

# Impacts of changing rainfall patterns on the hydrology of the Marne Saunders PWRA

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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 provides 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 Plan (WAP) for the Marne Saunders Prescribed Water Resources Area (PWRA) is currently under review. Hydro-ecological investigations were undertaken by the Department for Environment and Water (DEW) to inform the review being led by the Murraylands and Riverland Landscape Board. A component of the investigations includes the assessment of long-term rainfall and streamflow trends across the PWRA. This technical report presents the methodology and results of analyses of rainfall data across the PWRA and streamflow observations in the Marne and Saunders surface water catchments.

The scope of this investigation is to inform the review of the WAP 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 2024) period; and
- streamflow volumes and flow patterns during the post-WAP development period (2004 to 2024) were different from those used to develop the WAP (1974 to 2003).

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 analysis from 1900 to 2024 across five Bureau of Meteorology stations in the PWRA, with a focus on Mt Pleasant and Keyneton, revealed statistically significant long-term declines in annual, spring, and October rainfall. Step changes were evident between pre- and post-drought periods, particularly in spring, autumn, and late winter–spring rainfall (August to October) with shifts observed in spring (October) between the WAP development and post-WAP development periods. Post-drought recovery has been limited with median post-drought spring rainfall being the lowest amongst the three drought comparison periods and classified as 'Yet to recover', while winter and autumn rainfall also declined, placing both stations in the 'Partially recovered' category. Overall, the data indicate a sustained downward trend in rainfall with spring and autumn (to a lesser extent) showing the most pronounced long-term and post-drought changes.

**Streamflow:** Streamflow analysis across three drought-related periods and two WAP development periods reveals a significant and ongoing decline in catchment flows since the Millennium Drought in the Marne River catchment. Annual streamflow metrics – including median, mean, and maximum flows – were substantially 48% lower during the drought compared to pre-drought years, with post-drought and post-WAP flows declining even further by 84% and 88%, respectively. Median winter and spring flows, which contribute to most of the annual streamflow, dropped sharply during the drought and fell to zero post-drought. Monthly and daily data confirm widespread reductions, with all months recording zero median flow post-drought and a more than 60% decline in flowing days per year. These changes reflect a major shift in the flow regime, with streamflow levels remaining lower than both pre-drought and drought periods, indicating that the catchment is yet to recover.

**Rainfall-runoff response:** Rainfall–runoff analysis for the Marne River catchment from 1974 to 2024 reveals a significant and lasting shift in catchment response across three drought-related periods. The analysis shows reduced runoff generation during the drought compared to pre-drought years with a further decline in the post-drought period. This persistent change suggests a shift in catchment behaviour rather than a return to pre-drought conditions. While farm dam expansion in the 1990s likely contributed to reduced runoff during the pre-drought and drought periods, the continued decline, despite slightly higher post-drought rainfall, points to changes in rainfall patterns as the primary driver, with no significant changes observed to other drivers e.g. land use. Similar shifts observed in neighbouring catchments, in the Barossa and Mount

Lofty Ranges PWRAs, support the conclusion that the Marne River catchment has undergone a broader regional hydrological change since the Millennium Drought.

**In conclusion**, the findings of this investigation – the combined effects of declining rainfall, reduced streamflow, and a shift in rainfall–runoff response since the Millennium Drought – provide strong evidence of long-term and ongoing hydrological change in the Marne Saunders PWRA. Whilst not part of this investigation, such changes in the surface water system are likely to be replicated in the groundwater systems in this PWRA. These changes have important implications for the review of the Water Allocation Plan, particularly in ensuring that environmental water requirements and sustainable extraction limits reflect current and emerging catchment conditions. Continued monitoring and further investigation will be essential to determine whether the observed shifts are permanent or part of a prolonged adjustment phase, and to guide future planning under a changing climate.

# 1. Introduction

## Background

The Water Allocation Plan (WAP) for the Marne Saunders Prescribed Water Resources Areas (PWRA) is currently under review. Hydro-ecological investigations are being undertaken by the Department for Environment and Water (DEW) to inform the review, which is being led by the Murraylands and Riverland Landscape Board. This technical report presents a review of rainfall and streamflow observations in two surface water catchments in the PWRA, the Marne River and the Saunders Creek catchments.

As part of the review, a series of scientific investigations were undertaken to improve understanding of the behaviour of the water resources in the PWRA. Of particular importance is selecting an appropriate climate period, as the two fundamental metrics in establishing environmentally sustainable extraction limits in a plan – the resource capacity and the environmentally critical flow regime – vary based on climate 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 current WAP was developed using streamflow data from 1974 to 2003. Resource capacity was then quantified to be the average annual flow for the period with the impacts of development removed through modelling.

The 2019 WAP included an assessment of the capacity of surface water resources ('Resource capacity') to meet the various current and future demands and policies and principles for allocation and transfer of water. The WAP 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 the Marne Saunders PWRA is defined as the long-term mean winter 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 (Department of Environment, Land, Water and Planning (DELWP) 2020).

The practice of using historic average annual flows to establish the resource capacity has been reconsidered under the context of a changing climate, uncertainties around future climate, and their implications to rainfall-runoff responses, including non-stationarity. Recent investigations of historical water resources that informed the review of the Barossa WAP (Savadamuthu et al. 2023) and the eastern and western Mount Lofty Ranges WAPs (Savadamuthu and McCullough 2024) showed evidence of a possible shift in rainfall patterns since the beginning of the Millennium drought, and its impacts on the areas' rainfall-runoff response and environmentally significant flow regimes.

The purpose of this project is to support the review of the Marne Saunders WAP 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 2024)
- rainfall and streamflow patterns, and the relationship between the two for the post-WAP development period (2004 to 2024) are different from those used to develop the WAP (1974 to 2003).

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 into 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 WAP may not have been effective in meeting the objectives of the WAP 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 this area, if the WAP is to be amended. This technical report investigates changes in rainfall and streamflow in the Marne River and Saunders Creek 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 from the two surface catchments, the Marne River and the Saunders Creek (Marne Saunders), within the PWRA were analysed.

## 2.2. Rainfall site selection

Daily rainfall observations across the selected catchments were retrieved from the SILO database 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 2024. There are many BoM rainfall monitoring stations across the PWRA but only a small subset has data that were recorded at the BoM stations from 1900 onwards and not infilled (that is, estimated).

### 2.2.1. Data quality and usability

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 Marne Saunders, 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 2024. 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 the two surface water monitoring stations in the Marne Saunders catchments. The stations and periods of records used in this analysis were the following.

- Marne River at Marne Gorge (A4260529 (1993-2003) and A4260605 (2003-2024), daily streamflow data available from 1974 to 2024.
- Saunders Creek in Gorge (A4261174), daily streamflow data available for 2010 to 2024.

## 2.4. Hydrological analyses

Daily rainfall and streamflow records 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 2.1. These categories are consistent with categories used by the BoM to define surface water resources.

**Table 2.1. 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 subsections, in addition to all years on record (1900 to 2024) those being:

- WAP development (1974 to 2003);
- Post-WAP development (2004 to 2024);
- Pre-drought (1900 to 1996);
- Millennium drought (1997 to 2008);
- Post-drought (2009 to 2024); and
- Drought and post-drought (1997 to 2024).

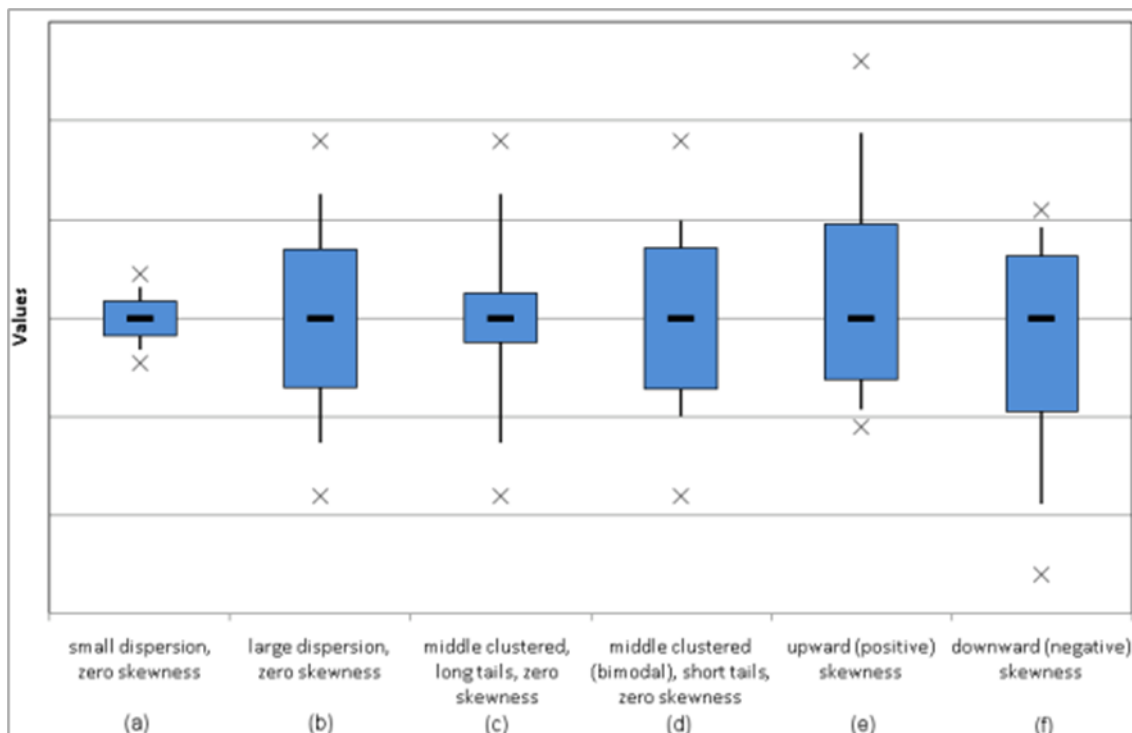
It should be noted that the WAP development and post-WAP development periods are planning periods that overlap climatic periods. The relevance for the WAP review is the analysis of hydrological data that were used to develop the WAPs, what has been observed in the period since the development of the 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 Marne Saunders. Similarly, 2008 represents the end of the Millennium drought with 2009 representing the start of a further period of altered climate conditions (post-drought). 2003 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 relatively 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 2.1 (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 2.1(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 2.1(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 2.1. Examples of box plots (after Massart et al. 2005)**

## 2.5. Recovery status categories

To obtain a PWRA-scale picture of the ‘recovery’ status of rainfall and streamflow during the post-drought period (2009 to 2024), 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 (wettest)’ 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 (driest)’ 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<sup>1</sup> 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, but more applicable when 2 samples have unequal variances and/or unequal sample sizes. As with Student's *t*-test, 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).

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<sup>1</sup> CUSUM charts have four bounds because they separately track gradual increases and gradual decreases, and each direction needs a reset line and a warning line.

# 3. Rainfall analysis

## 3.1. Overview

The spatial distribution of long-term annual average rainfall across the PWRA is shown in Figure 3.2. The distribution is shown to follow the topography of the landscape with a west to east downward gradient. As shown in Figure 3.2 higher rainfall areas are in the south-western areas with average annual rainfall higher than 600mm and dropping down quickly through the plains in the east to a low of  $\approx 300$  mm. Further catchment scale information is provided in the WAP for the PWRA.

For the purposes of this investigation, 5 rainfall sites were selected:

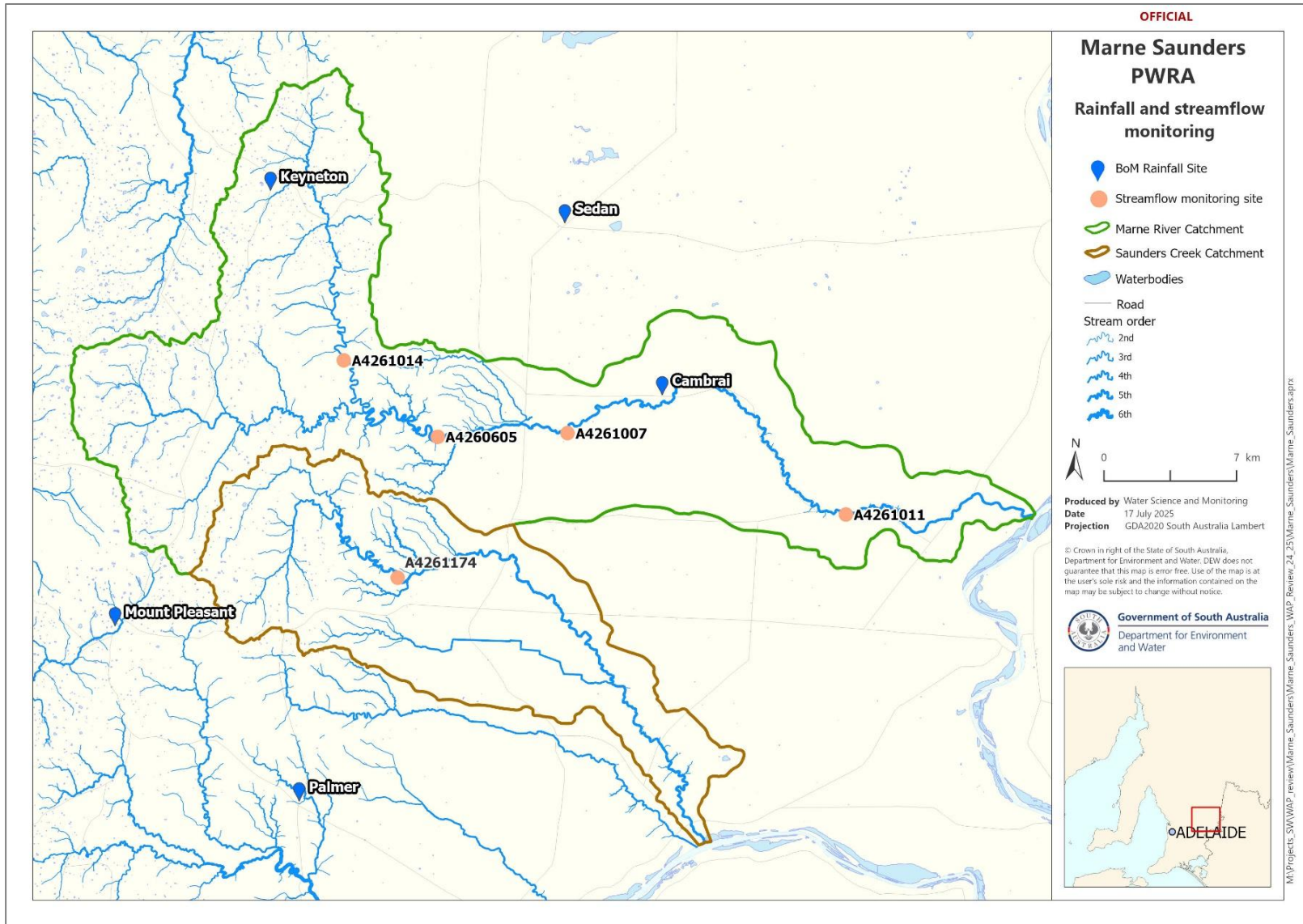
- to generally cover the spatial distribution of rainfall across the PWRA;
- to meet the data quality criteria mentioned in Section 2.2; and
- with higher priority given to stations located in the headwater/high rainfall sections of the catchments considered in the streamflow and rainfall-runoff investigations.

A list of the rainfall sites, and the catchment and PWRA in which they are located, are provided in Table 3.1 and displayed in Figure 3.1.

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

- long-term annual, seasonal, and monthly rainfall trends;
- 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; and
- 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 the primary station is provided in the following sections. Results for the remaining reporting stations are provided as tables and charts in the Appendices.



**Figure 3.1. Selected SILO rainfall stations and streamflow monitoring locations for Marne Saunders PWRA**

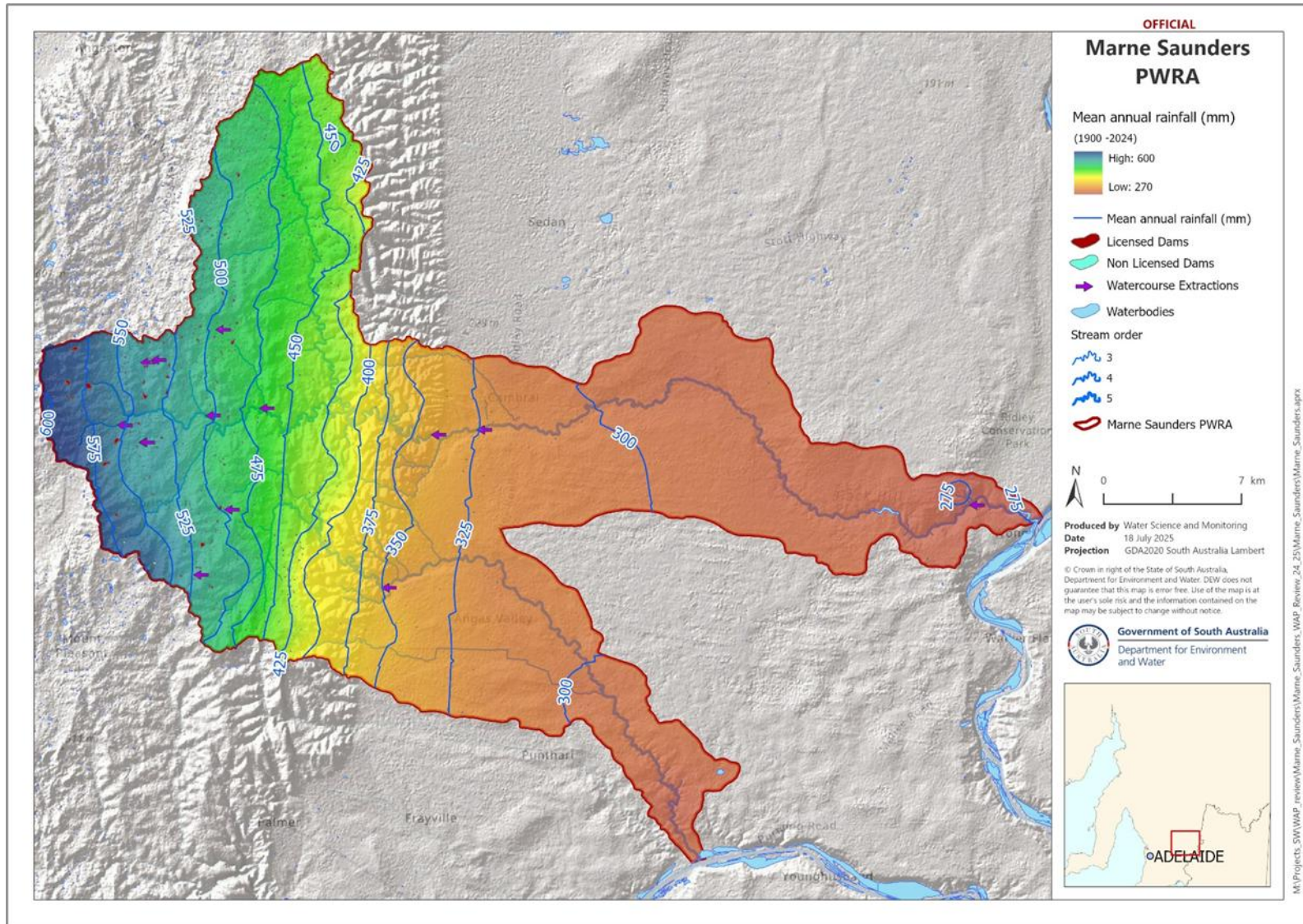


Figure 3.2. Long-term mean annual rainfall spatial distribution across the PWRA

## 3.2. Overview of rainfall stations

Rainfall observations from 5 long-term operational rainfall station from within and in the vicinity of the PWRA were used in these analyses. The overall quality of data within the SILO records for these series across 1900 to 2024 are summarised in Table 3.1.

**Table 3.1. Proportion of daily SILO rainfall series (1900 to 2024) associated with the Marne Saunders PWRA with various quality codes**

Site ID	Site name	Catchment	SILO Data Quality Codes <sup>2</sup>		
			0	15	25
23725	Keyneton	Marne River	88%	3%	10%
23737	Mount Pleasant	Torrens River	91%	8%	1%
24513	Cambrai (Kongolia)	Marne River	99%	1%	0%
24531	Sedan	Marne River	93%	2%	5%
24525	Palmer	Saunders Creek	94%	4%	2%

<sup>2</sup> 0 represents station-recorded data, 15 represents de-accumulated values from interpolated data and 25 represents interpolated daily observations.

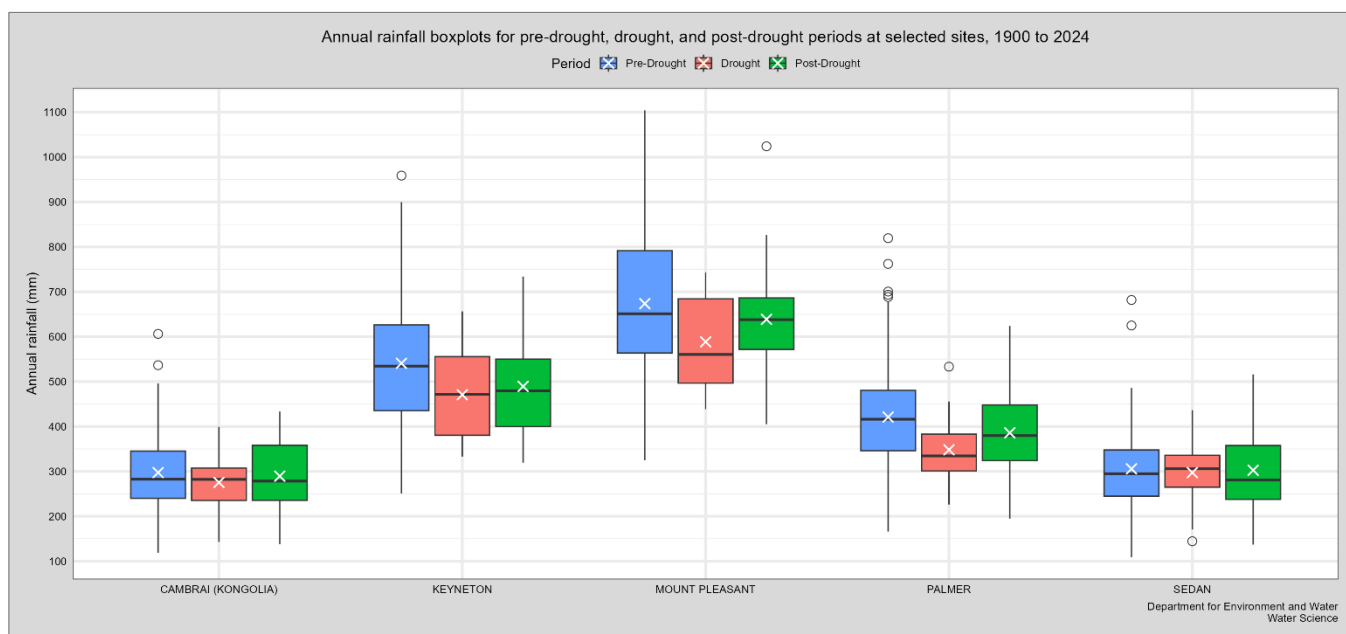
Due to the absence of a suitable rainfall station in the wetter (south-western) sections the PWRA, data from the nearest station located at Mount Pleasant (23737) in the Torrens catchment were used in this study.

Table 3.2 summarises key statistics for annual rainfall data, which demonstrates the high spatial variability of rainfall across the PWRA, as well as the annual variability within each station with the upper reaches of the catchments (Mt Pleasant) being considerably wetter than the downstream parts (Cambrai and Sedan) of the catchments.

