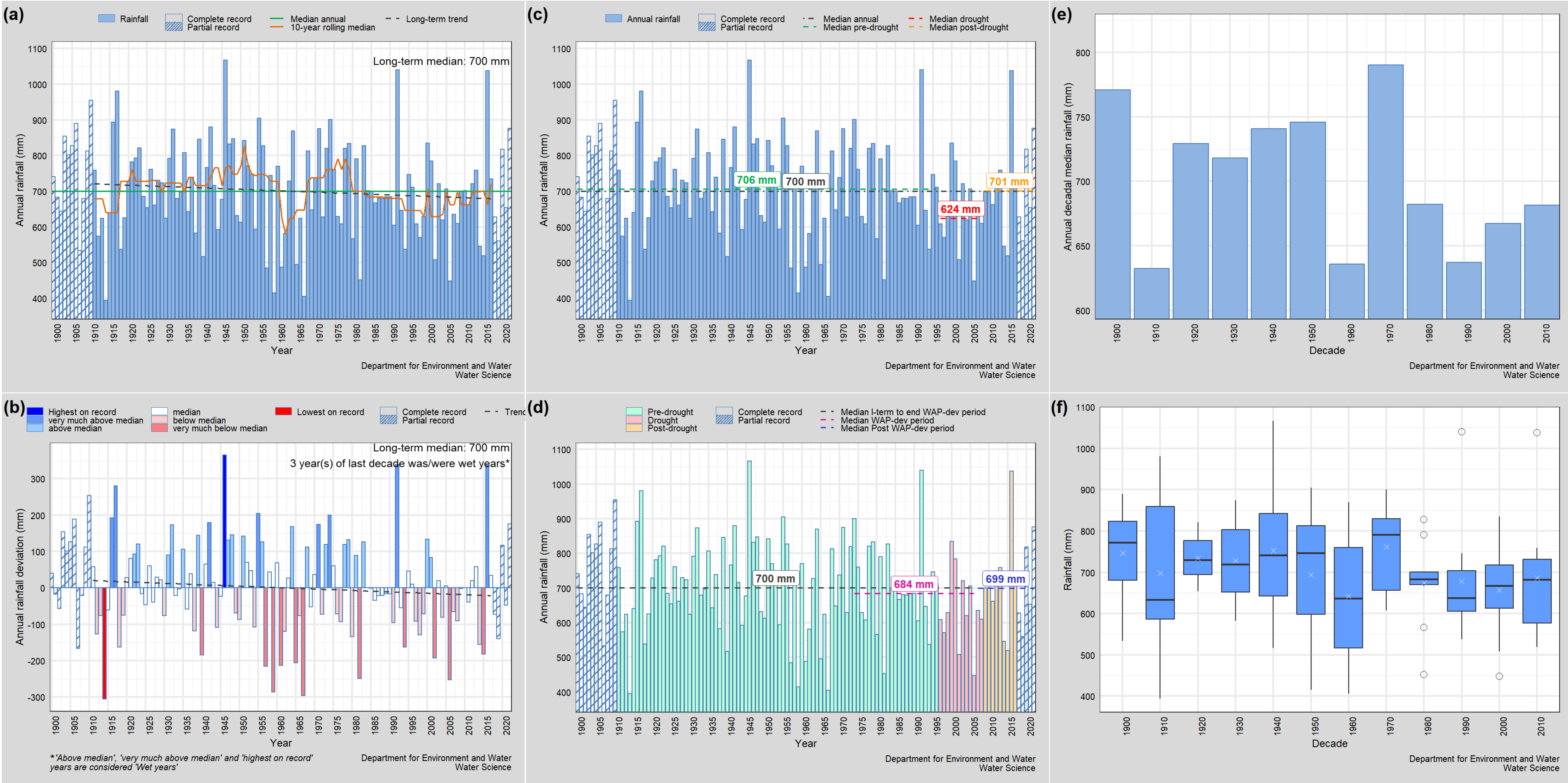
Annual and decadal rainfall plots – Hahndorf P) (23720), Onkaparinga catchment