**Table 3.2. Summary statistics for selected annual rainfall data (mm) for Marne Saunders PWRA (1900 to 2024)**

Statistics	Keyneton (23725)	Mt Pleasant (23737)	Cambrai (24513)	Sedan (24531)	Palmer (24525)
Annual average (mm)	525	659	294	304	407
Annual median (mm)	507	639	280	295	392
Annual maximum (mm)	959	1104	606	682	819
Annual minimum (mm)	251	325	119	109	166
Standard deviation	141	158	88	99	118

Figure 3.3 shows the distribution of annual rainfall for the 5 sites used in the analysis for the three drought-related periods as boxplots with the absolute median values and relative changes provided in Table 3.3. Data presented in Figure 3.3 shows that across all sites, except Mount Pleasant (23737), the pre-drought period displays relatively symmetric distributions of annual rainfall, suggesting more consistent rainfall patterns historically. In contrast, the post-drought period generally exhibits positive skewness, particularly at Cambrai (24513) and Sedan (24531), indicating a wider range of rainfall observations in the upper quartile (above median annual rainfall years).



**Figure 3.3. Distribution of annual rainfall for different periods**

(Median (—), average (X), and outliers (O) shown)

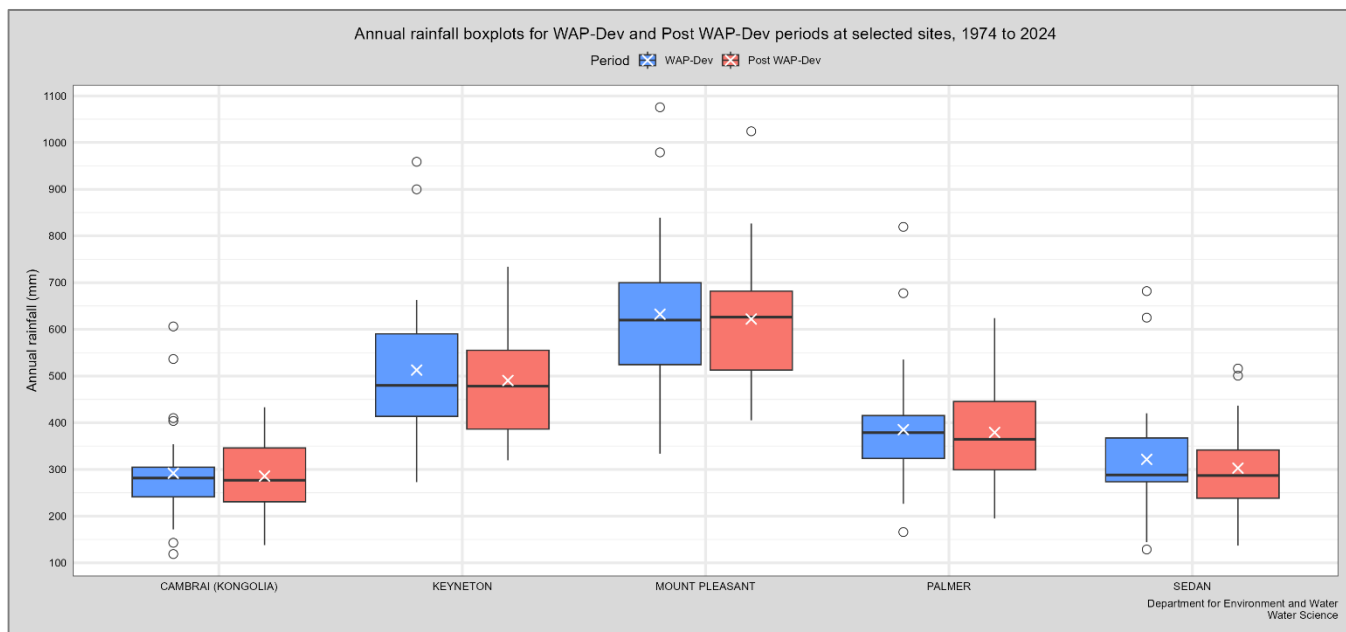
**Table 3.3 Median annual rainfall (mm) for different periods for the Marne Saunders PWRA (1900-2024)**

Period	Keyneton (23725)	Mount Pleasant (23737)	Cambrai (24513)	Sedan (24531)	Palmer (24525)
All years (1900 to 2024)	507	639	280	295	392
Pre-drought (1900 to 1996)	535	651	283	295	416
Drought (1997 to 2008)	471	560	282	306	335
Post-drought (2009 to 2024)	479	638	278	281	380
<b>Change compared to pre-drought</b>					
Drought	-63	-91	-1	11	-82
(%)	<i>(-12 %)</i>	<i>(-14 %)</i>	<i>(-0.2 %)</i>	<i>(4%)</i>	<i>(-20%)</i>
Post-drought	-55	-13	-4	-14	-36
(%)	<i>(-10 %)</i>	<i>(-2%)</i>	<i>(-2 %)</i>	<i>(-5%)</i>	<i>(-9%)</i>

Data presented in Table 3.3 and Figure 3.3 show that of the five stations:

- four stations (Keyneton, Mount Pleasant, Cambrai, and Palmer) recorded reductions in median annual rainfall during the drought period (ranging from 0.2% to 20%), while Sedan showed a slight increase (4%), compared to the pre-drought period;
- rainfall is yet to fully recover to pre-drought conditions at all the rainfall stations during the post-drought period; and
- partial recovery during the post-drought period was observed at Keyneton, Mount Pleasant and Palmer. However, at Sedan and Cambrai, rainfall in the post-drought period declined further (driest) compared to the drought period.

Figure 3.4 shows the distribution of annual rainfall during the WAP development (1974 – 2003) and post-WAP (2004 – 2024) development periods for the 5 sites and Table 3.4 shows the annual medians and relative changes related to the WAP periods. Median rainfall values were similar between the two periods at all sites (differences less than 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 3.4. Distribution of annual rainfall during WAP development periods**

Median (—), average (X), and outliers (O) shown.

**Table 3.4 Median annual rainfall (mm) for different WAP periods across the Marne Saunders PWRA (1900 to 2024)**

Period	Keyneton	Mount Pleasant	Cambrai	Sedan	Palmer
	(23725)	(23737)	(24513)	(24531)	(24525)
All years (1900 to 2024)	507	639	280	295	392
Pre-WAP (1900 to 1973)	528	651	285	295	402
WAP development (1974 to 2003)	480	620	282	288	379
Post-WAP development (2004 to 2024)	478	626	277	287	364
Change (WAP development to post-WAP-development) (%)	-2 (0%)	6 (1%)	-5 (-2%)	-2 (-1%)	-14 (-4%)

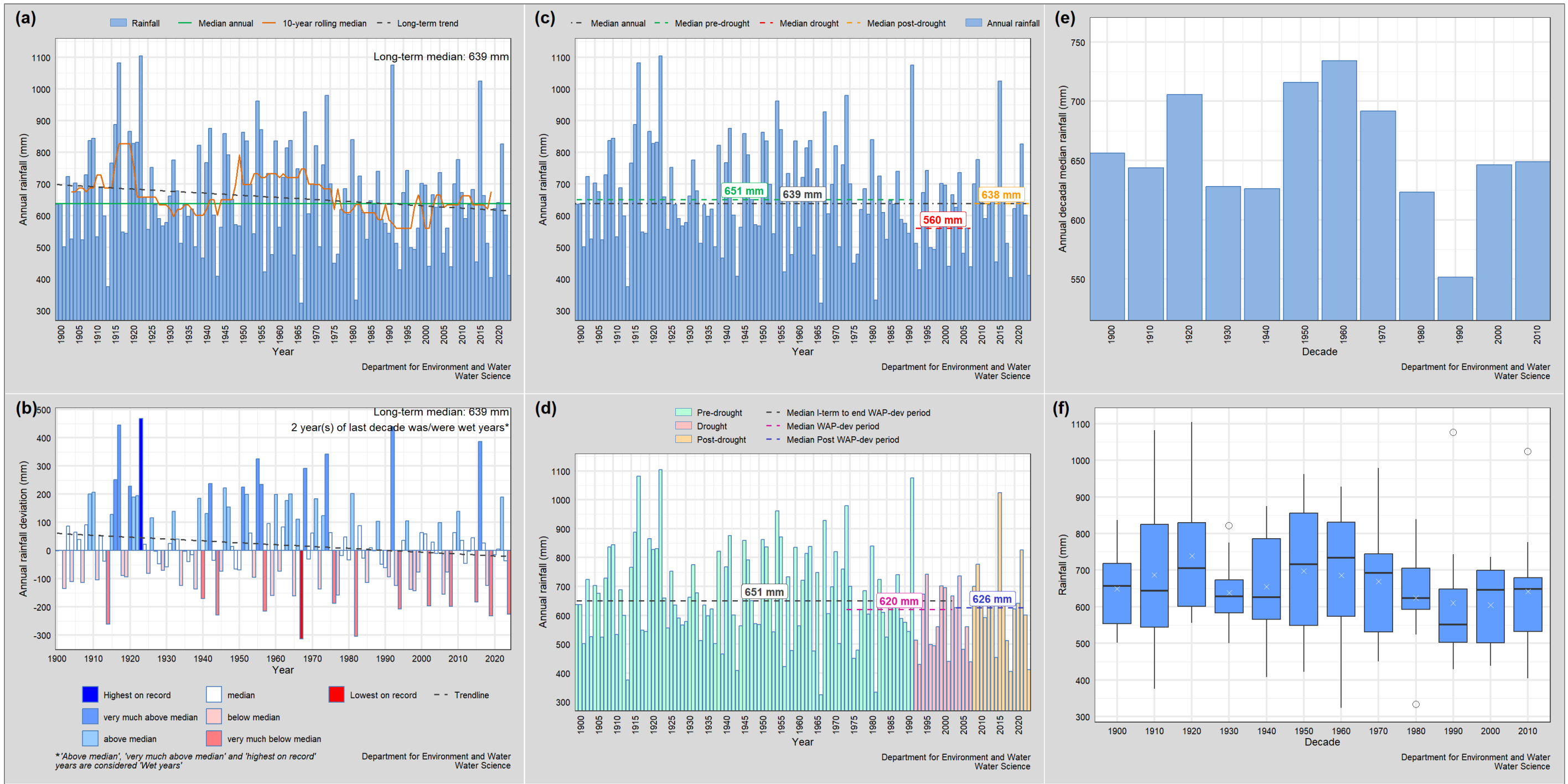
### 3.3. Detailed rainfall analysis – Mount Pleasant

Detailed rainfall analysis for Mount Pleasant (23737) at various timescales is presented in this section with results for the other stations included in Appendix 7.4.

#### 3.3.1. Annual rainfall analysis

Rainfall totals for Mount Pleasant (23737) at annual and decadal levels with various period medians and trends included are plotted in Figure 3.5(a) to (f). The trends of annual rainfall and decadal medians suggest a long-term gradual decline in annual rainfall over the period of record from 1900 to 2024 (refer to Figure 3.5(a) and (e)). Annual deviations from the long-term median rainfall shown in Figure 3.5 (b), indicating that only 3 of the past 15 years were ‘above-median’ or ‘wet’ rainfall years, as per the classification in Table 2.1.

Medians for the drought-related periods (Figure 3.5(c)) show that median rainfall of the drought period (560 mm) is substantially below the long-term (639mm) and pre-drought (651mm) medians. While the post-drought median (638mm) is higher than that of the drought period, it is **yet to fully recover** to pre-drought period median. For WAP development and post-WAP development periods (Table 3.5 (d)) the data indicate similar median values for the 2 periods, both of which are below the long-term median.



**Figure 3.5. Rainfall plots at Mount Pleasant (BOM site 23737) for 1900 to 2024 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**

### 3.3.2. Seasonal rainfall analysis

The previous section outlined evidence of trends towards drier conditions at Mount Pleasant in recent decades when rainfall was analysed at an annual timescale. To further investigate its seasonal behaviour, historical daily rainfall was aggregated to seasonal totals and compared on a season-by-season basis.

Table 3.5 summarises median seasonal rainfall over the 3 drought-related 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:

- rainfall during autumn, winter and spring were much lower during the drought. Autumn and winter rainfall showed some recovery in the post-drought period but were still lower than the pre-drought period medians. On the other hand, **post-drought spring rainfall showed no recovery and was the lowest (driest) among the three drought related periods.**
- in contrast, that median summer rainfall remained almost consistent through the three drought related periods.

**Table 3.5 Median seasonal rainfall (mm) at Mount Pleasant (BOM site 23737) for different drought related periods**

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2024)	(1900 to 1996)	(1997 to 2008)	(2009 to 2024)	Drought mm (%)	Post-drought mm (%)
Summer	66	65	68	68	3 (4%)	3 (5%)
Autumn	135	140	105	135	-36 (-25%)	-5 (-3%)
Winter	263	267	248	257	-19 (-7%)	-10 (-4%)
Spring	164	174	136	126	-38 (-22%)	-48 (-28%)
<b>Annual</b>	<b>639</b>	<b>651</b>	<b>560</b>	<b>638</b>	<b>-91 (-14%)</b>	<b>-13 (-2%)</b>

Table 3.6 summarises seasonal medians for the WAP development and post-WAP development periods. These values demonstrate that the **post-WAP development phase (2004 onwards) was drier in winter and spring (driest)**, but not in autumn and summer, when compared to the WAP development period.

**Table 3.6. Median seasonal rainfall (mm) at Mount Pleasant (BOM site 23737) 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 2024)	(1974 to 2003)	(2004 to 2024)	(mm)	(%)
Summer	66	60	70	10	16%
Autumn	135	126	135	9	7%
Winter	263	258	250	-9	-3%
Spring	164	153	117	-36	-23%
<b>Annual</b>	<b>639</b>	<b>620</b>	<b>626</b>	<b>6</b>	<b>1 %</b>

### 3.3.3. Monthly rainfall analysis

Table 3.7 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, the greatest percentage reduction in median rainfall was observed in March (41%) and April (32%). In contrast, notable increases were recorded in January (73%), June (12%) and December (19%) compared to the pre-drought period.
- The post-drought period data indicates all months except January, February, May, June and November were drier than the pre-drought period (Yet to recover).
- September and October (spring months) showed a further decrease in median rainfall from drought conditions in the post-drought period (driest), whereas November median rainfall recovered to pre-drought levels.
- **September and October (followed by March)** were the most impacted across the drought periods with the monthly median decreasing progressively through the 3 comparison periods (**driest**).
- January and June have been on the other side of change with the monthly medians during the drought and post-drought periods being higher than the pre-drought period median.

**Table 3.7. Median monthly rainfall (mm) for Mount Pleasant (BOM site 23737) for different periods relative to the drought**

Season	All years (1900 to 2024)	Pre-drought (1900 to 1996)	Drought (1997 to 2008)	Post-drought (2009 to 2024)	Change from Pre-drought	
					Drought	Post-drought
					mm (%)	mm (%)
Jan	18	18	31	20	13 (73%)	2 (12%)
Feb	14	14	13	15	-2 (-13%)	0 (1%)
Mar	16	17	10	12	-7 (-41%)	-5 (-31%)
Apr	35	41	28	33	-13 (-32%)	-8 (-19%)
May	61	63	60	64	-3 (-4%)	1 (1%)
Jun	83	80	90	87	10 (12%)	6 (8%)
Jul	87	91	79	85	-11 (-12%)	-6 (-6%)
Aug	88	91	78	80	-13 (-14%)	-11 (-12%)
Sep	64	72	62	48	-10 (-15%)	-24 (-33%)
Oct	50	57	48	38	-10 (-17%)	-20 (-34%)
Nov	30	31	26	36	-6 (-18%)	5 (16%)
Dec	22	23	28	18	5 (19%)	-5 (-21%)
<b>Annual</b>	<b>639</b>	<b>651</b>	<b>560</b>	<b>638</b>	<b>-91 (-14%)</b>	<b>-13 (-2%)</b>

Table 3.8 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 and October (in spring) during the post-WAP development period, relative to the WAP development period.

These results show that reductions in rainfall during **September (25%)** and **October (34%)** remain the key changes in which climatic impacts are observed to affect the post-WAP development relative to WAP development periods. Except for June and November, which showed 11% and 20% increase respectively,

the other months had median rainfall largely consistent across the two WAP-related periods with differences remaining within 4 mm between medians.

**Table 3.8. Median monthly rainfall (mm) for Mount Pleasant (BOM site 23737) for different WAP development periods**

Month	All years	WAP development	Post WAP-development	Change (WAP dev. to Post WAP-dev.)	
	(1900 to 2024)	(1974 to 2003)	(2004 to 2024)	(mm)	(%)
Jan	18	20	21	1	4 %
Feb	14	10	13	3	32
Mar	16	16	13	-3	-19%
Apr	35	32	35	3	10%
May	61	61	57	-4	-6%
Jun	83	78	87	9	11%
Jul	87	97	82	-15	-16%
Aug	88	88	81	-7	-8%
Sep	64	65	49	-16	-25%
Oct	50	50	33	-17	-34%
Nov	30	28	34	6	20%
Dec	22	19	21	3	15%
<b>Annual</b>	<b>639</b>	<b>620</b>	<b>626</b>	<b>6</b>	<b>1 %</b>

### 3.3.4. Rainfall recovery – Period medians

Annual and seasonal median rainfall data for the 3 drought comparison periods for each of the 5 rainfall stations investigated are provided in Appendix 7.1. To obtain a PWRA-scale picture of the recovery status of rainfall during the post-drought period (2009 to 2024), 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. Summary of the recovery status of the two high rainfall stations (Mount Pleasant (23737) and Keyneton (23737)) located in areas where majority of the runoff is generated within the PWRA is provided in the table below.

**Table 3.9. Summary of post-drought rainfall recovery status for stations Mount Pleasant (23737) and Keyneton (23737)**

Post-drought period rainfall recovery status	Number of stations (out of 2)				
	Annual	Seasonal			
		Winter	Spring	Autumn	Summer
Fully recovered (wettest)	0	0	0	0	1
Partially recovered	2	2	0	2	0
Yet to recover (driest)	0	0	2	0	1

Data presented in Table 3.9 show that of the 2 high rainfall stations investigated:

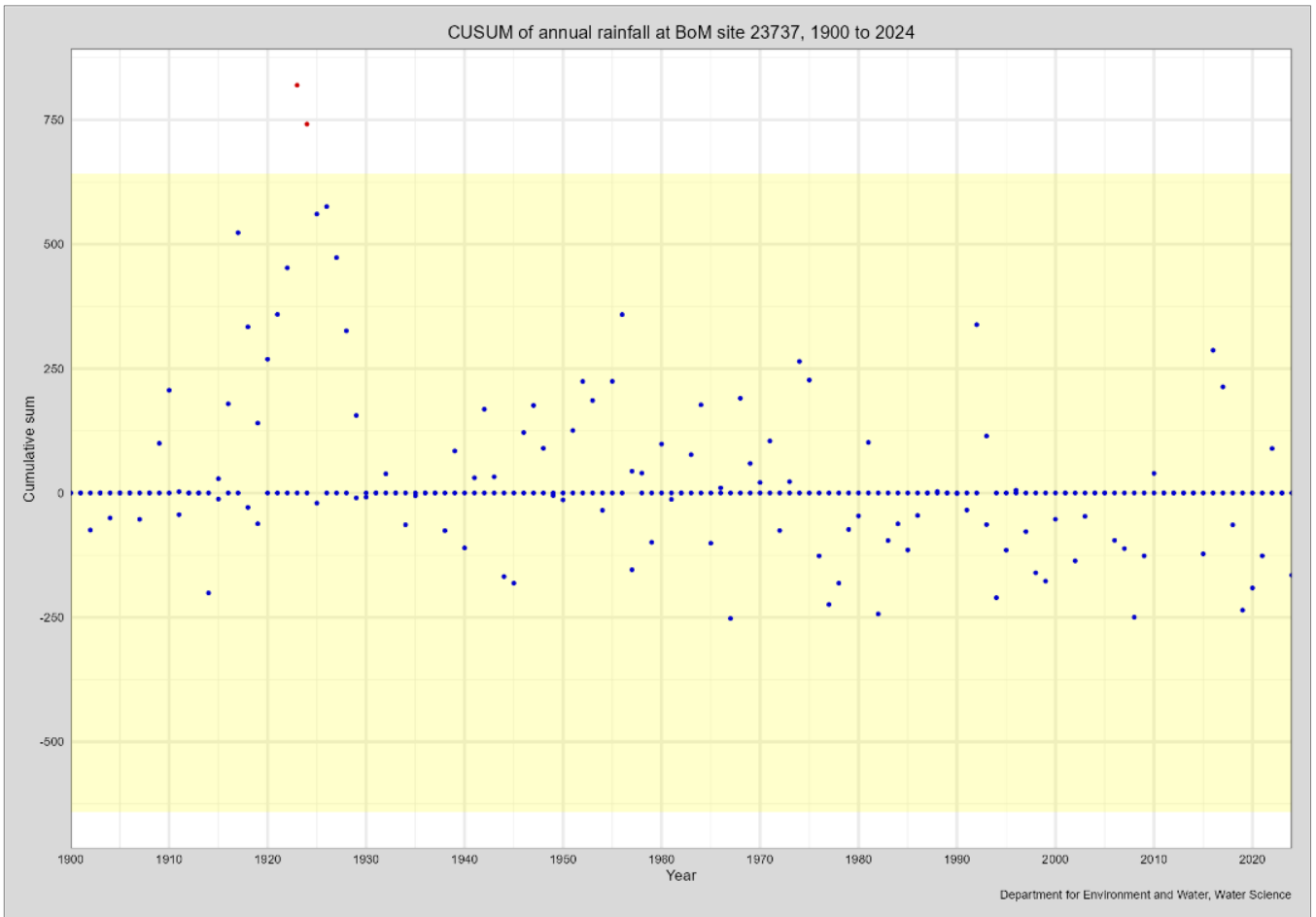
- rainfall during the **spring season has clearly had the most impact since the beginning of the Millennium drought**, with rainfall at both stations falling in the ‘**Yet to recover (driest)**’ category during the post-drought period;

- rainfall during the winter and autumn seasons has also been impacted – although to a lesser extent than spring – since the beginning of the Millennium drought with both stations falling in the ‘Partially recovered’ category during the post-drought period; and
- that, when considering annual totals, both stations have ‘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.**

## 3.4. Trend and shift analyses of rainfall

### 3.4.1. Detailed analysis of Mount Pleasant (23737)

CUSUM charts were prepared for the time series of rainfall at Mount Pleasant (23737) aggregated to annual totals (Figure 3.6). The annual CUSUM chart does not show any data points falling outside of the ‘action’ bounds (yellow shading), other than a period in the 1920s to 1930s falling above the upper action limit. This behaviour can be attributed to a high rainfall period in the early 1920s (refer to Figure 3.5(a)). Since then, the data points are generally distributed close to the long-term mean line until early mid-1990s, after which the majority of the data points are distributed below the mean. This indicates a general downward shift in annual rainfall since the early-mid 1990s with a few very wet years in between. Further analysis – seasonal and monthly - was undertaken to investigate if this potential shift in annual rainfall was uniform through the year, the results of which are presented in the following sections.



**Figure 3.6. CUSUM chart of annual rainfall (1900 to 2024) for Mount Pleasant (BOM site 23737)**

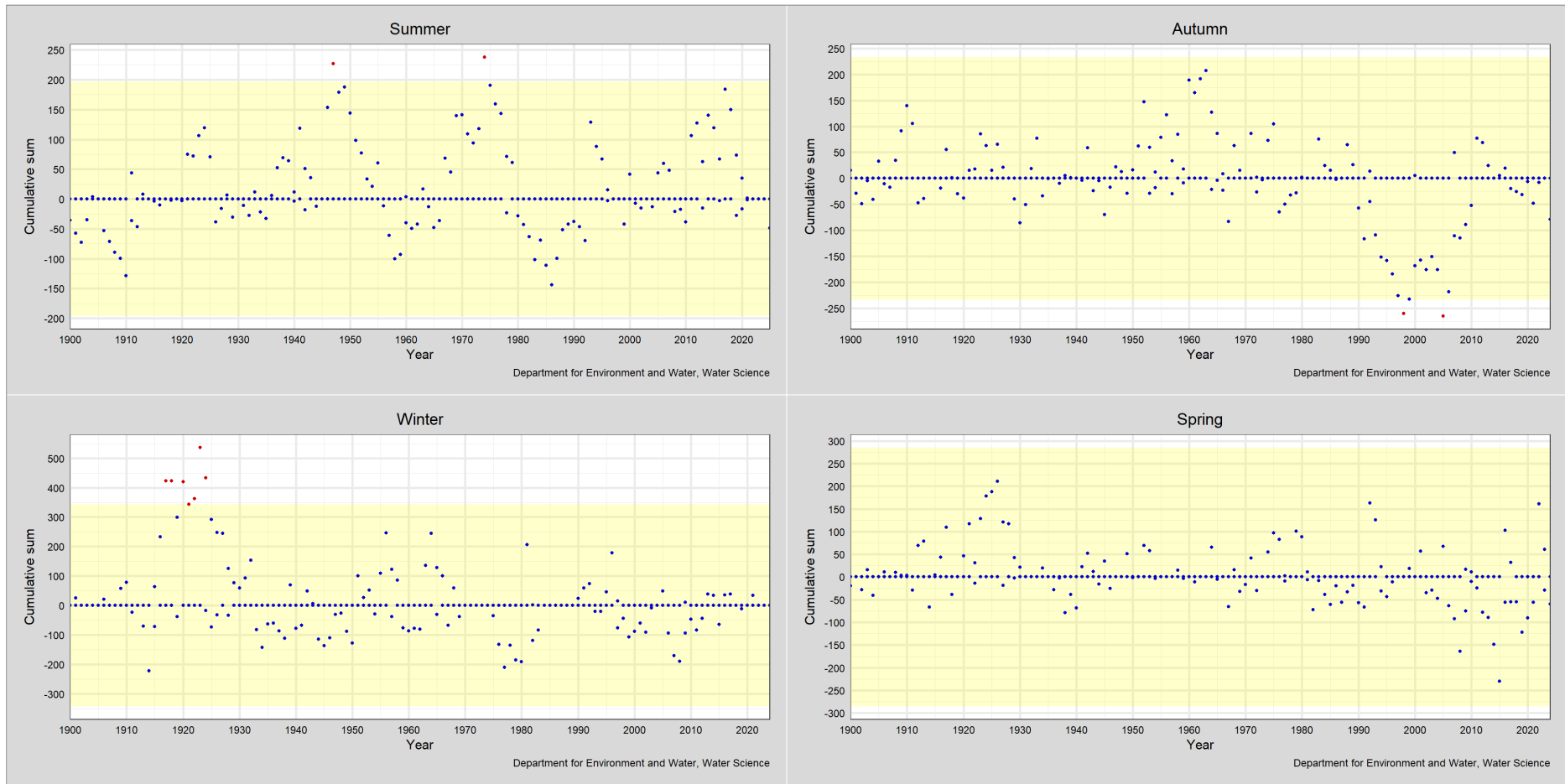
Figure 3.7 shows the CUSUM charts of seasonal rainfall totals. These results show that:

- the cumulative sums of winter rainfall mostly reflect the annual pattern (Figure 3.7), indicating a general downward shift in annual rainfall since the early-mid 1990s with a few very wet years in between during the last few decades;
- for Autumn rainfall, most data points since the early-mid 1990s are distributed below the long-term mean. The cumulative sum declined toward the lower action limit by the late 1990s before gradually increasing back toward the long-term mean over the subsequent period. However, the majority of the years remain below the long-term mean indicating a potential shift in autumn rainfall totals since the Millennium drought;
- for Spring rainfall, a declining trend from 2000s with partial recovery at the end of the reporting period (2024). In contrast, summer cumulative sum rainfall data show that most values since the 1990s sit above the long-term mean; and
- this supports previous analysis that showed reductions in median rainfall in the post-drought period except in summer.

Figure 3.8 shows CUSUM charts of monthly rainfall totals with the key relevant observations to note being that:

- October rainfall totals reveal a significant downward trend in its cumulative sum since the commencement of the Millennium drought aligning closely with the behaviour for spring;

- April and May rainfall show 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; and
- after 2010, in February, March, November and December CUSUM charts show data points falling above the upper action limit indicating few higher rainfall events.



**Figure 3.7. CUSUM charts of seasonal rainfall (1900 to 2024) for Mount Pleasant (BOM site 23737)**

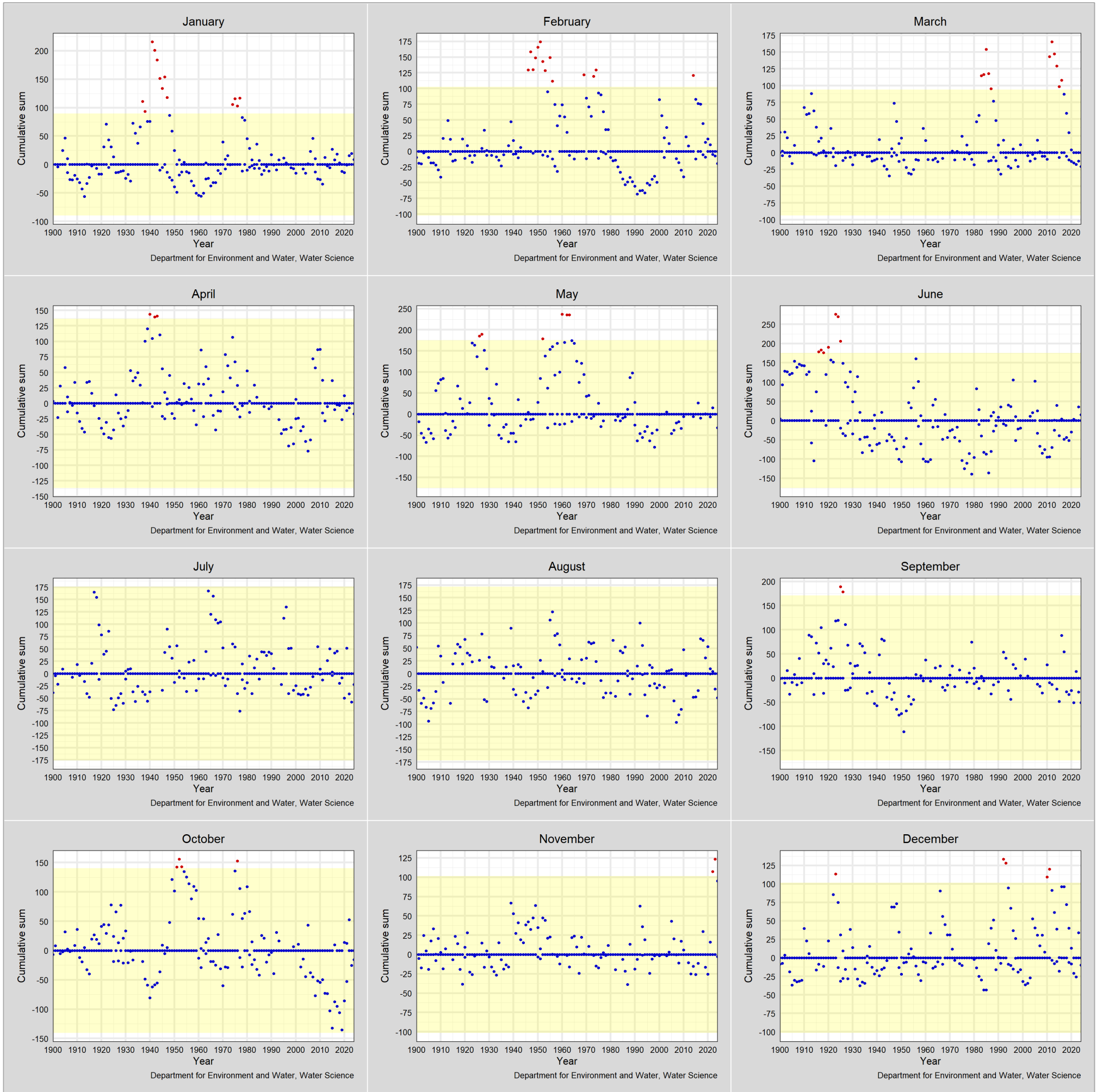


Figure 3.8. CUSUM charts of monthly rainfall (1900 to 2024) for Mount Pleasant (BOM site 23737)

- Review of CUSUM plots for the other 4 stations (Appendices 7.5, 7.6 and 7.7) and when compared to those for Mount Pleasant, show:
  - that no significant trends were observed in annual rainfall totals at all the 4 sites which are lower rainfall sites located at lower elevations in comparison to Mount Pleasant site;
  - that seasonal plots for stations at Keyneton (23725), Sedan (24531) and Palmer (24525) are similar the ones for Mount Pleasant with Autumn rainfall being the highest impacted since the drought; and
  - similar trends to Mt Pleasant with October being the highest impacted month.

Table 3.10 summarises the results of the statistical tests for data from Mount Pleasant. 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 less statistical significance (between 5% and 10%).

Results of the statistical tests presented in Table 3.10.

- The Mann-Kendall test shows evidence of statistically significant declining trends in long-term (from 1900) annual, seasonal (in spring) and monthly rainfall (during September and October).
- The 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, August, September and October) rainfall; and
  - WAP development and post-WAP development periods, in seasonal (spring) and monthly (September and 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 Mount Pleasant (23737) site have been shown to occur predominantly during autumn and spring in the months of April and October, and to a lesser degree in the months of August and September.

**Table 3.10 Summary of statistical tests for separating rainfall data for Mount Pleasant (BOM site 23737) at different years, and aggregating across various periods**

Period	Mann-Kendall (1900-2024)		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	-0.105	0.082	0.022	0.016	0.474	0.467
Summer	0.054	0.371	0.814	0.814	0.923	0.900
Autumn	-0.069	0.254	0.018	0.006	0.579	0.502
Winter	-0.050	0.409	0.297	0.187	0.635	0.473
Spring	-0.156	0.010	0.014	0.045	0.064	0.164

Period	Mann-Kendall (1900-2024)		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
Jan	0.064	0.294	0.872	0.597	0.591	0.466
Feb	-0.031	0.611	0.369	0.462	0.631	0.753
Mar	-0.053	0.386	0.210	0.333	0.687	0.510
Apr	-0.040	0.512	0.035	0.041	0.587	0.634
May	-0.013	0.828	0.296	0.030	0.402	0.348
Jun	-0.082	0.173	0.663	0.593	0.580	0.579
Jul	0.010	0.869	0.241	0.335	0.454	0.400
Aug	-0.047	0.440	0.084	0.067	0.526	0.471
Sept	-0.114	0.060	0.062	0.070	0.023	0.076
Oct	-0.108	0.075	0.031	0.020	0.032	0.048
Nov	-0.002	0.976	0.473	0.531	0.852	0.899
Dec	0.025	0.679	0.489	0.646	0.920	0.906

### 3.4.2. Statistical analysis summary of other Marne Saunders Sites

Results of statistical analyses of rainfall records at the other 4 sites are provided in Appendix 7.2 and Appendix 7.3 and summarised below.

- Mann-Kendall analysis results show statistically **significant decreasing trend in long-term** (since 1900) in:
  - annual rainfall at Keyneton (23725) and Palmer (24525). While there is a decreasing trend, it is less significant at Cambrai Kongolia (24513) and Sedan (24531),
  - seasonal rainfall: Spring rainfall at Keyneton (23725) and Palmer (24525), Winter rainfall at Keyneton (23725) and Autumn rainfall at Palmer (24525) and
  - monthly rainfall: October rainfall Keyneton (23725) and Mt Pleasant (23737), being the highest impacted month.

Data on trend and level of statistical for all seasons and months for all the stations are provided in Appendix 7.2 and Appendix 7.3.

- 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 rainfall at Keyneton (23725) and Palmer (24525),
  - Spring rainfall at Keyneton (23725) and Palmer (24525); Autumn rainfall at Keyneton (23725), Palmer (24525) and Cambrai Kongolia (24513), and
  - October rainfall at all stations except at Sedan (24531) and September rainfall at Keyneton (23725) and Palmer (24525).

In the context of annual rainfall over WAP-related periods (from 1974 onwards), a statistically significant shift was observed for the month of October at all stations and for September at Keyneton (23725) and Palmer (24525).

# 4. Streamflow

## 4.1. 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 3.1. Analyses of streamflow records for the period 1974 to 2024 (where records were of usable quality) were undertaken using various methods primarily to investigate possible:

- trends in long-term annual, seasonal, monthly and daily streamflow data; and
- 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.

## 4.2. Marne River

Streamflow records from the Marne River at Marne Gorge (A4260605) gauging station for the period 1974 to 2024 were used in the analysis.

Streamflow data for the period 1974 to 2024 reflects the high variability, reaching peak discharge volumes of 33,552 ML (1974) and a minimum annual discharge of 0 ML (2018, 2019 & 2020) with the long-term annual median being 2,019 ML.

### 4.2.1. Data quality and usability

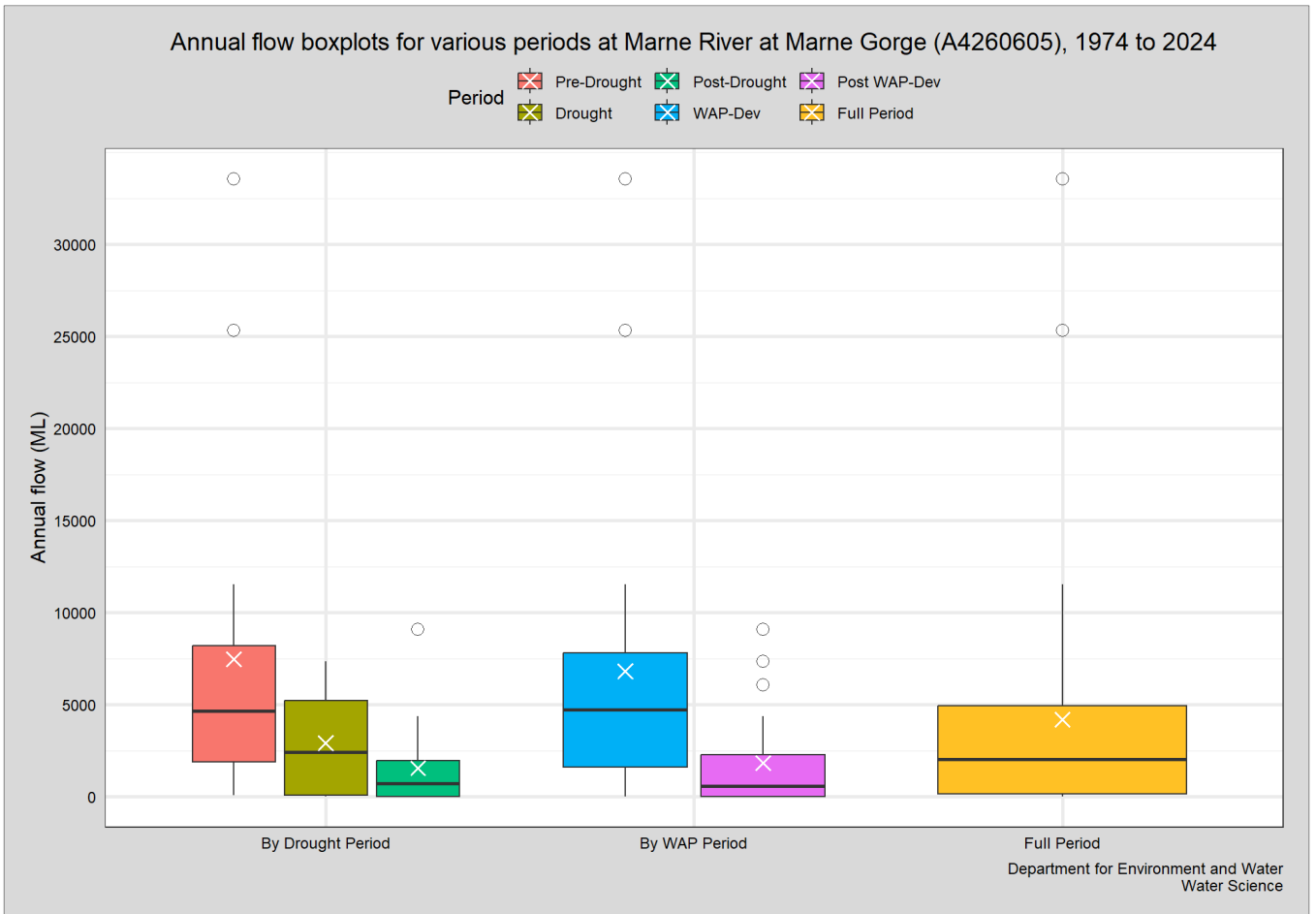
While data for the period 1974 to 2024 was used in the analysis, the following observations are to be noted regarding data quality and data used in the analysis.

- Years that had ‘good quality’ daily records during most of the flowing months but included some ‘missing’ or ‘unusable’ daily records during the drier months are displayed as hashed bars in the plots. All data in such years were used in the analysis.
- Years where majority of the data is ‘unavailable’ or ‘unusable’ due to poor data quality are displayed as yellow-coloured rectangles in all the plots. Data considered ‘unusable due to poor data quality’ were not used in any of the analysis. Based on these criteria, data for majority of the years in the period 1989-2000 were not included in the analysis.

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.

### 4.2.2. Annual streamflows

Figure 4.1 shows the distribution of annual streamflow at Marne Gorge (A4260605) for the various drought- and WAP- related periods as boxplots. Annual streamflow (median, mean and maximum) during the drought period was much lower than that during pre-drought period. **The range of annual flows and median annual flow during the post-drought period further declined and has remained significantly lower than the pre-drought and drought median.** Median annual flow in the post-WAP development period is also significantly lower than during the WAP development period.



**Figure 4.1. Distribution of annual streamflow totals for Marne River at Marne Gorge (A426060) for different periods during 1974 to 2022.**

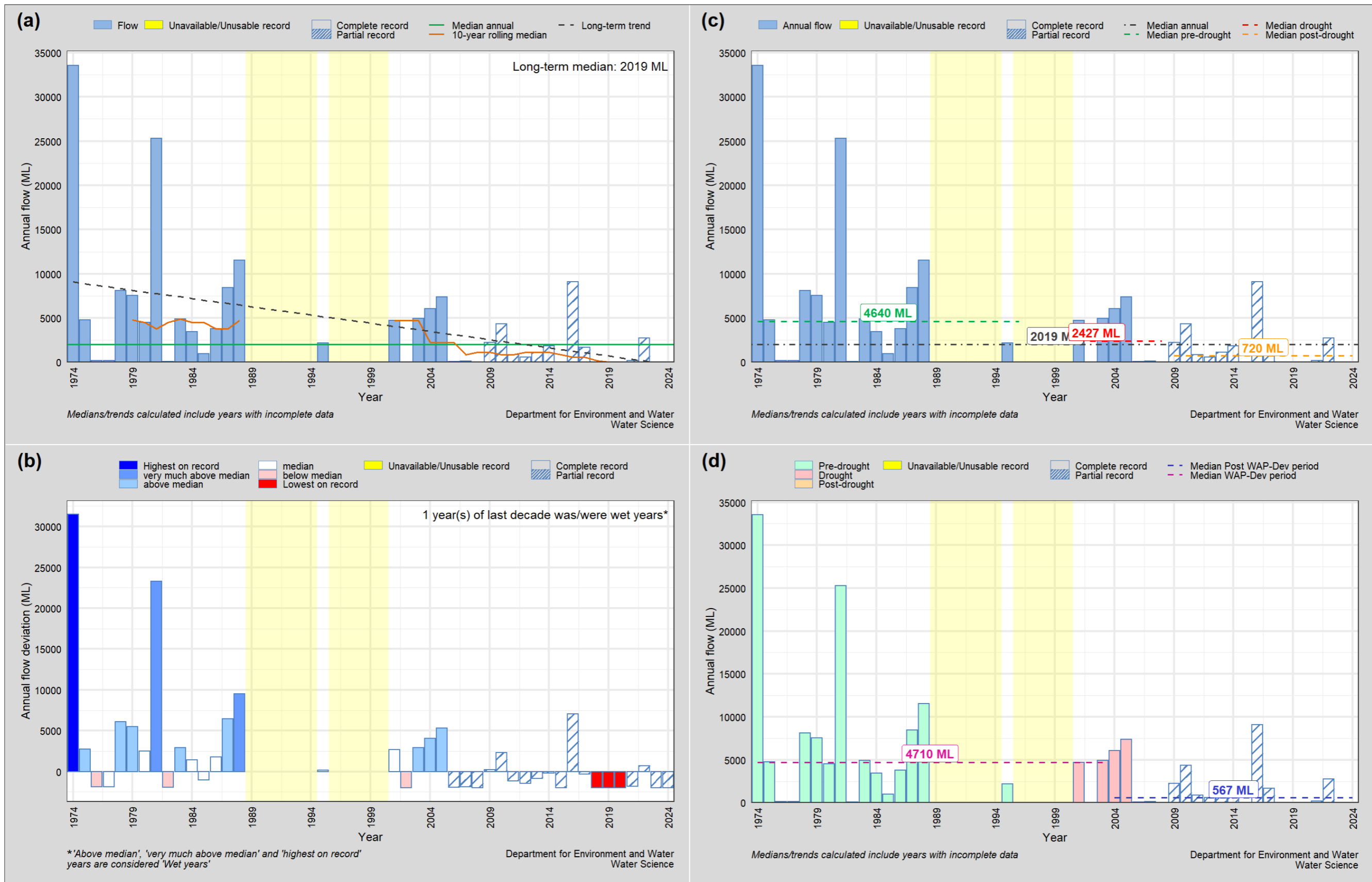
Median (—), average (X), and outliers (O) shown.

Figure 4.2 (a) shows a time series of annual streamflow totals for 1974 to 2024 with long-term median annual flow shown alongside a 10-year rolling average and long-term trend, both of which show a substantial decline in streamflow totals over the period of observation.

Figure 4.2 (b) shows annual deviations 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, compared to the pre-drought period. There was no flow recorded during three consecutive years in 2018, 2019 and 2020, followed by another ‘no-flow’ year in 2024, indicating a recent extremely dry spell.

Figure 4.2 (c) and Table 4.1 shows annual streamflow with median annual flows displayed for pre-drought, drought, and post-drought periods as well as the full period average. Results show that the median annual streamflow during the drought period was 2,213 ML (48%) lower than the pre-drought period. In the post-drought period, the median annual flow further declined by 1,708 ML and remained significantly below the pre-drought median by 3,920 ML (84%).

Figure 4.2 (d) and Table 4.2 show 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 2004 onwards) by 4142 ML (88%).



**Figure 4.2. (a) Annual streamflow totals for Marne River at Marne Gorge (A4260605) for 1974 to 2024, (b) Deviations in annual streamflow totals in Marne River at Marne Gorge (A4260605) from long-term median, (c) Annual streamflow totals for Marne River at Marne Gorge (A4260605) showing medians before and after the drought (1997 to 2008), (d) Annual streamflow totals for Marne River at Marne Gorge (A4260605) showing medians during WAP development (1974 to 2003) and during Post WAP-development.**

### 4.2.3. Seasonal streamflows

Results of analysis of streamflow records at the A4260605 station at seasonal time steps are summarised below in Table 4.1 and Table 4.2. Table 4.1 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 very small proportion of the annual totals, they are critical in keeping stream beds wet and maintaining in-stream ecosystem functionality.