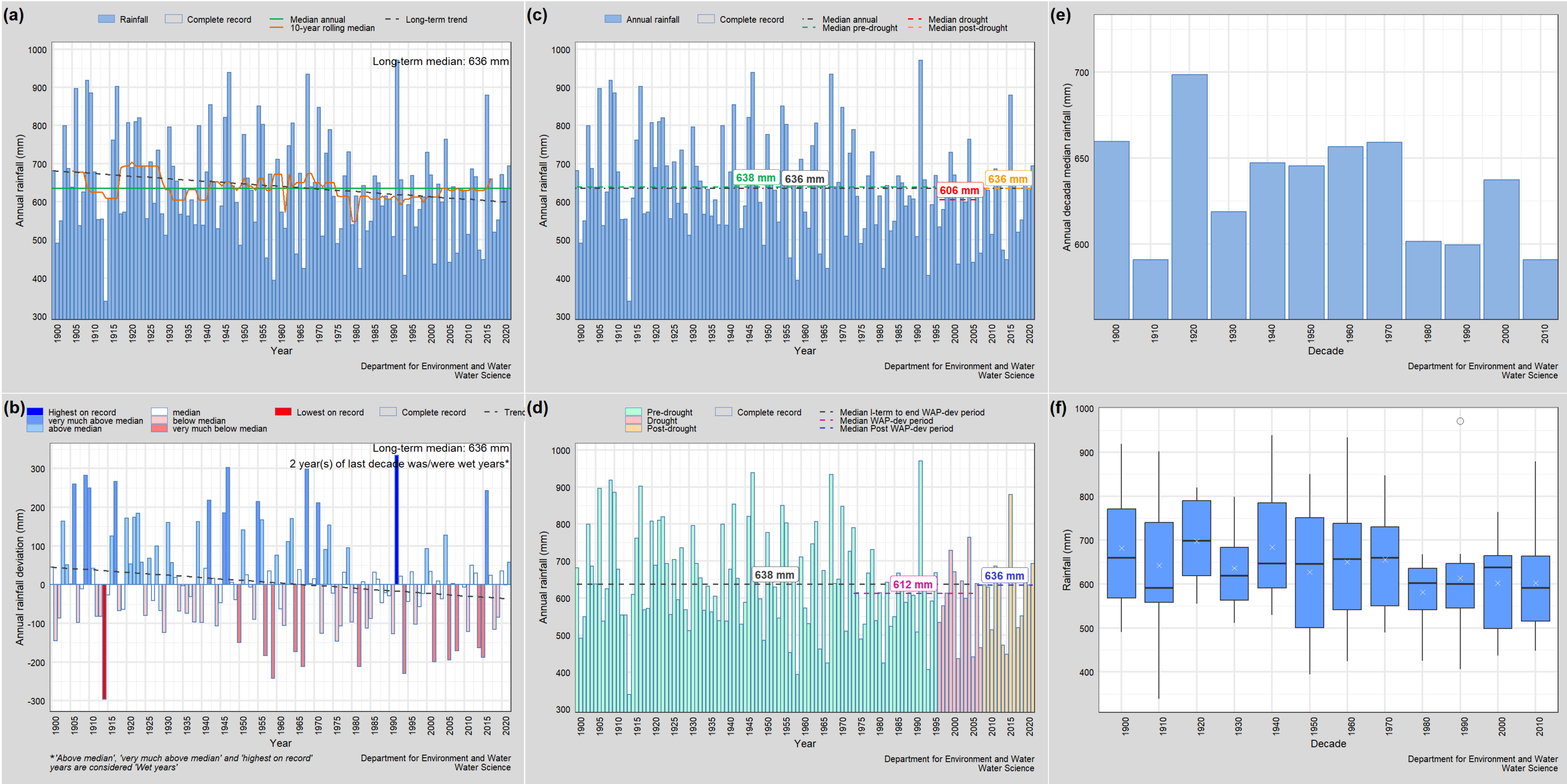
Annual and decadal rainfall plots – Echunga GC (23713), Onkaparinga catchment