Median winter and spring flows declined significantly during the Millenium drought period compared to the pre-drought period, and fell to zero in the post-drought period, reflecting continuous dry conditions. Summer and autumn flows constitute a minor share of the annual total with median flows during these seasons recorded as zero in both the drought and post-drought periods.

**Regarding recovery of seasonal flows to pre-drought conditions, none of the seasons have recovered to pre-drought conditions.** Median streamflow during the main flow seasons of winter and spring has dropped to zero, indicating a shift towards drier conditions with no signs of recovery yet.

**Table 4.1. Median annual and seasonal streamflow for Marne River at Marne Gorge (A4260605) across periods defined by the Drought**

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1974 to 2024)	(1974 to 1996)	(1997 to 2008)	(2009 to 2024)	Drought (ML (%))	Post-drought (ML (%))
Summer	3	5	0	0	-5 (-100%)	-5 (-100%)
Autumn	0	6	0	0	-6 (-100%)	-6 (-100%)
Winter	1057	2006	974	0	-1,032 (-51%)	-2,006 (-100%)
Spring	891	1477	1131	0	-347 (-23%)	-1,477 (-100%)
<b>Annual</b>	<b>2019</b>	<b>4640</b>	<b>2427</b>	<b>720</b>	<b>-2213 (-48%)</b>	<b>-3,920 (-84%)</b>

Table 4.2 summarises seasonal median flow for WAP development and post-WAP development periods. Streamflow has significantly declined across all seasons since WAP development with substantial reductions observed in winter and spring; the major flow seasons. Annual streamflow decreased by 88% with winter and spring flows declining by over 99%.

**Table 4.2. Median annual and seasonal streamflow for Marne River at Marne Gorge (A4260605) across periods representing WAP development**

Season	All years	WAP development	Post-WAP development	Change (WAP dev. to post-WAP dev.)	
	(1974 to 2024)	(1974 to 2003)	(2004 to 2024)	(ML)	(%)
Summer	3	5	0	-5	-100%
Autumn	0	6	0	-6	-100%
Winter	1057	1830	22	-1808	-99%
Spring	891	1720	7	-1712	-100%
<b>Annual</b>	<b>2019</b>	<b>4710</b>	<b>567</b>	<b>-4142</b>	<b>-88%</b>

## 4.2.4. 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 4.3 and Table 4.4 respectively. The monthly data shows median flow in each calendar month has declined sharply since the beginning of the drought. Similar to the seasonal streamflow data, winter and spring flows have reduced significantly with all months recording zero flow in the post-drought period. Notably, July, October, and November experienced substantial reductions, while September showed an increase during the Millennium drought before declining to zero post-drought. 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 4.3 Median monthly streamflow for Marne River at Marne Gorge (A4260605) for drought periods**

Season	All years	Pre-drought	Drought	Post-drought	Change from Pre-drought	
	(1900 to 2024)	(1900 to 1996)	(1997 to 2008)	(2009 to 2024)	Drought ML (%)	Post - drought ML(%)
Jan	0	1	0	0	-1 (-100%)	-1(-100%)
Feb	0	1	0	0	-1 (-100%)	-1(-100%)
Mar	0	2	0	0	-2 (-100%)	-2(-100%)
Apr	0	2	0	0	-2 (-100%)	-2(-100%)
May	0	2	0	0	-2 (-100%)	-2(-100%)
Jun	0	14	0	0	-13 (-100%)	-14(-100%)
Jul	30	435	68	0	-367(-84%)	-435(-100%)
Aug	508	813	586	0	-227(-28%)	-813(-100%)
Sep	394	735	1100	0	365(50%)	-735 (-100%)
Oct	67	141	29	0	-111(-79%)	-141(-100%)
Nov	3	10	1	0	-9(-93%)	-10(-100%)
Dec	1	2	0	0	-2(-100%)	-2(-100%)
<b>Annual</b>	<b>2019</b>	<b>4640</b>	<b>2427</b>	<b>720</b>	<b>-2213 (-48%)</b>	<b>-3920 (-84%)</b>

**Table 4.4 Median monthly streamflow for Marne River at Marne Gorge (A4260605) for WAP periods**

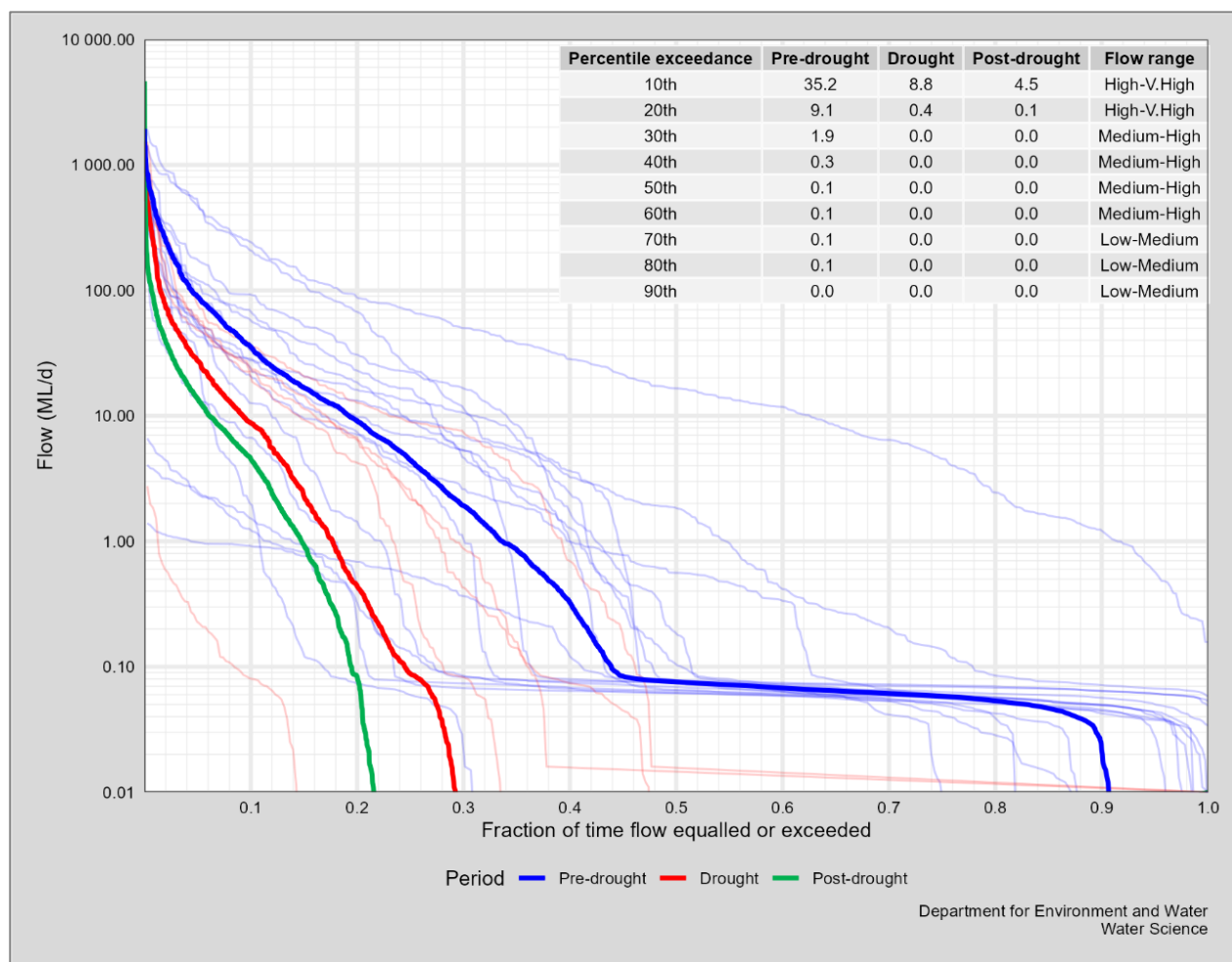
Month	All years	WAP development	Post-WAP development	Change (WAP dev. to post-WAP dev.)	
	(1974 to 2022)	(1974 to 2003)	(2004 to 2024)	(ML)	(%)
Jan	0	1	0	-1	-100
Feb	0	1	0	-1	-100
Mar	0	2	0	-2	-100
Apr	0	2	0	-2	-100
May	0	2	0	-2	-100
Jun	0	9	0	-9	-100
Jul	30	246	0	-246	-100
Aug	508	599	6	-594	-99
Sep	394	775	0	-775	-100
Oct	67	140	0	-140	-100
Nov	3	11	0	-11	-100

Month	All years	WAP development	Post-WAP development	Change (WAP dev. to post-WAP dev.)	
	(1974 to 2022)	(1974 to 2003)	(2004 to 2024)	(ML)	(%)
Dec	1	2	0	-2	-100
Annual	2019	4710	567	-4142	-88

### 4.2.5. 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 4.3 show that:

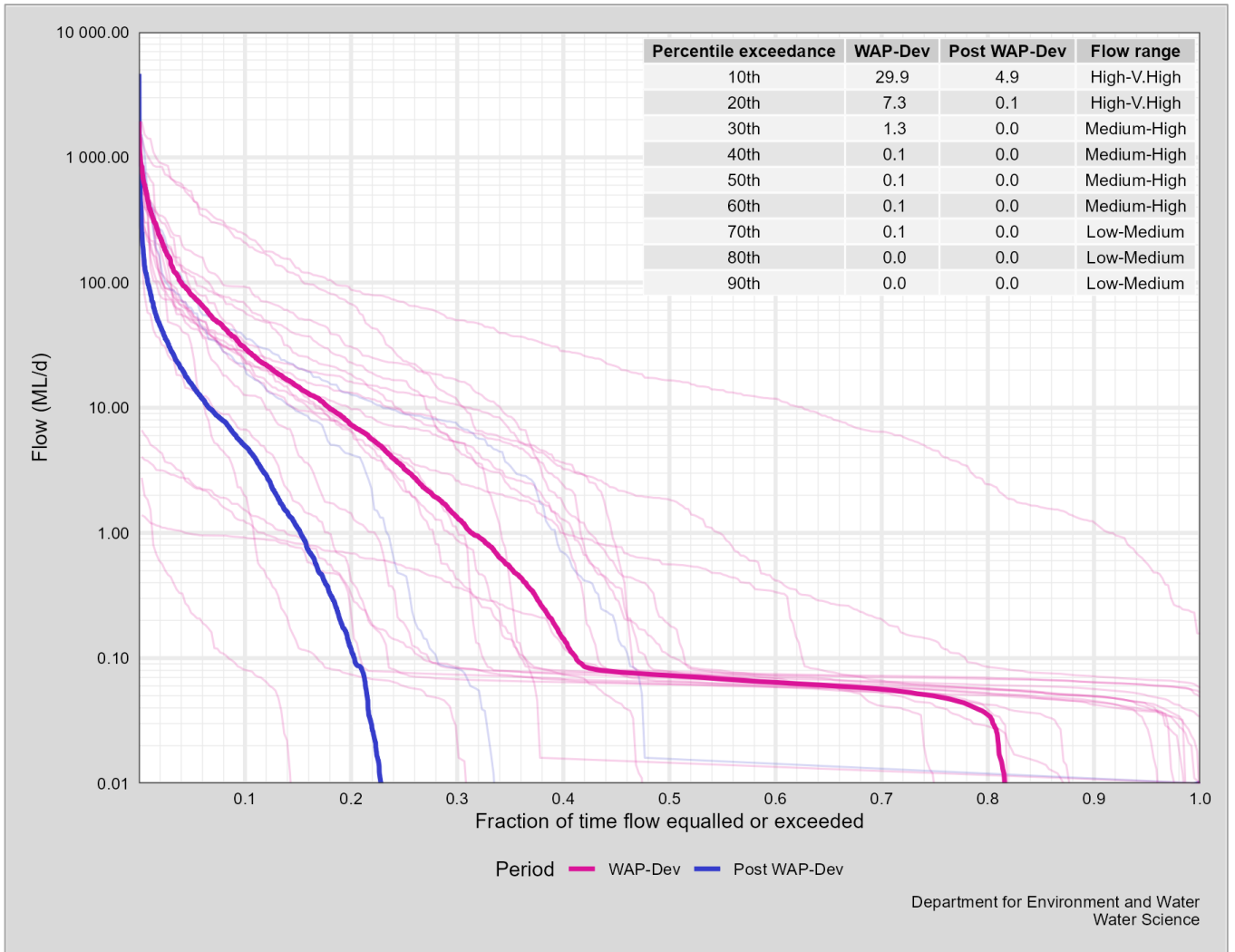
- all flow ranges have been affected since the beginning of the drought with post-drought flows being lowest of the three drought-related periods; and
- the average number of flowing days per year in the Marne River declined significantly during the Millennium drought, decreasing by more than 60% (around 200 days), with further reduction observed in the post-drought period. In addition, there has been a marked reduction in low flows (flows < 0.1 ML/d) since the onset of the drought, indicating **substantial impacts on surface-groundwater interactions** and hydrological connectivity with subsequent ecological impacts. Overall, these changes mean the river channel has been **wet for much less** of the time than it was before the drought.



**Figure 4.3. Daily flow exceedance curves for Marne River at Marne Gorge (A4260605) for periods related to the drought**

Figure 4.4 shows the distribution of daily flow for the WAP development period and for the post-WAP development period since 2004 with both distributions summarised. The results are similar to those observed during the drought related periods presented previously.

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 WAP. The results presented here provide further **evidence of alteration of the flow regime since the beginning of the drought** and during the post-WAP development period.



**Figure 4.4. Flow duration curves for daily flow in Marne River at Marne Gorge (A4260605) for periods related to the WAP development periods**

## 4.3. Saunders Creek

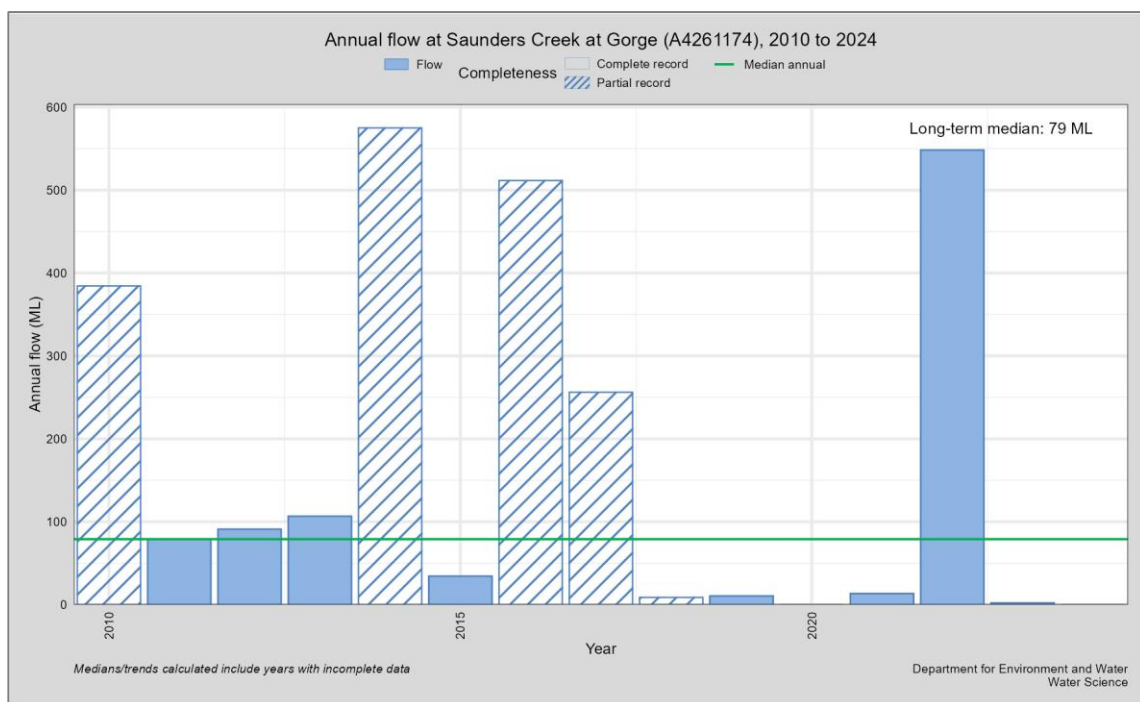
### 4.3.1. Data quality and usability

Streamflow data for Saunders Creek Gorge (A4261174) were analysed for the period 2010 to 2024 as data are only available from August 2009. The following observations are to be noted regarding data quality and data used in the analysis.

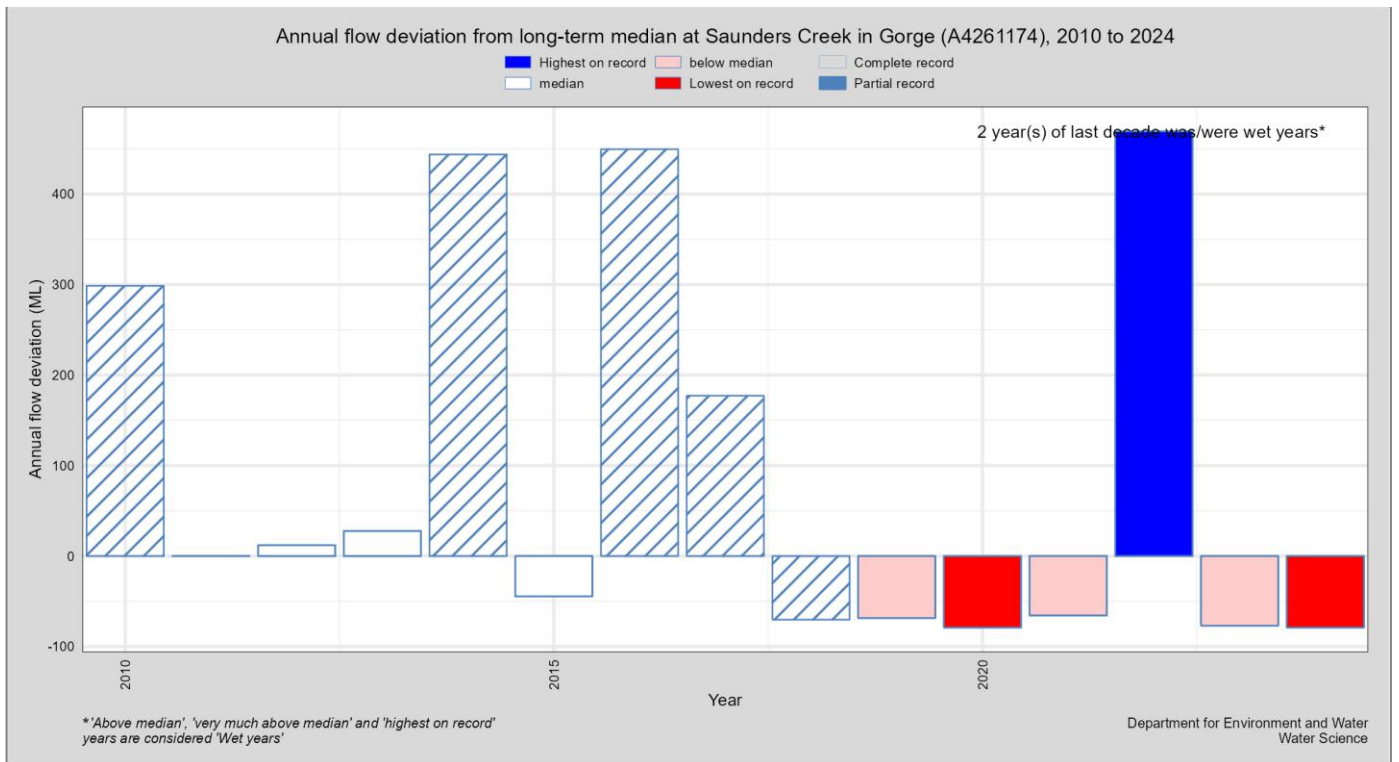
- Streamflow records for Saunders Creek catchment are limited to the post-drought and post-WAP period. Hence, analyses of data across different drought and WAP-development periods were not undertaken for this station.
- Years that had 'good quality' daily records during most of the flowing months but included some 'missing' or 'unusable' daily records during the drier months are displayed as hashed bars in the plots. All data in such years were used in the analysis.
- Years where majority of the data are 'unavailable' or 'unusable' due to poor data quality are displayed as yellow-coloured rectangles in all the plots. Data considered 'unusable due to poor data quality' were not used in any of the analysis. Based on these criteria years in seasonal and monthly flow were not included in the analysis.

### 4.3.2. Annual streamflows

Figure 4.5 shows a time series of annual streamflow totals for 2010 to 2024 and the median annual flow for this period is 79 ML/yr. Figure 4.6 shows deviations of annual rainfall from the period median. Apart from wet years in 2016 and 2022, recent decades have shown a greater number, and higher frequency, of below-median streamflow years. No flow was recorded in 2020 and again in 2024 with similarly dry conditions in 2018, 2019, 2021, and 2023 where annual flow remained below 15 ML. This pattern indicates a prolonged dry spell in recent years which is similar to conditions experienced in the Marne River catchment.



**Figure 4.5. Annual streamflow totals at Saunders Creek in Gorge (A4261174) 2010- 2024**



**Figure 4.6. Deviations in annual streamflow totals at Saunders Creek in Gorge (A4261174) from long-term median**

### 4.3.3. Seasonal streamflows

Figure 4.7 shows the seasonal streamflow totals from 2010 to 2024, alongside the long-term median annual flow. Both summer and autumn show a long-term median of zero flow, similar to the post-drought behaviour observed in the Marne River catchment. The highest streamflow volumes were recorded during winter. The highest total annual streamflow on record occurred in 2022 (Figure 4.6) with spring contributing the majority of the seasonal flow volume.

Streamflow in summer, autumn, and winter shows a drying trend, while spring shows a possible increase, likely driven by high flow in 2022. Further investigation is required to determine whether this reflects an actual shift or an isolated event.

### 4.3.4. Monthly streamflows

The distribution of monthly streamflow for the Saunders Creek catchment is presented in Appendix 7.8. All months, except October and November, show a declining trend, following a consistent pattern with seasonal trends.

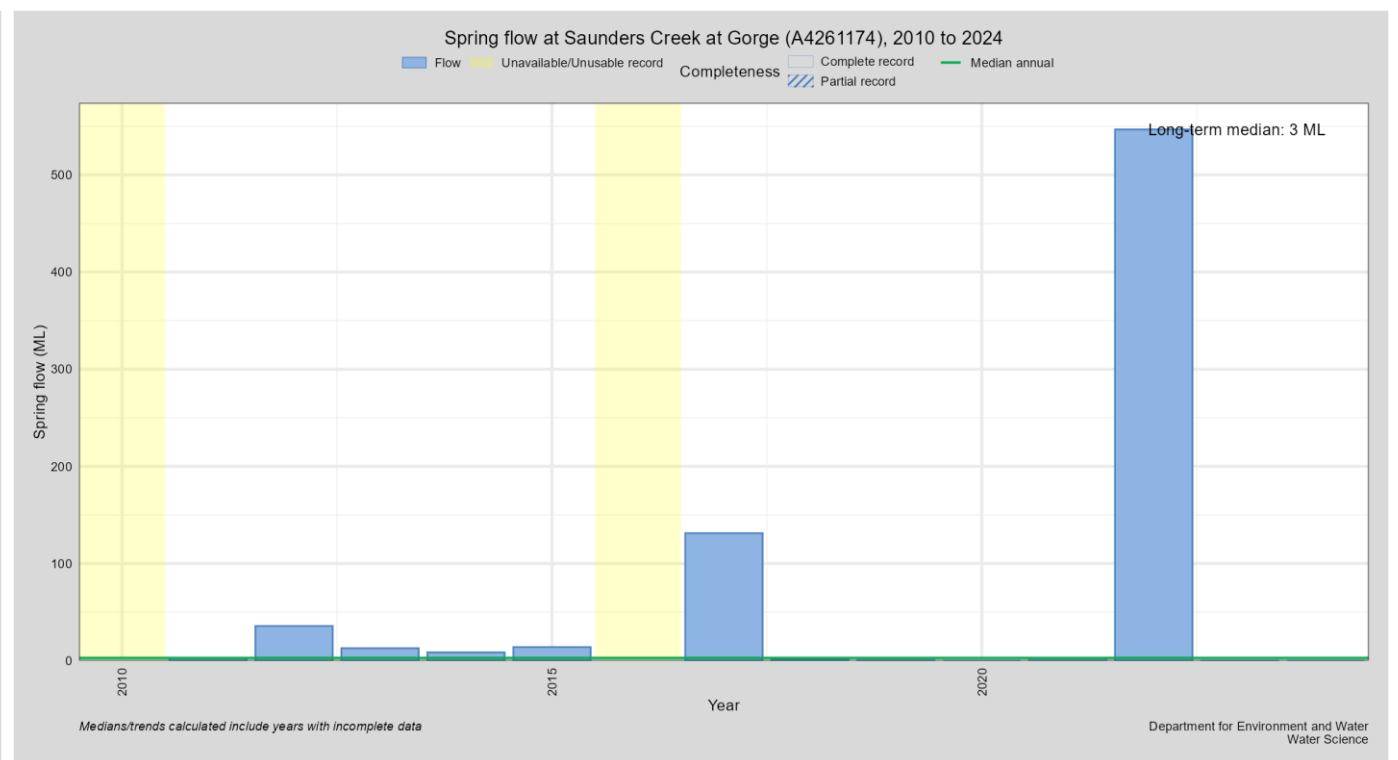
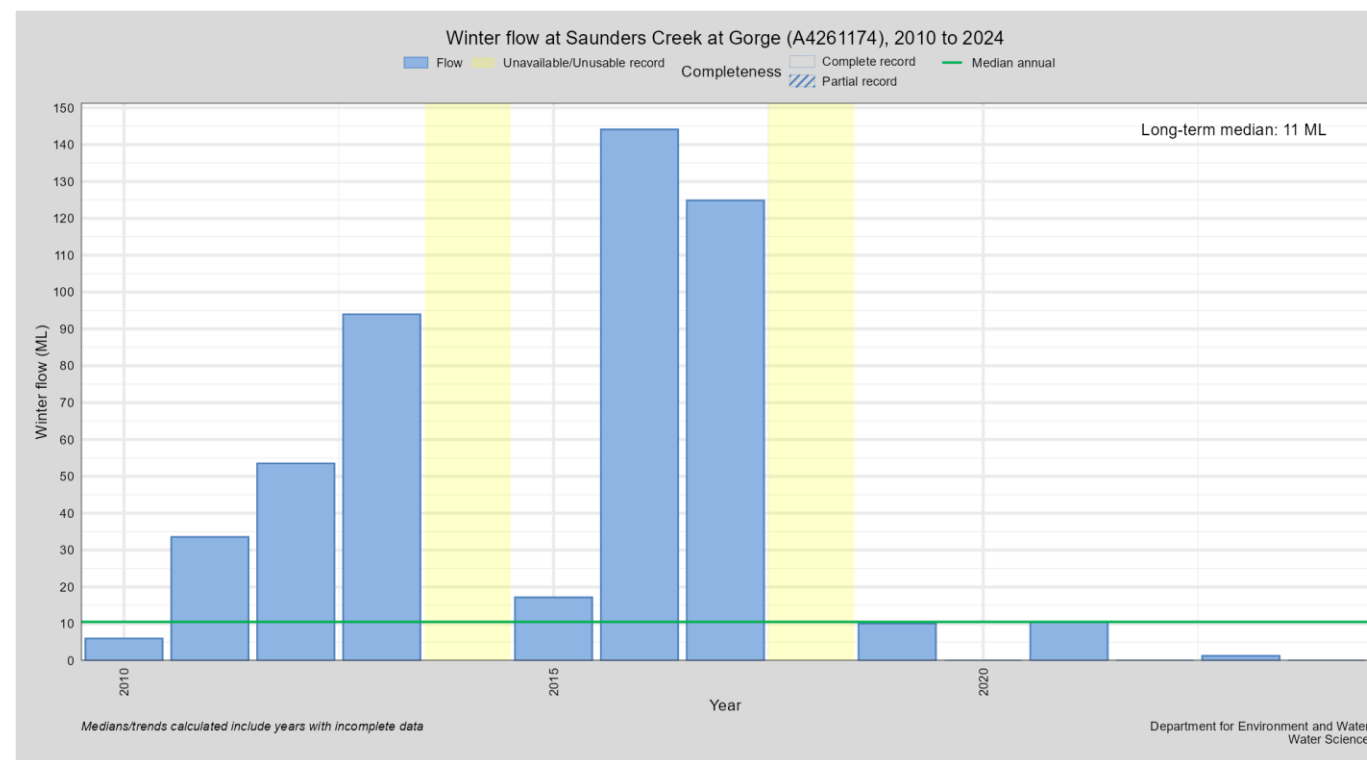
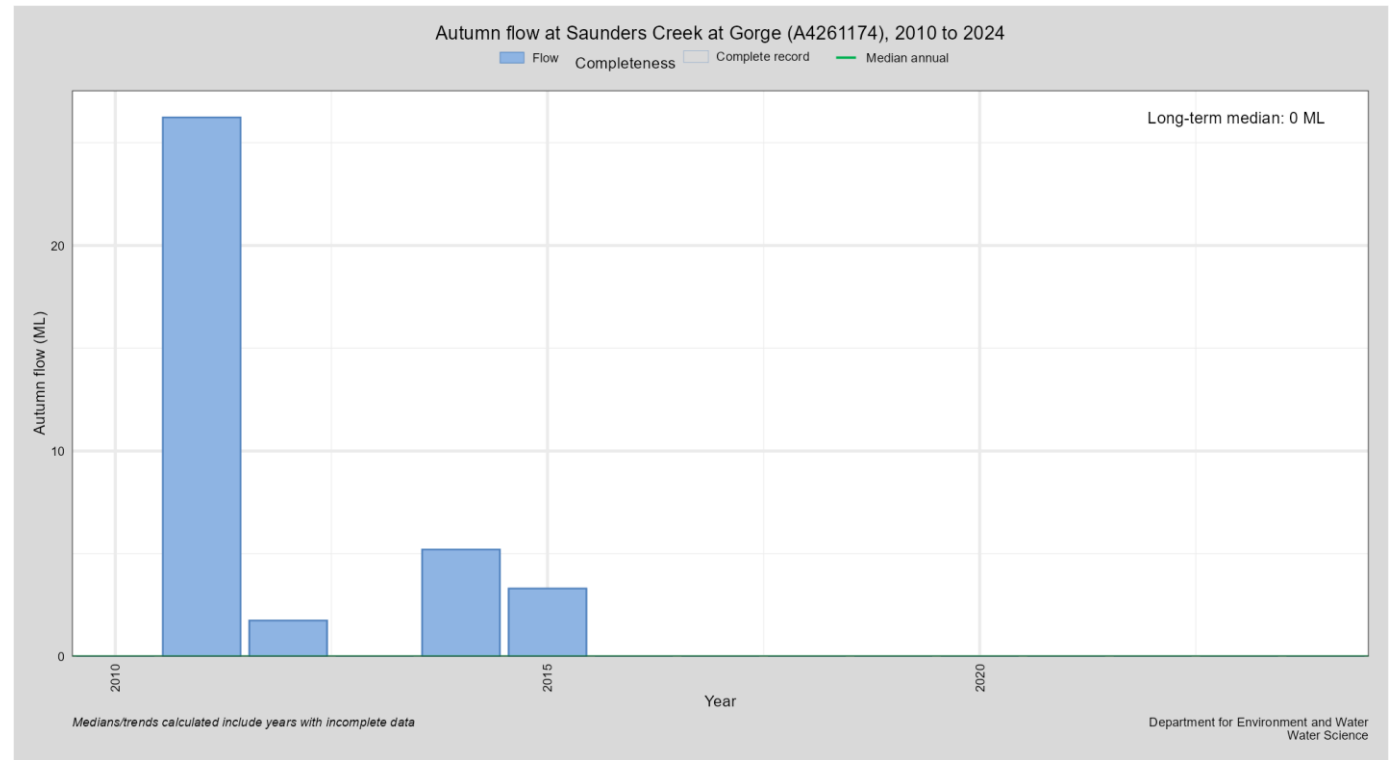
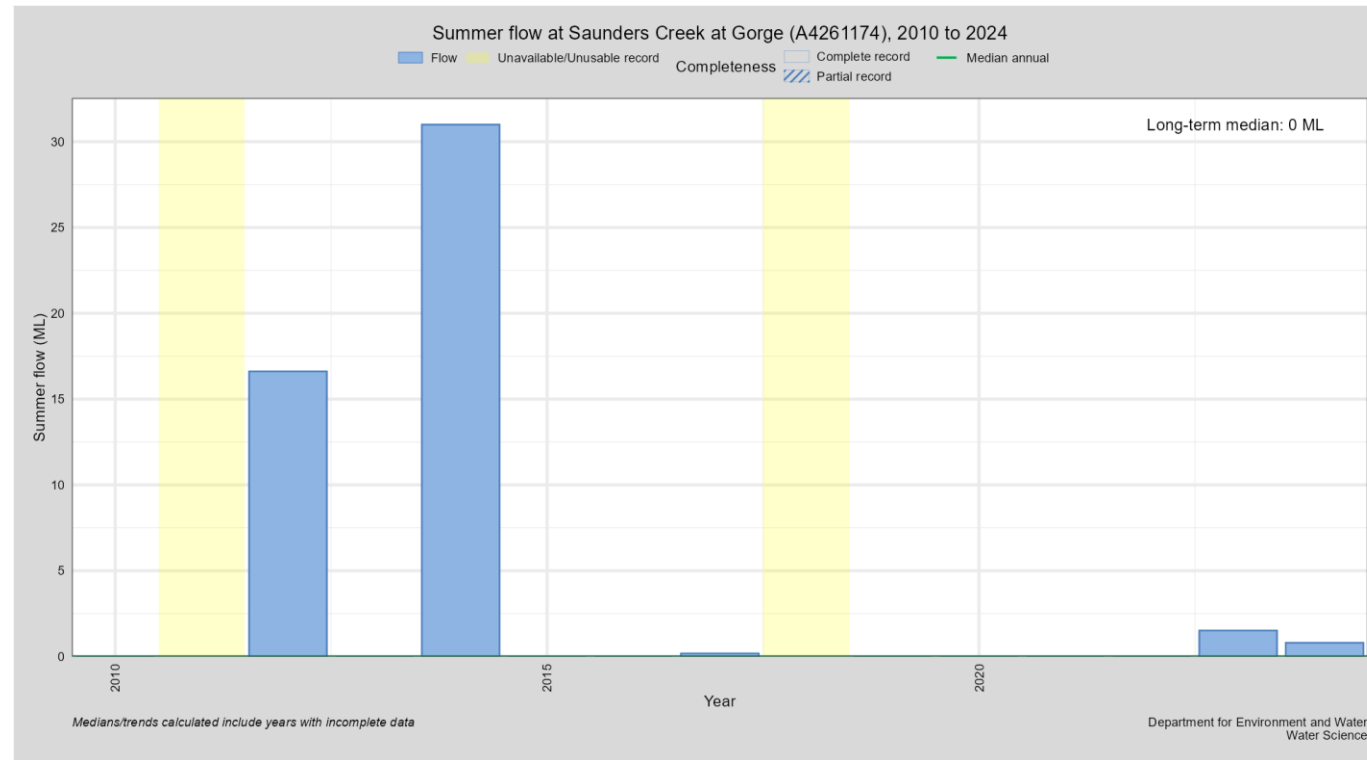


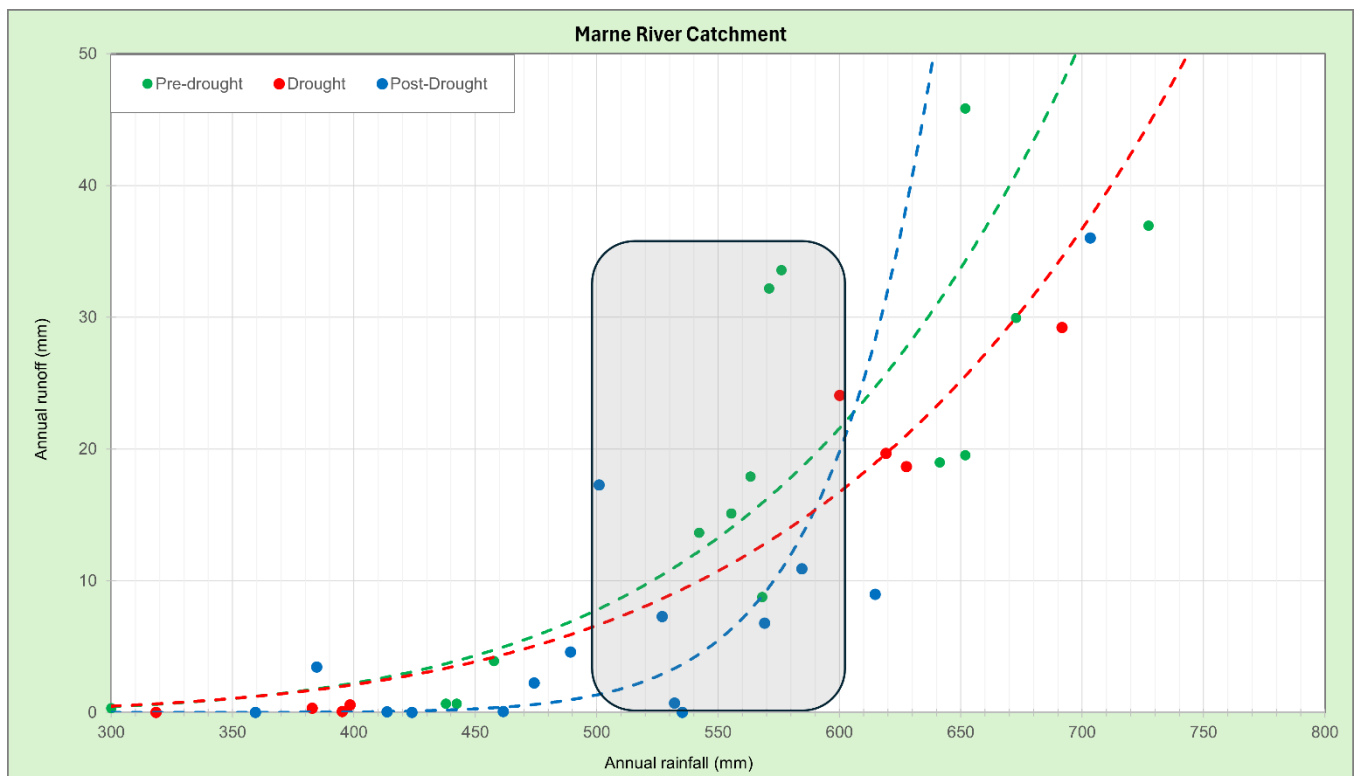
Figure 4.7. Seasonal streamflow totals at Saunders Creek in Gorge (A4261174) 2010- 2024

# 5. Rainfall–runoff response

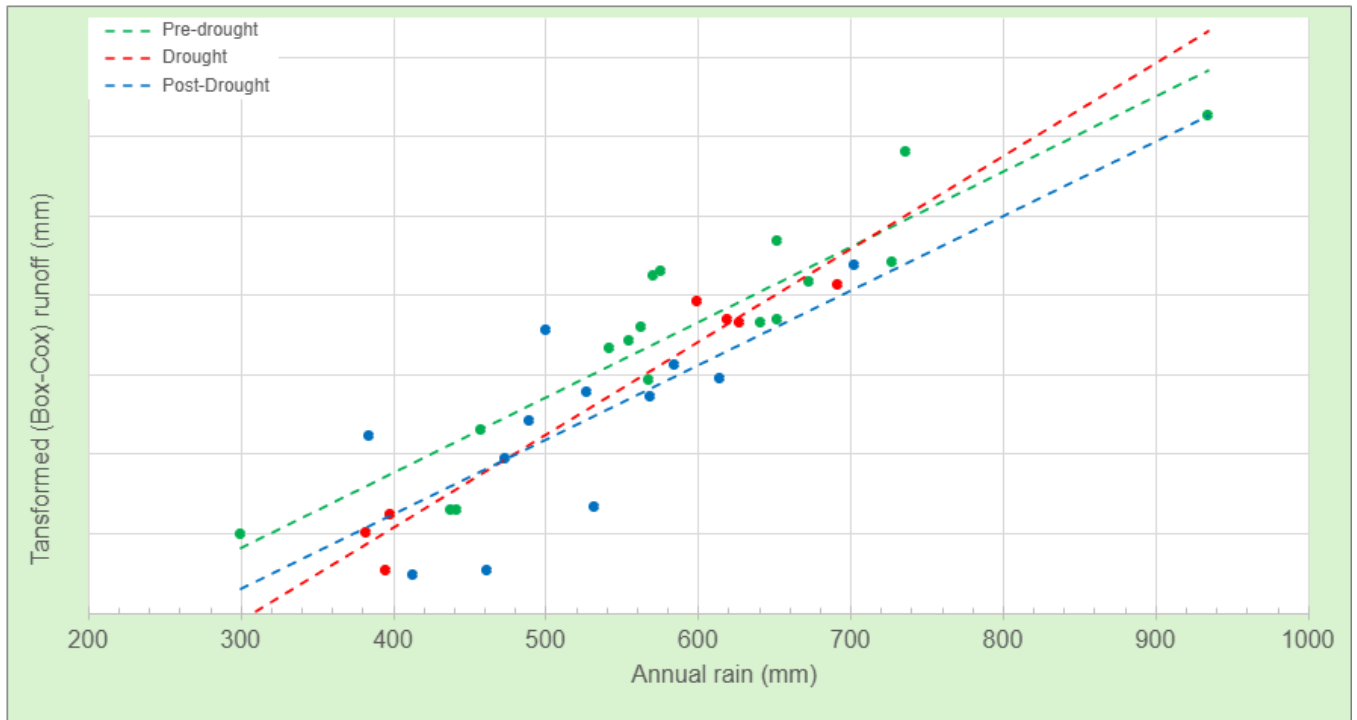
Likely shifts in rainfall patterns across different Millennium drought and WAP development-related periods are discussed in the previous sections. Additional investigation into the effects of shift in rainfall patterns on catchment rainfall–runoff response is provided in this section.

Runoff response to annual rainfall totals for the catchment area upstream of the streamflow gauging station Marne River at Marne Gorge (A4260605) is presented in Figure 5.1. The plot presents a series of data points, each representing observed rainfall–runoff value for a given year, noting that runoff is converted from megalitres to millimetres (refer to Section 2.6 for further details). The full 51-year period of record from 1974 to 2024, where data for individual years were considered ‘usable’ (refer to section 4.2.1), 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 (green), Millennium drought (red) or post-drought (blue). Figure 5.2 shows the same annual rainfall-runoff relationship but presented as linear plots by converting runoff data using Box-Cox function transformation.

Inspection of the plots in Figure 5.1 and Figure 5.2 show a clear difference in runoff response for a given amount of annual rainfall during the three drought-related periods. The annual runoff observed for a given annual rainfall amount is generally the highest for pre-drought (green) years, lowest for drought (red) years with data for the post-drought (blue) years lacking any pattern or correlation to the other drought related periods. The data indicates significant reduction in runoff generation during drought period when compared to pre-drought years. A further reduction in annual runoff generated is evident during the post-drought years. For lower rainfall years (less than 500 mm/yr), runoff in post-drought years consistently falls below pre-drought as well as drought levels. This behaviour is also observed during the average (500mm to 600mm – displayed within the grey box in the chart) rainfall years, suggesting a lasting change (or shift) in catchment response rather than a return to pre-drought conditions.



**Figure 5.1. Rainfall-runoff plots for Marne River Catchment (using tanh function)**



**Figure 5.2. Rainfall-runoff plots for Marne River catchment (using Box-Cox transformation)**

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 groundwater resources in the Marne Saunders Prescribed Water Resources Area (PWRA) are assumed to have ceased following the 1999 moratorium. However, significant farm dam development occurred in the Marne catchment during the 1990s with total dam capacity more than doubling between 1991 and 1999 (Savadamuthu, 2022). This expansion is likely to have contributed to reduced runoff, particularly low flows, during the late pre-drought (1974–1996) and drought (1997–2008) periods.

The altered rainfall-runoff response observed during the drought can possibly be attributed to both climatic changes and increased dam storage. Although post-drought rainfall was lower than in the pre-drought period, it exceeded drought-period levels. Nevertheless, runoff during the post-drought period was lower than during the drought, suggesting that changes in rainfall patterns, rather than further dam development, were the primary driver of the shift in rainfall-runoff response in the post-drought period.

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. In summary, there is sufficient evidence to suggest that the underlying rainfall-runoff response of Marne River catchment has potentially changed (or shifted) in the period since the Millennium drought with the shift in the post-drought period primarily due to changed rainfall patterns.

It is uncertain, currently, 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 – 2003 with one rainfall-runoff relationship developed for the entire period used in deriving resource capacities in the WAP. Given the observed shift in rainfall-runoff response identified since the start of the drought, 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. Summary, conclusions and discussion

## 6.1. Rainfall

**Overview:** Rainfall records from five BoM stations located within (and in the vicinity) of the Marne Saunders Prescribed Water Resources Area (PWRA) were analysed using a range of methodologies to assess long-term trends, identify periodic shifts within the historical record, and evaluate the impacts of drought on both total rainfall and seasonal distribution. Although data from all five stations were included in the analysis, records from Mt Pleasant (23737) and Keyneton (23725) ('the two key stations') are of primary relevance for understanding runoff generation within the catchment. This is due to their representation of rainfall patterns in the higher-rainfall, headwater regions of the catchment.

**Summary:** Overall, data from the five stations demonstrate a steep west-to-east downward rainfall gradient and the high temporal variability of historical rainfall across the PWRA. Some of the key results of the analyses of rainfall records from the two key stations are summarised below.

### Trends and shifts in long-term data

- Long-term trend (*Mann-Kendall test*): Statistically significant declining trend was observed in long-term (1900-2024) annual, spring season and October rainfall at both stations.
- CUSUM plots: Annual CUSUM plots for both stations show no data points outside the action bounds, except for a high rainfall period in the 1920s–1930s exceeding the upper limit. From the mid-1990s onward, most data points fall below the long-term mean, indicating a general downward shift in annual rainfall with occasional wet years. Winter records mostly reflect the annual trend with Autumn and Spring (to a lesser degree) being the highest impacted since the mid-1990s at both stations
- Shifts in rainfall (*Wilcoxon and Welch's tests*): Evidence of statistically significant shifts were identified between:
  - pre- and post-1996 periods, in annual, seasonal (autumn and spring) and monthly (August, September and October) rainfall at both stations; and
  - WAP development and post-WAP development periods, in seasonal (spring) and monthly (September and October) rainfall.

### Recovery status (drought periods)

- Seasonal – Spring rainfall is the highest impacted with post-drought median rainfall being the lowest ('driest') amongst the drought-related periods at both stations. Rainfall during the winter and autumn seasons have also been impacted – although to a lesser extent than Spring – since the beginning of the Millennium drought with both stations falling in the 'Partially recovered' category during the post-drought period.
- Annual - When considering annual totals, both stations have 'partially recovered' during the post-drought period.

**Conclusion:** Overall, seasonal rainfall during spring (predominantly in October) and autumn to a lesser degree (in April) has undergone a statistically significant shift since the start of the drought (since 1997) at both stations. There is also evidence of decline in long-term annual rainfall (since 1920).