Annual and decadal rainfall plots – Victor Harbor (23743), Fleurieu



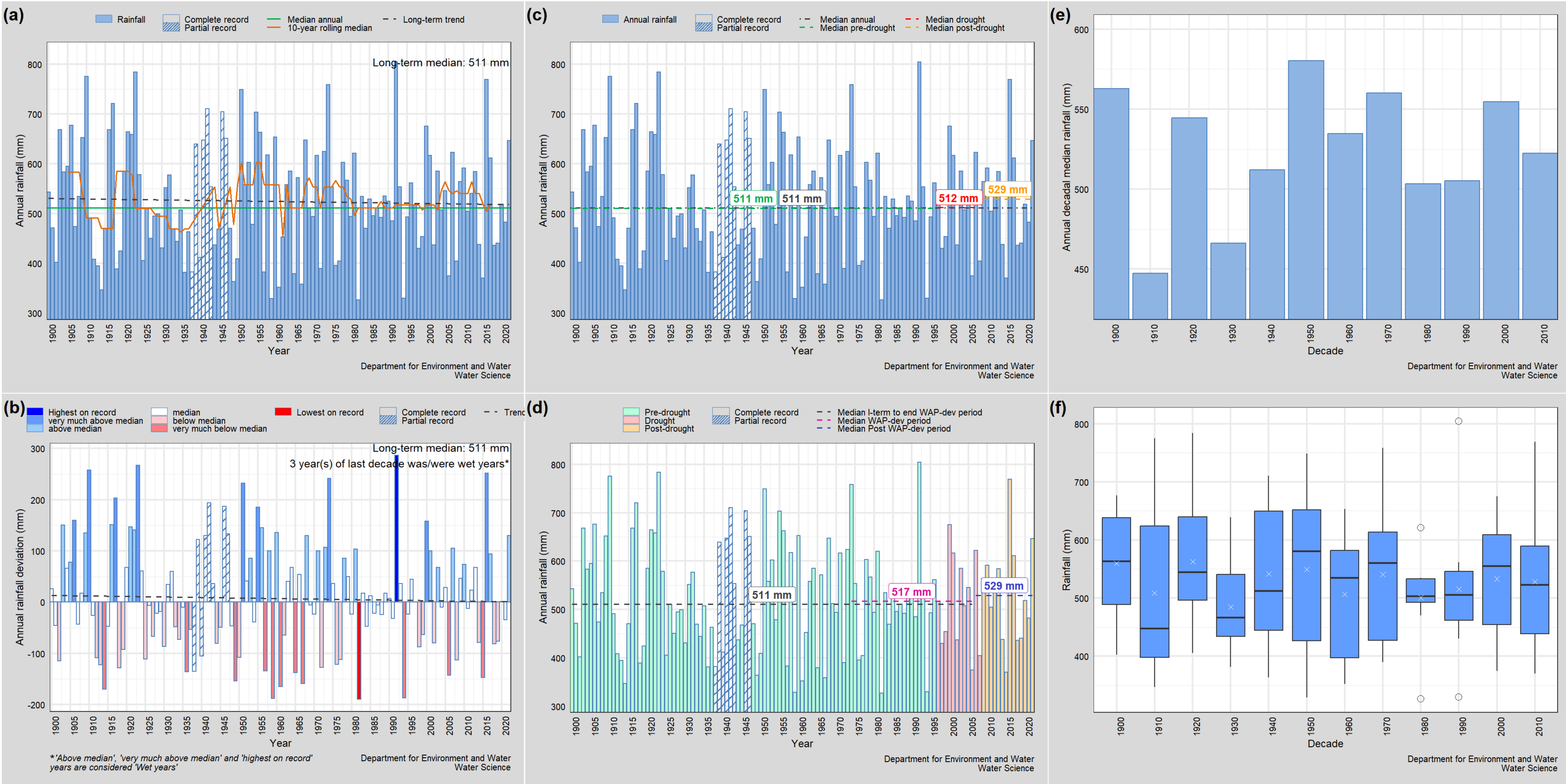
Annual and decadal rainfall plots – Willunga (23753), Fleurieu



Annual and decadal rainfall plots – Second Valley (23744), Fleurieu

Annual and decadal rainfall plots – Yankalilla (23754), Fleurieu

Annual and decadal rainfall plots – Normanville (23741), Fleurieu



Annual and decadal rainfall plots – Port Elliot CP (23742), Fleurieu

8 References

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