## 6.2. Streamflow

**Overview:** Streamflow records from long-term gauging stations in the Marne and Saunders catchments within the Prescribed Water Resources Areas (PWRAs) reveal a highly variable and declining streamflow regime. In particular, the Marne River catchment has experienced a steady reduction in annual streamflow since 1974, when flow measurements started, with only a few exceptions during particularly wet years such as 2016 and 2022. Notably, no streamflow was recorded for three consecutive years—2018, 2019, and 2020—and again in 2024. The past two decades have also seen a marked increase in the frequency of below-median streamflow years compared to the pre-drought period.

**Marne River Catchment:** A comparative analysis of annual, seasonal, and monthly streamflow across three drought-related periods and two WAP development periods provides valuable insights into the extent of catchment recovery since the Millennium drought and the development of the WAP.

Annual streamflow metrics - including median, mean, and maximum flows - were significantly lower during the drought period than in the pre-drought years. Following the drought, streamflow declined even further with post-drought median annual flows remaining well (-84%) below both pre-drought and drought levels. The post-WAP development period also recorded lower median annual flows (-88%) compared to the WAP development period, indicating a continued trend of reduced streamflow.

Seasonal analysis shows that median winter and spring flows, which typically contribute to most of the annual streamflow, declined sharply during the drought and dropped to zero in the post-drought period. This reflects persistent dry conditions. Summer and autumn flows contribute to only a minor portion of the annual total, and median flows during these seasons were recorded as zero during both the drought and post-drought periods. Since the WAP was developed, streamflow has declined across all seasons with the most substantial reductions observed in winter and spring. Median flows in these seasons dropped to zero, indicating a shift towards increasingly dry conditions.

Monthly streamflow data further supports these findings. Median flows in each calendar month have declined significantly since the onset of the drought. In the post-drought period, all months recorded zero median flow. July, October, and November experienced particularly sharp reductions, while September showed a temporary increase during the drought before declining to zero post-drought. Approximately 75% of annual flow in each period was concentrated in the three-month window from July to September, making reductions during these months especially impactful on overall annual flow volumes.

Daily flow records reveal that all flow ranges have been affected since the beginning of the drought. The average number of flowing days per year in the Marne River catchment decreased by more than 60% - equivalent to a reduction of approximately 200 days - during the Millennium drought with further declines observed in the post-drought period. Similar patterns were evident when comparing daily flows between the two WAP-related periods. These results suggest a significant reduction in the proportion of time that streambeds remain wet, which has implications for both hydrological and ecological conditions.

Key metrics such as the number of flowing days and the distribution of low, medium, and high flows are essential for characterising the flow regime of a catchment. These metrics also inform environmental water requirements used to assess ecosystem needs under the WAP. The observed changes provide strong evidence of a substantial alteration in the flow regime since the onset of the Millennium drought and during the post-WAP development period

**Saunders Creek catchment:** Due to limited streamflow data availability for Saunders Creek (records only available from 2010), a detailed comparative analysis of drought-related and WAP development periods could not be undertaken. However, the available records indicate an extended period of very dry conditions, consistent with trends observed in the Marne River catchment.

**Conclusion:** In summary, streamflow in the Marne River catchment has been in decline since 1974, when flow measurements started, with the past few decades characterised by prolonged and extremely dry

conditions. Post-drought streamflow levels are lower than those recorded during both the pre-drought and drought periods, indicating that the catchment is yet to recover. Winter and spring flows have declined significantly, and the data provides compelling evidence of a major shift in flow patterns since the onset of the Millennium drought.

### 6.3. Rainfall-runoff response

**Overview:** For the 51-year period of record from 1974 to 2024, streamflow data for individual years (that were considered ‘usable’) and catchment-averaged rainfall data were plotted and generalised rainfall-runoff relationships using a TanH function and a second one using a Box-Cox transformation function were fitted for the three drought-related periods.

**Summary:** Results of rainfall-runoff response analysis show a clear difference in runoff response for a given amount of annual rainfall during the three drought-related periods. A significant reduction in runoff generation was observed during Millennium drought period when compared to pre-drought years. A further reduction in annual runoff generated is evident during the post-drought years. For lower rainfall years (less than 500 mm/yr), runoff in post-drought years consistently falls below pre-drought as well as drought levels. This behaviour is also observed during the average (500mm to 600mm) rainfall years, suggesting a lasting change (or shift) in catchment response rather than a return to pre-drought conditions.

**Interpretation:** New capture, diversion, and extraction of surface and groundwater resources in the Marne Saunders Prescribed Water Resources Area (PWRA) are assumed to have ceased following the 1999 moratorium. However, significant farm dam development occurred in the Marne catchment during the 1990s with total dam capacity more than doubling between 1991 and 1999 (Savadamuthu, 2022). This expansion is likely to have contributed to reduced runoff, particularly low flows, during the late pre-drought (1974–1996) and Millennium drought (1997–2008) periods.

The altered rainfall-runoff response observed during the Millennium drought likely reflects both climatic changes and increased dam storage. While post-drought rainfall exceeded drought-period levels, it remained below pre-drought levels. However, post-drought runoff was lower than during the Millennium drought, suggesting that changes in rainfall patterns—rather than further dam development—were the primary driver of reduced runoff efficiency in the post-drought period.

**Conclusion:** In summary, there is sufficient evidence to suggest that the underlying rainfall–runoff response of Marne River catchment has potentially changed (or shifted) in the period since the Millennium drought with the shift in the post-drought period primarily due to changed rainfall patterns. It is uncertain, currently, 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).

The shift in catchment rainfall-runoff response observed in the Marne River catchment since the onset of the drought was also observed in other catchments in the neighbouring Barossa PWRA (Savadamuthu et al. 2022) and Mount Lofty Ranges (MLR) PWRAs (Savadamuthu et al. 2024).

**Recommendation:** 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 (which may not be evident as surface flow) 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 – 2003 with one rainfall-runoff relationship developed for the entire period used in

deriving resource capacities in the WAP. Given the observed shift in rainfall-runoff response identified since the start of the Millennium drought, recalibration of the model to include recent streamflow data (to include this shift (or non-stationarity)) is recommended for future use of the model, including while amending the WAP. 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, Barossa PWRA (Savadamuthu et al. 2022) and MLR PWRAs (Savadamuthu et al. 2024). In the case of the Marne River and Saunders Creek catchments, whether this observed shift in rainfall patterns (and the implied change to rainfall–runoff response) is temporary or reflective of the near-future<sup>2</sup> 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 Marne River catchment, 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 the 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 WAP.

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<sup>2</sup> 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

Table 7.1. 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)	(%)	
KEYNETON	23725	Marne River	Marne Saunders	535	471	479	-63	-12	-55	-10	Partially recovered
MOUNT PLEASANT	23737	Marne River / Saunders Creek	Marne Saunders	651	560	638	-91	-14	-13	-2	Partially recovered
CAMBRAI KONGOLIA	24513	Marne River	Marne Saunders	283	282	278	-1	0	-4	-2	Yet to recover
SEDAN	24531	Marne River	Marne Saunders	295	306	281	11	4	-14	-5	Yet to recover
PALMER	24525	Saunders Creek	Marne Saunders	416	335	380	-82	-20	-36	-9	Partially Recovered

Table 7.2. 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)	(%)	
KEYNETON	23725	Marne River	Marne Saunders	210	168	182	-42	-20	-27	-13	Partially recovered
MOUNT PLEASANT	23737	Marne River / Saunders Creek	Marne Saunders	267	248	257	-19	-7	-10	-4	Partially recovered
CAMBRAI KONGOLIA	24513	Marne River	Marne Saunders	85	81	78	-3	-4	-6	-7	Yet to recover
SEDAN	24531	Marne River	Marne Saunders	90	103	86	13	14	-4	-4	Yet to recover
PALMER	24525	Saunders Creek	Marne Saunders	148	127	146	-21	-14	-1	-1	Partially recovered

Table 7.3. 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)	(%)	
KEYNETON	23725	Marne River	Marne Saunders	138	106	97	-32	-23	-42	-30	Yet to recover
MOUNT PLEASANT	23737	Marne River / Saunders Creek	Marne Saunders	174	136	126	-38	-22	-48	-28	Yet to recover
CAMBRAI KONGOLIA	24513	Marne River	Marne Saunders	75	69	65	-7	-9	-10	-14	Yet to recover
SEDAN	24531	Marne River	Marne Saunders	83	69	72	-15	-18	-11	-13	Partially recovered
PALMER	24525	Saunders Creek	Marne Saunders	110	78	85	-32	-29	-24	-22	Partially recovered

Table 7.4. 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)	(%)	
KEYNETON	23725	Marne River	Marne Saunders	109	79	104	-30	-27	-5	-4	Partially recovered
MOUNT PLEASANT	23737	Marne River / Saunders Creek	Marne Saunders	140	105	135	-36	-25	-5	-3	Partially recovered
CAMBRAI KONGOLIA	24513	Marne River	Marne Saunders	59	48	64	-12	-20	5	8	Recovered
SEDAN	24531	Marne River	Marne Saunders	62	43	56	-18	-30	-5	-9	Partially recovered
PALMER	24525	Saunders Creek	Marne Saunders	82	55	68	-26	-32	-13	-16	Partially recovered

Table 7.5. 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)	(%)	
KEYNETON	23725	Marne River	Marne Saunders	53	80	43	27	51	-10	-19	Yet to recover
MOUNT PLEASANT	23737	Marne River / Saunders Creek	Marne Saunders	65	68	68	3	4	3	5	Recovered
CAMBRAI KONGOLIA	24513	Marne River	Marne Saunders	45	66	48	22	48	3	7	Recovered
SEDAN	24531	Marne River	Marne Saunders	38	66	50	29	77	13	34	Recovered
PALMER	24525	Saunders Creek	Marne Saunders	52	59	49	7	12	-3	-6	Yet to recover

## 7.2. Mann-Kendall Test results

Table 7.6. Mann-Kendall Test results for rainfall sites in Marne- Saunders PWRA (1900 to 2024)

Period	Keyneton (23725)		Mount Pleasant (23737)		Cambrai Kongolia (24513)		Sedan (24531)		Palmer (24525)	
	tau	p-val	tau	p-val	tau	p-val	tau	p-val	tau	p-val
Annual	-0.140	0.021	-0.105	0.082	-0.015	0.811	-0.014	0.818	-0.109	0.072
Summer	0.042	0.493	0.054	0.371	0.097	0.109	0.092	0.130	0.071	0.241
Autumn	-0.063	0.302	-0.069	0.254	-0.022	0.722	-0.045	0.460	-0.108	0.075
Winter	-0.123	0.042	-0.050	0.409	-0.100	0.100	-0.042	0.492	-0.069	0.256
Spring	-0.132	0.029	-0.156	0.010	-0.028	0.643	-0.049	0.420	-0.128	0.035
January	0.035	0.571	0.064	0.294	0.047	0.445	0.070	0.252	0.114	0.060
February	-0.011	0.854	-0.031	0.611	0.011	0.864	0.029	0.631	0.001	0.990
March	-0.024	0.690	-0.053	0.386	-0.043	0.484	-0.042	0.485	-0.087	0.150
April	0.012	0.843	-0.040	0.512	0.030	0.617	0.062	0.305	-0.012	0.849
May	-0.066	0.279	-0.013	0.828	-0.043	0.475	-0.047	0.439	-0.052	0.389
June	-0.110	0.070	-0.082	0.173	-0.116	0.056	-0.083	0.171	-0.068	0.264
July	-0.029	0.639	0.010	0.869	-0.004	0.944	0.038	0.536	-0.001	0.991
August	-0.099	0.103	-0.047	0.439	-0.071	0.244	-0.068	0.259	-0.040	0.515
September	-0.096	0.113	-0.114	0.060	-0.094	0.121	-0.087	0.153	-0.149	0.014
October	-0.104	0.086	-0.108	0.075	-0.068	0.264	-0.068	0.262	-0.087	0.150
November	0.074	0.220	-0.002	0.976	0.090	0.136	0.098	0.105	0.051	0.404
December	0.029	0.636	0.025	0.679	0.078	0.197	0.058	0.342	0.022	0.723

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

Table 7.7. Wilcoxon Rank Sum and Welch's t-test results for rainfall sites in Marne Saunders PWRA (1900 to 2024) for drought period

Period	Keyneton (23725)		Mount Pleasant (23737)		Cambrai Kongolia (24513)		Sedan (24531)		Palmer (24525)	
	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.
Annual	0.020	0.014	0.022	0.016	0.290	0.187	0.479	0.425	0.026	0.023
Summer	0.929	0.884	0.814	0.814	0.971	0.946	0.984	0.968	0.768	0.670
Autumn	0.021	0.008	0.018	0.006	0.125	0.065	0.097	0.057	0.020	0.019
Winter	0.108	0.086	0.297	0.187	0.079	0.055	0.339	0.284	0.058	0.047
Spring	0.025	0.092	0.014	0.045	0.196	0.358	0.196	0.438	0.037	0.082
January	0.826	0.598	0.872	0.597	0.855	0.767	0.927	0.856	0.868	0.529
February	0.695	0.626	0.369	0.462	0.602	0.538	0.811	0.741	0.641	0.579
March	0.396	0.509	0.210	0.333	0.217	0.317	0.291	0.365	0.238	0.417
April	0.194	0.165	0.035	0.041	0.206	0.357	0.416	0.506	0.110	0.094
May	0.063	0.002	0.296	0.030	0.170	0.019	0.091	0.003	0.141	0.006
June	0.476	0.393	0.663	0.593	0.414	0.511	0.691	0.708	0.401	0.433
July	0.233	0.321	0.241	0.335	0.303	0.094	0.506	0.462	0.149	0.083
August	0.036	0.031	0.084	0.067	0.035	0.018	0.044	0.058	0.116	0.058
September	0.094	0.089	0.062	0.070	0.177	0.245	0.208	0.295	0.017	0.014
October	0.032	0.012	0.031	0.020	0.046	0.104	0.050	0.144	0.050	0.047
November	0.847	0.842	0.473	0.531	0.914	0.896	0.913	0.904	0.913	0.879
December	0.684	0.660	0.489	0.646	0.883	0.836	0.759	0.768	0.473	0.637

Table 7.8. Wilcoxon Rank Sum and Welch's t-test results for rainfall sites in Marne Saunders PWRA (1900 to 2024) for WAP period

Period	Keyneton (23725)		Mount Pleasant (23737)		Cambrai Kongolia (24513)		Sedan (24531)		Palmer (24525)	
	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.	Wil.	Wel.
Annual	0.269	0.221	0.474	0.467	0.351	0.408	0.392	0.388	0.447	0.429
Summer	0.828	0.703	0.923	0.900	0.953	0.877	0.884	0.817	0.879	0.792
Autumn	0.496	0.385	0.579	0.502	0.642	0.485	0.579	0.492	0.320	0.433
Winter	0.454	0.321	0.635	0.473	0.168	0.206	0.145	0.157	0.377	0.425
Spring	0.031	0.148	0.064	0.164	0.142	0.204	0.123	0.276	0.078	0.185
January	0.466	0.302	0.591	0.466	0.565	0.477	0.638	0.506	0.663	0.463
February	0.568	0.491	0.631	0.753	0.624	0.644	0.733	0.579	0.580	0.558
March	0.660	0.642	0.687	0.510	0.631	0.684	0.591	0.701	0.496	0.639
April	0.691	0.608	0.587	0.634	0.609	0.701	0.733	0.725	0.428	0.414
May	0.160	0.129	0.402	0.348	0.225	0.084	0.157	0.069	0.164	0.205
June	0.369	0.396	0.580	0.579	0.527	0.590	0.511	0.571	0.660	0.641
July	0.534	0.500	0.454	0.400	0.211	0.111	0.200	0.141	0.328	0.275
August	0.399	0.297	0.526	0.471	0.392	0.220	0.299	0.168	0.504	0.407
September	0.022	0.064	0.023	0.076	0.105	0.148	0.077	0.140	0.016	0.055
October	0.031	0.040	0.032	0.048	0.008	0.023	0.009	0.049	0.043	0.052
November	0.833	0.884	0.852	0.899	0.938	0.917	0.930	0.928	0.943	0.939
December	0.826	0.846	0.920	0.906	0.900	0.875	0.775	0.823	0.908	0.856

## 7.4. Annual and decadal rainfall plots for individual sites

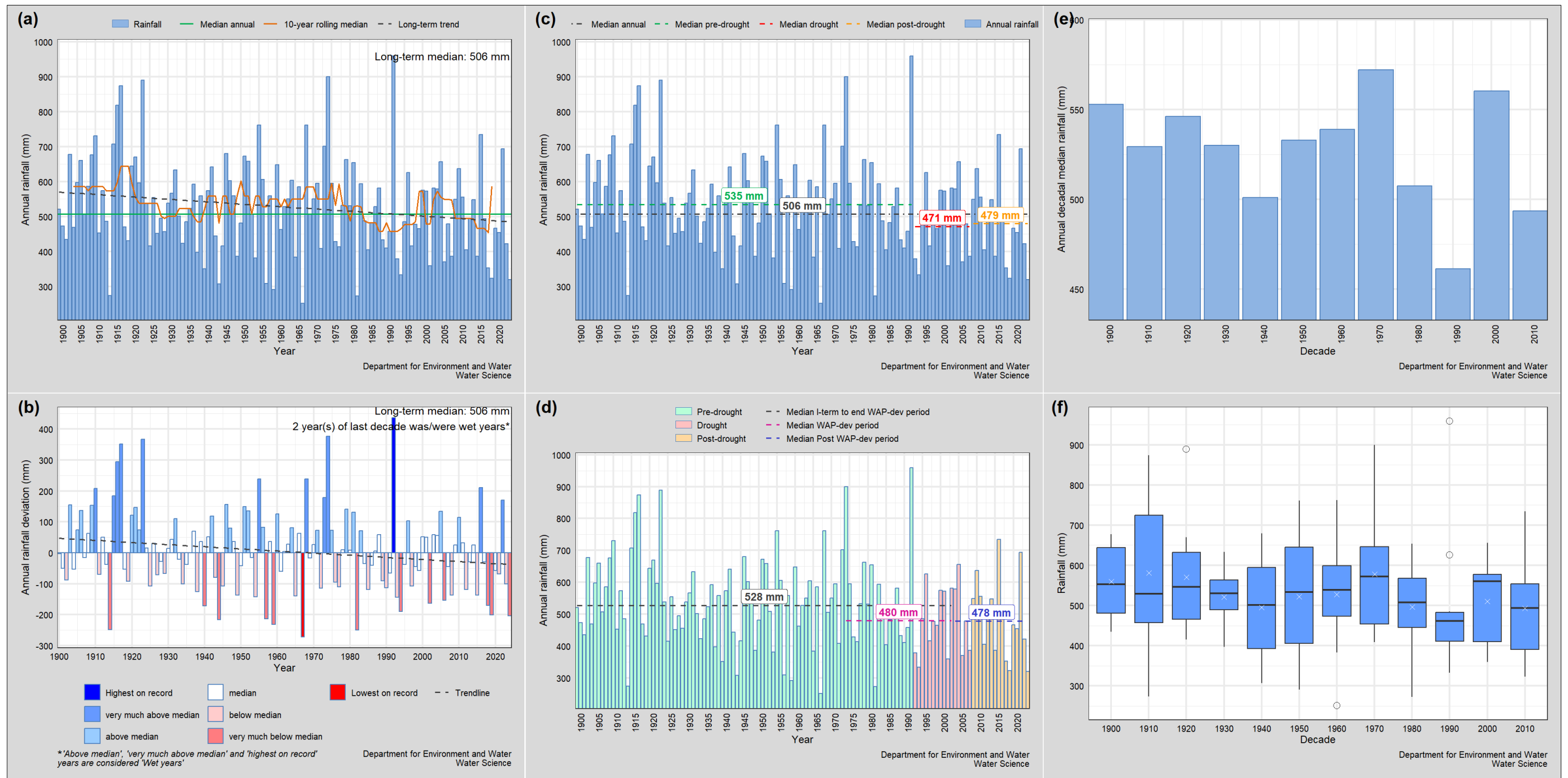


Figure 7.1. Annual and decadal rainfall plots – Keyneton (23725), Marne Saunders PWRA

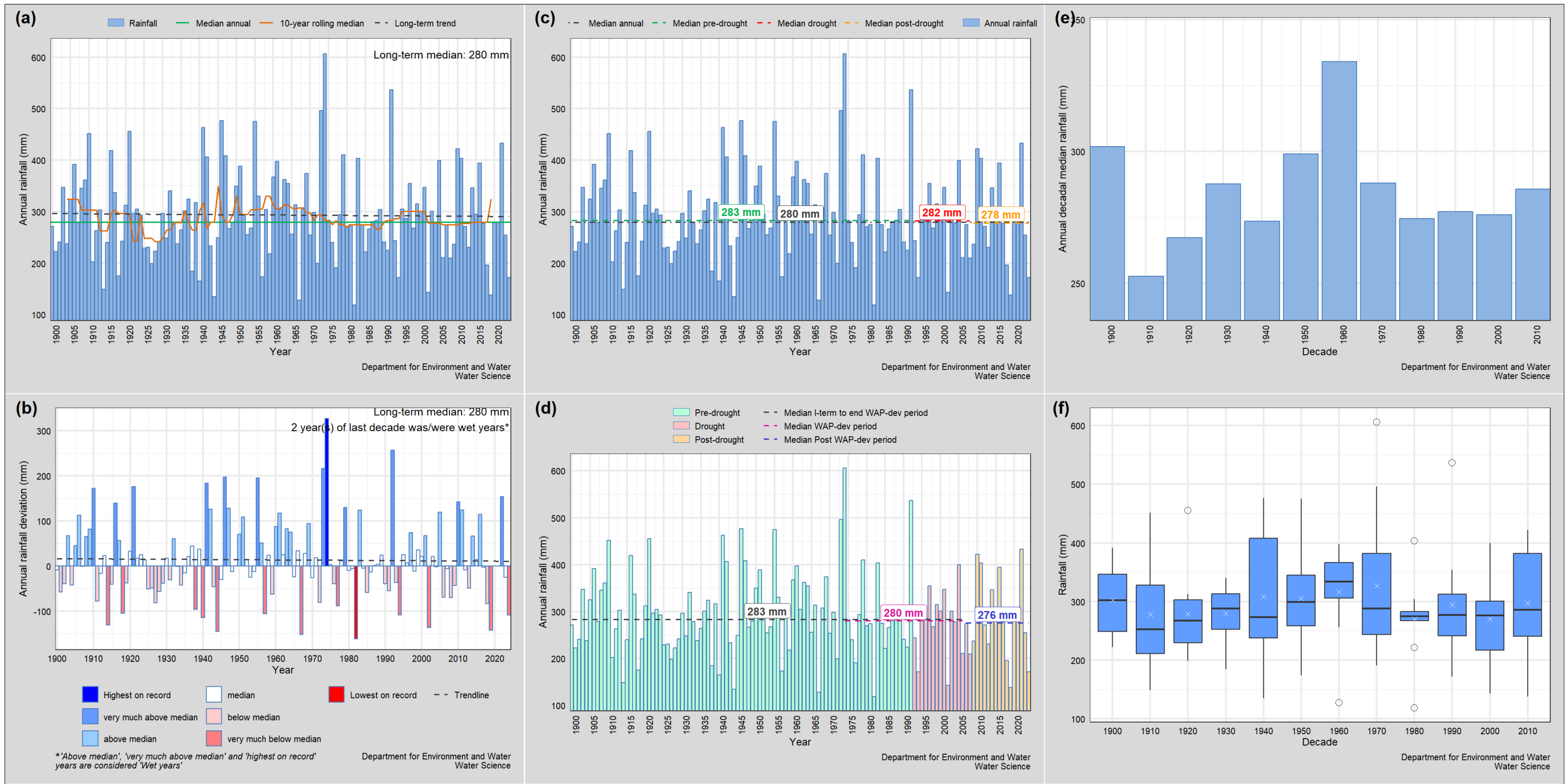


Figure 7.2. Annual and decadal rainfall plots – Cambrai Kongolia (24513) Marne Saunders PWRA

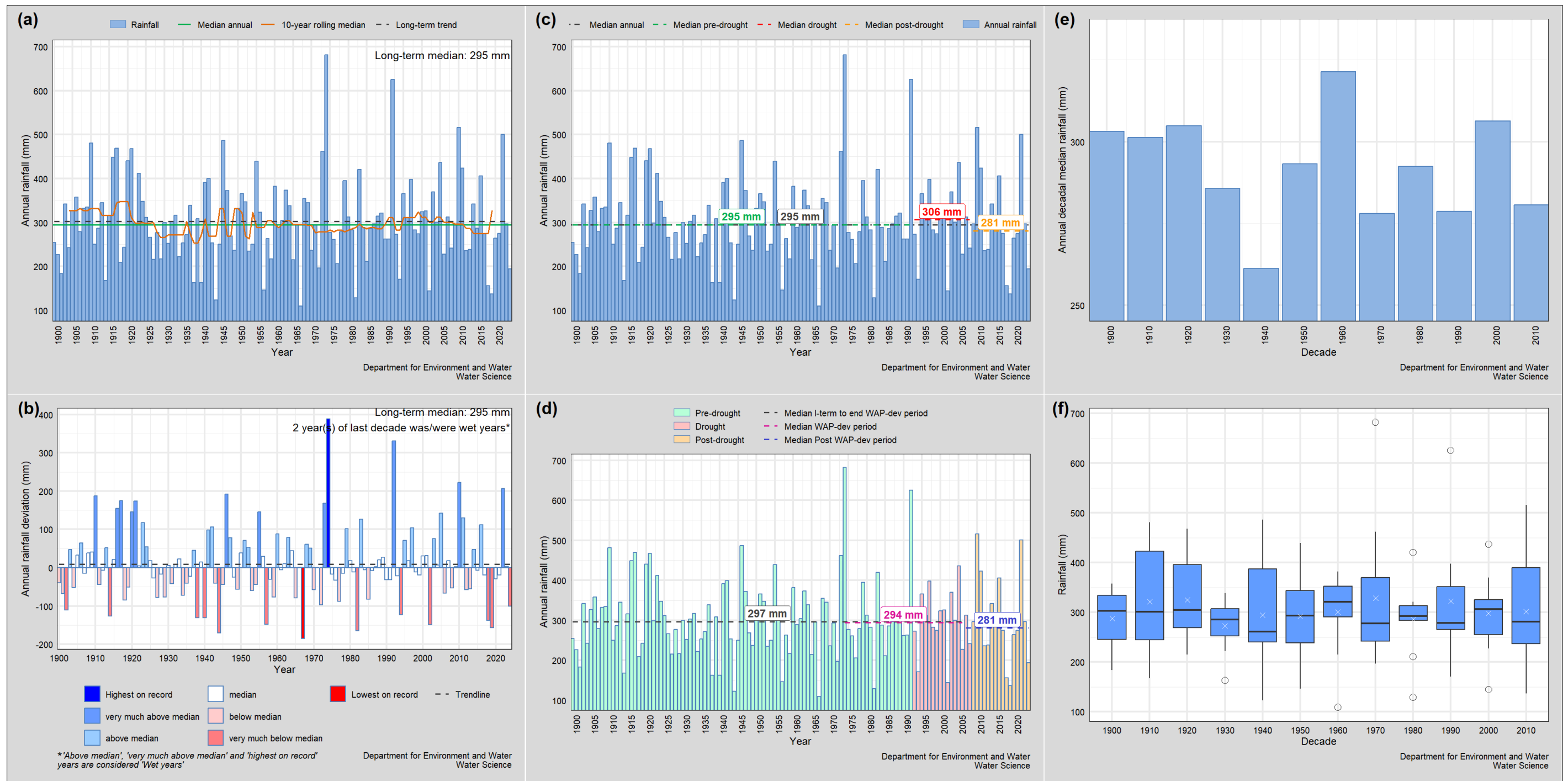


Figure 7.3. Annual and decadal rainfall plots – Sedan (24531) Marne Saunders PWRA

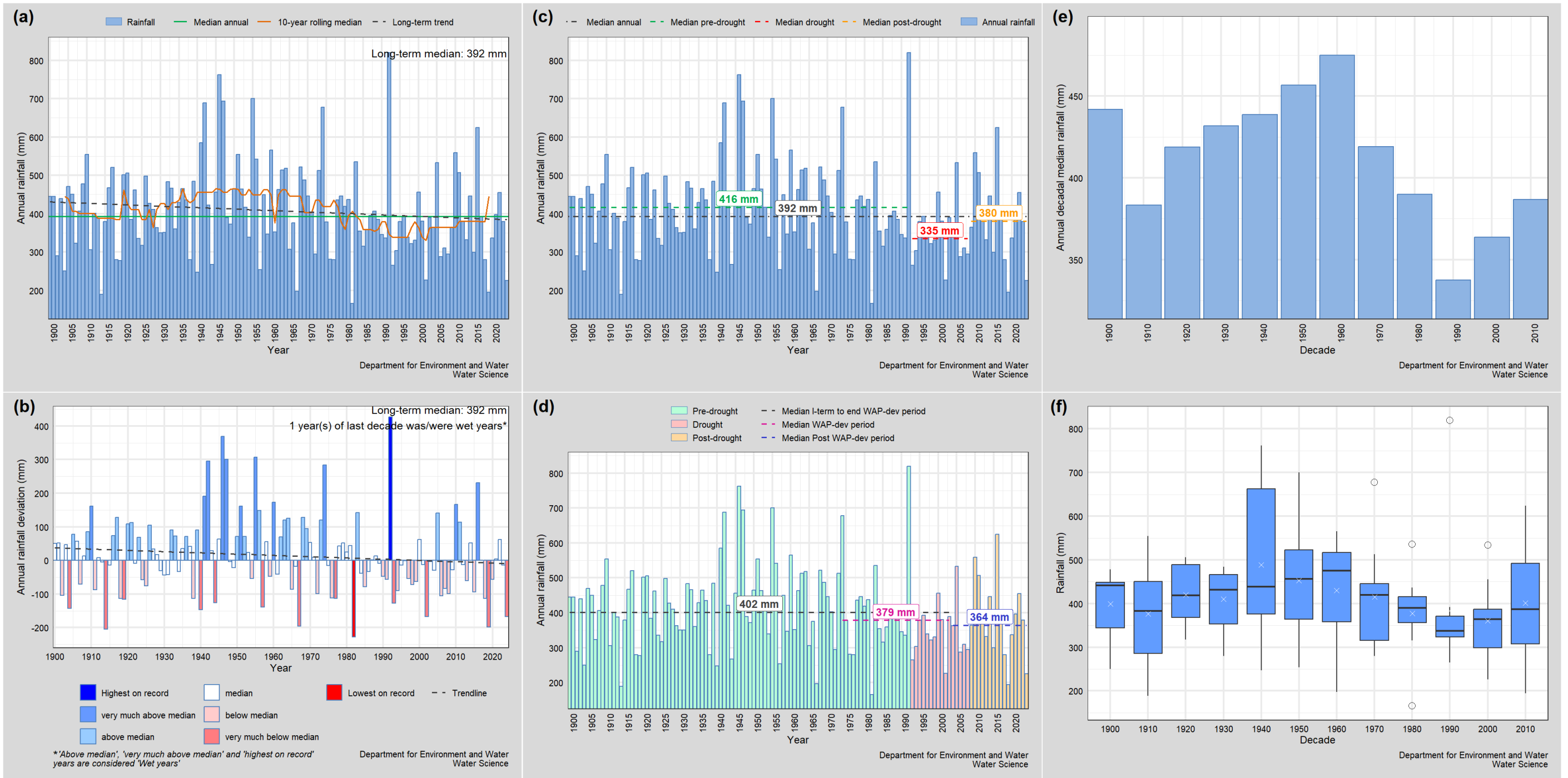


Figure 7.4. Annual and decadal rainfall plots – Palmer (24525), Marne Saunders PWRA

## 7.5. CUSUM charts of annual rainfall

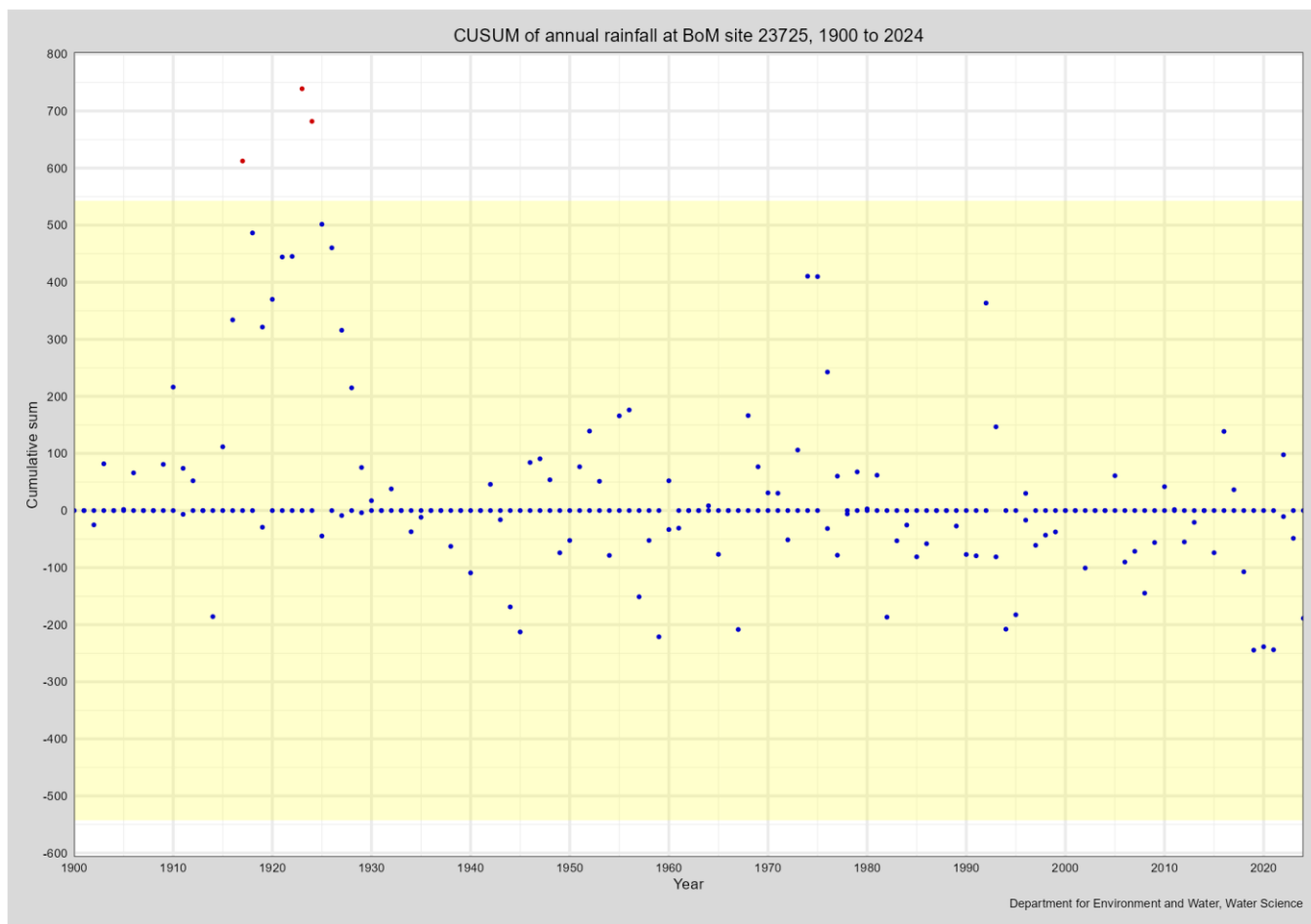
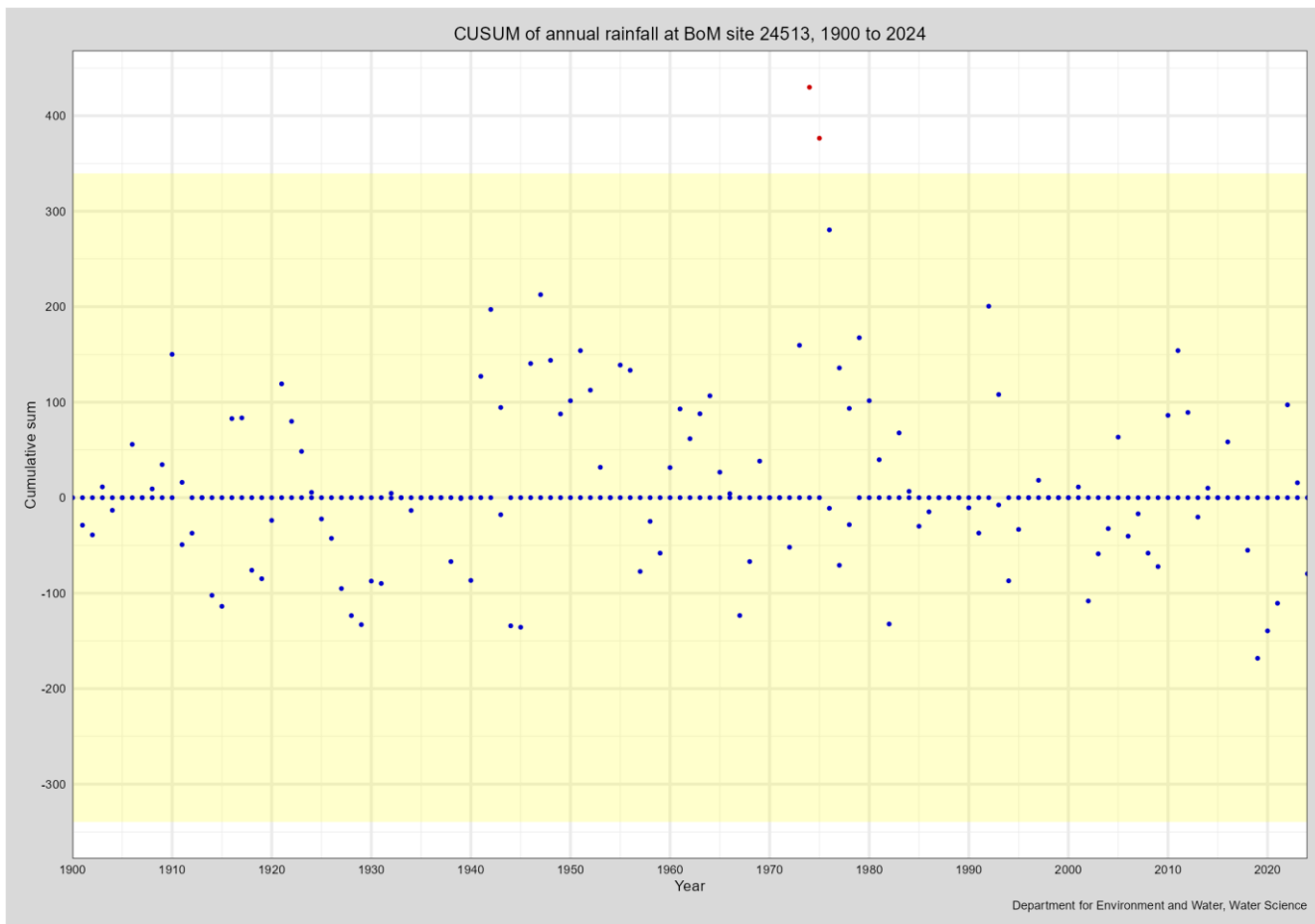
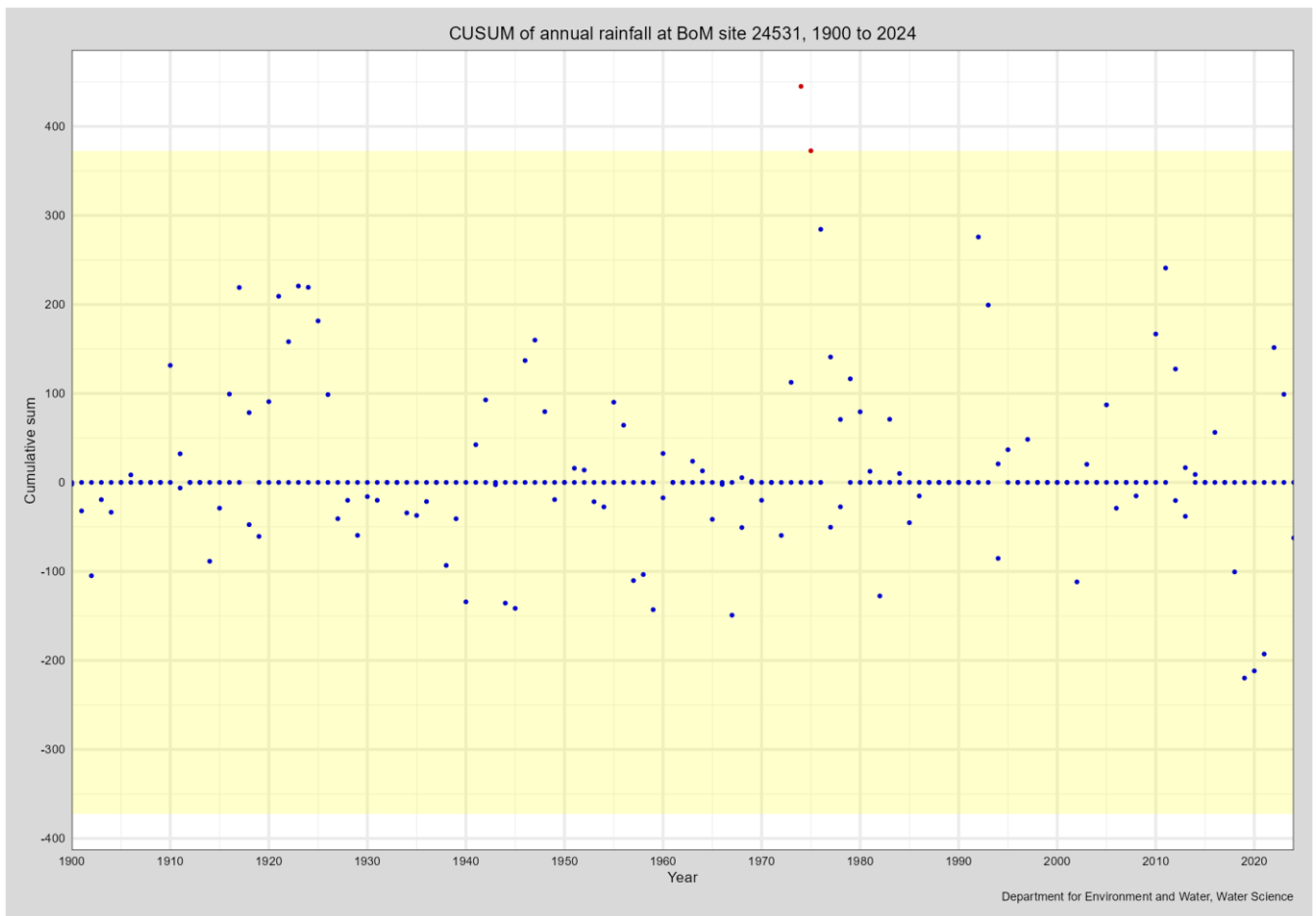


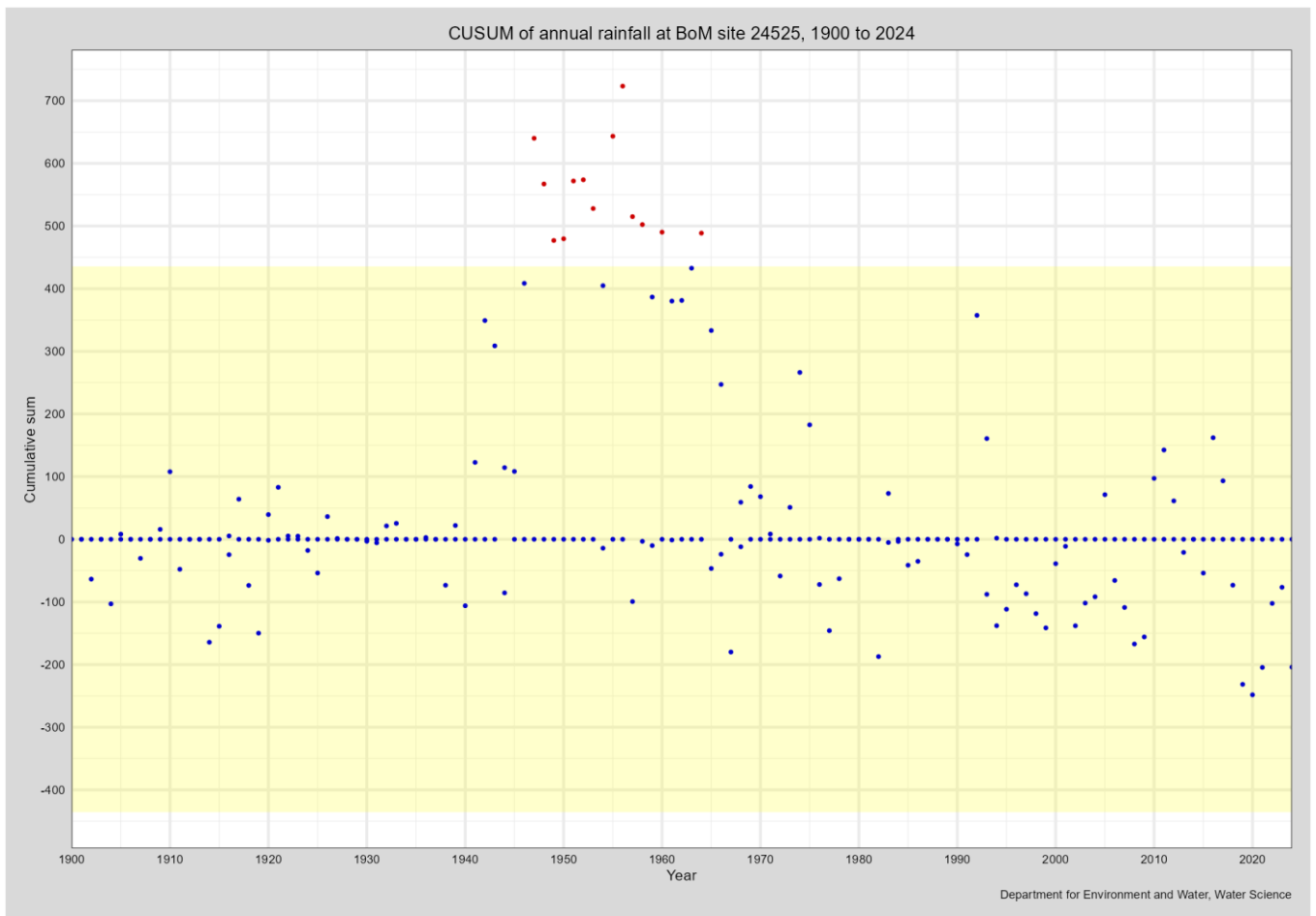
Figure 7.5. CUSUM charts of annual rainfall (1900 to 2024) Keyneton (23725) Marne Saunders PWRA



**Figure 7.6. CUSUM charts of annual rainfall (1900 to 2024) Cambrai Kongolia (24513) Marne Saunders PWRA**



**Figure 7.7. CUSUM charts of annual rainfall (1900 to 2024) Sedan (24531), Marne Saunders PWRA**



**Figure 7.8. CUSUM charts of annual rainfall (1900 to 2024) Palmer (24525) Marne Saunders PWRA**

## 7.6. CUSUM charts of seasonal rainfall

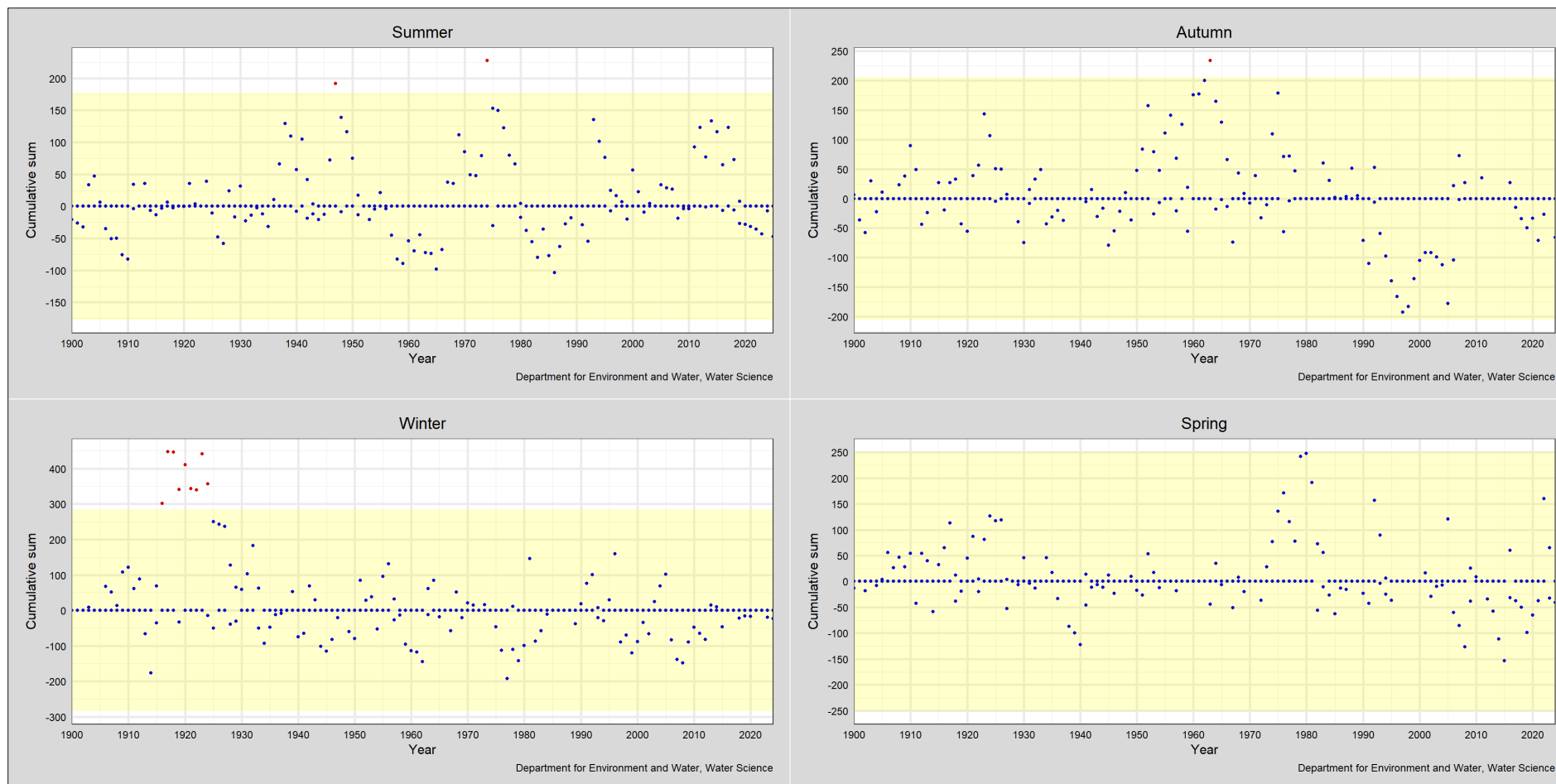


Figure 7.9. CUSUM charts of seasonal rainfall (1900 to 2024) Keyneton (23725) Marne Saunders PWRA

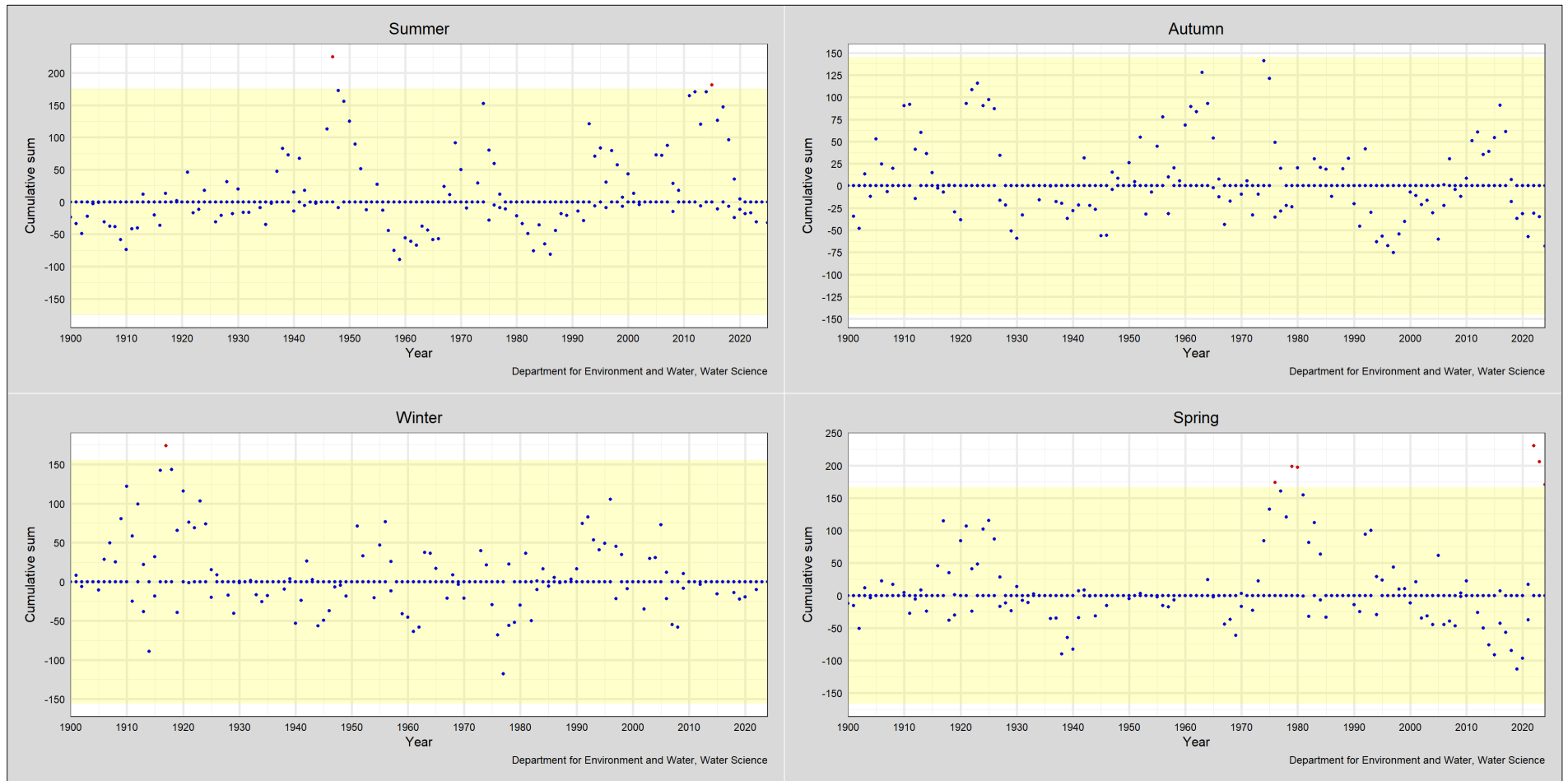


Figure 7.10. CUSUM charts of seasonal rainfall (1900 to 2024) Cambrai Kongolia (24513) Marne Saunders PWRA

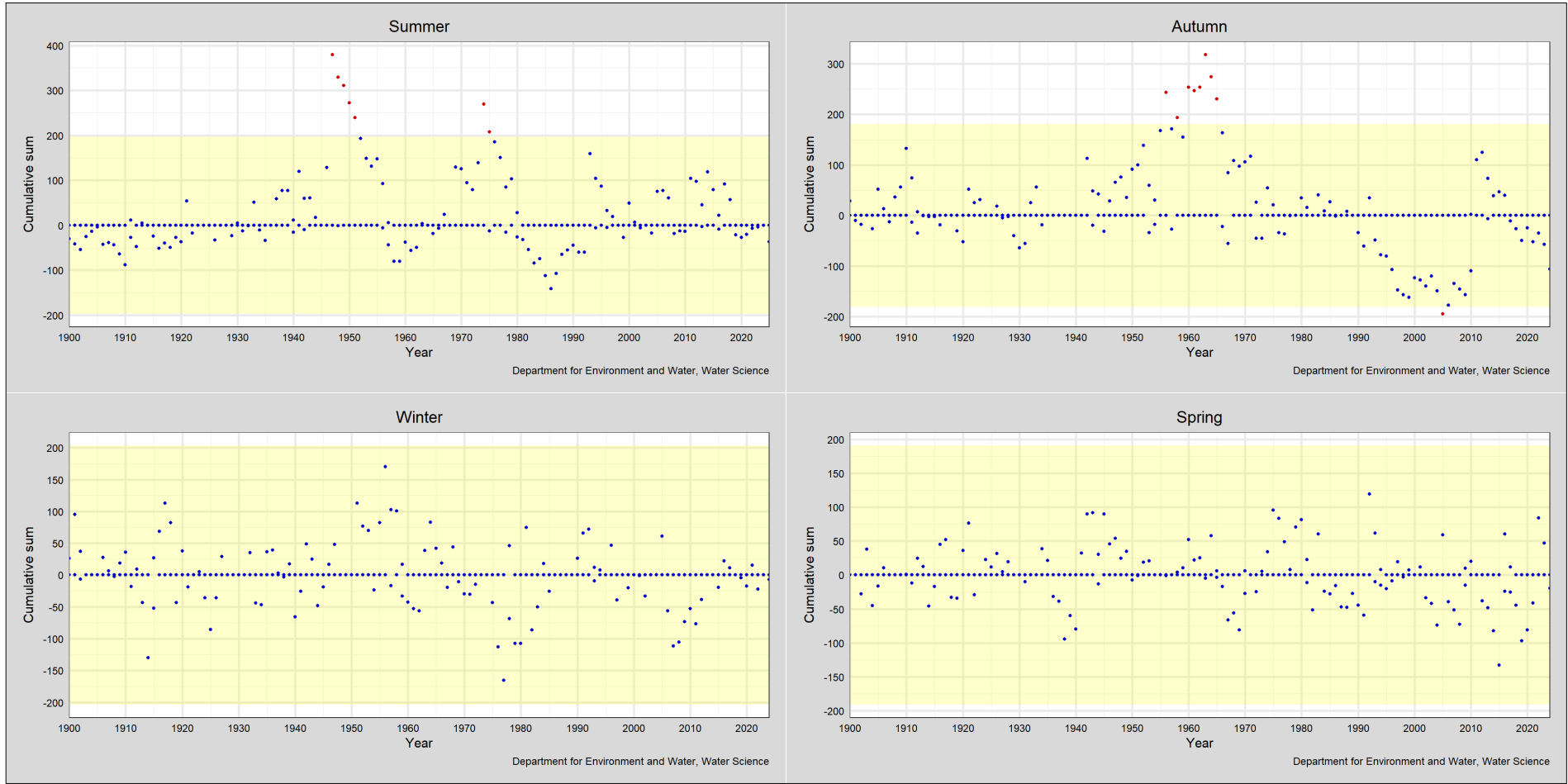
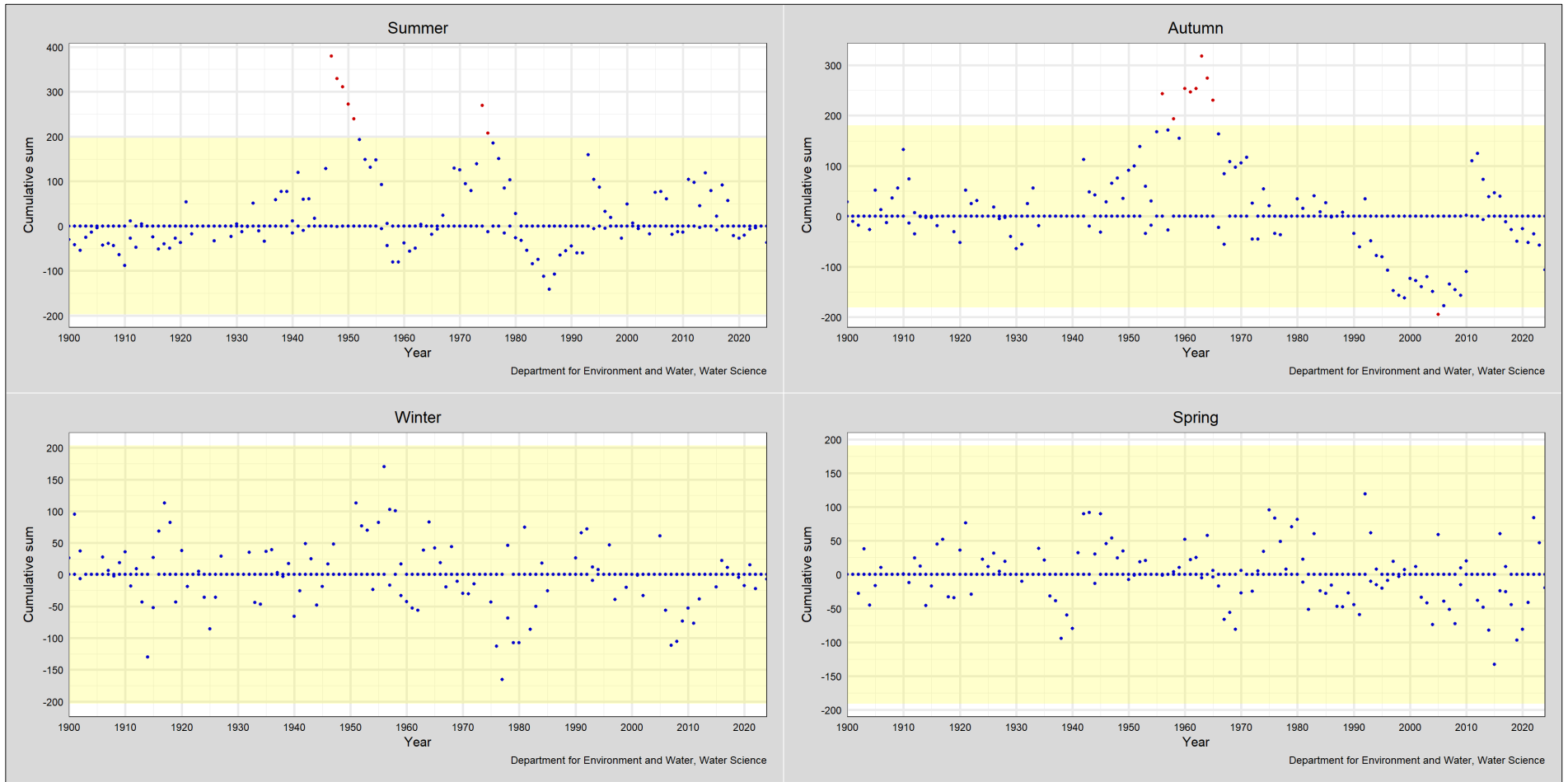


Figure 7.11. CUSUM charts of seasonal rainfall (1900- 2024) Sedan (24531), Marne Saunders PWRA



**Figure 7.12. CUSUM charts of seasonal rainfall (1900 to 2024) Palmer (24525) Marne Saunders PWRA**

## 7.7. CUSUM charts of monthly rainfall

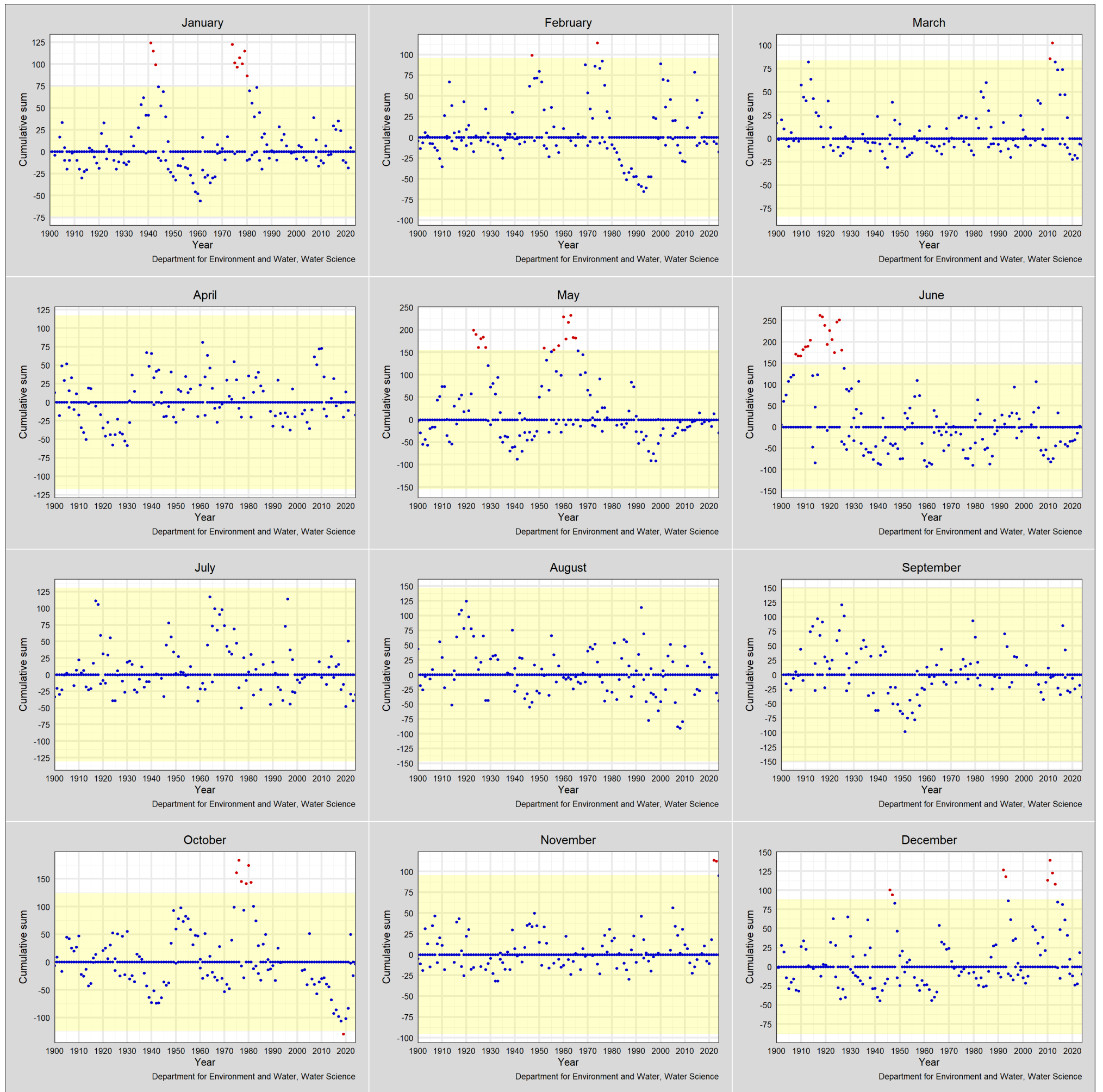


Figure 7.13. CUSUM charts of monthly rainfall (1900 to 2024) for Keyneton (23725) Marne Saunders PWRA

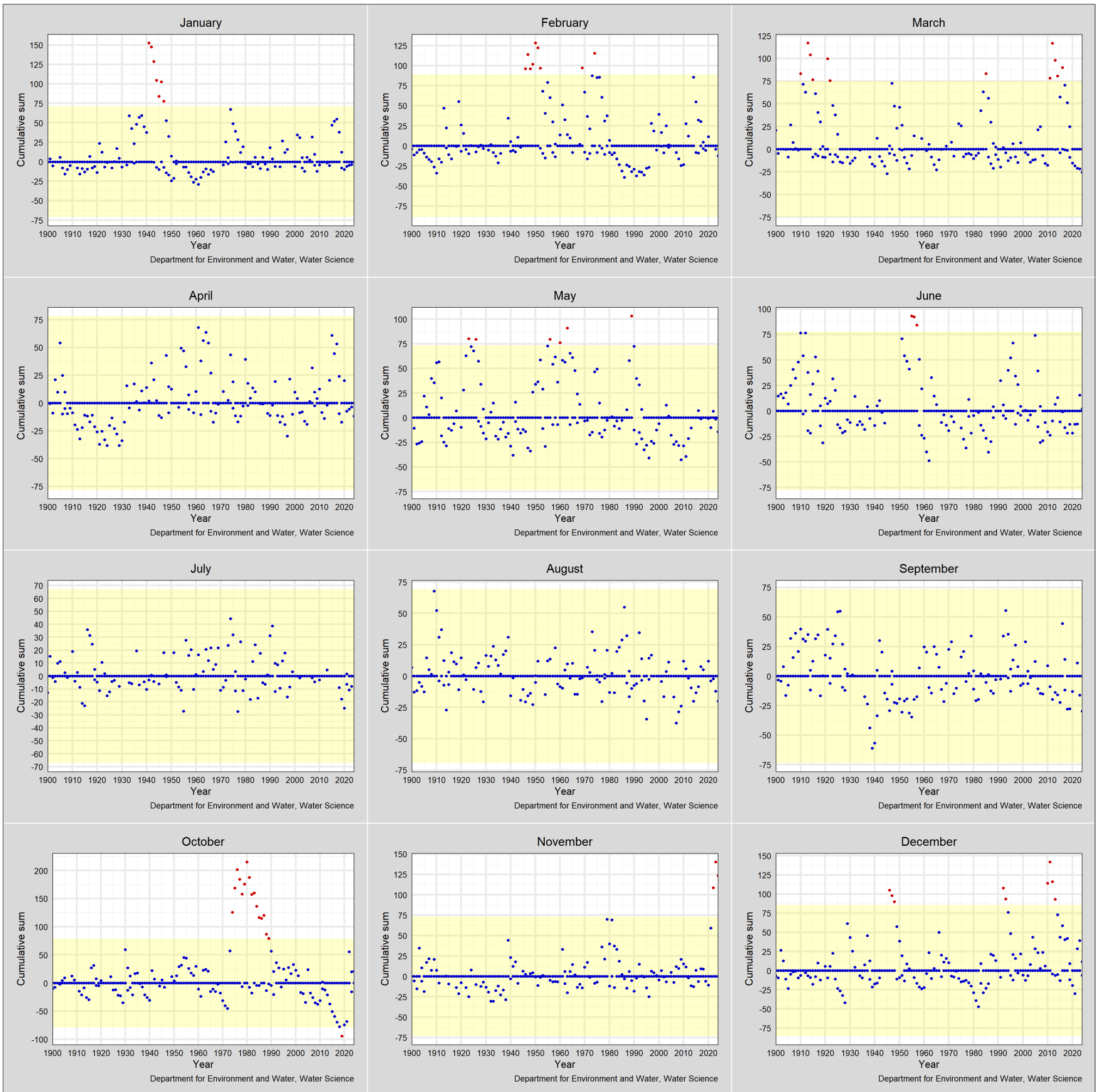


Figure 7.14. CUSUM charts of monthly rainfall (1900 to 2024) for Cambrai Kongolia (24513) Marne Saunders PWRA

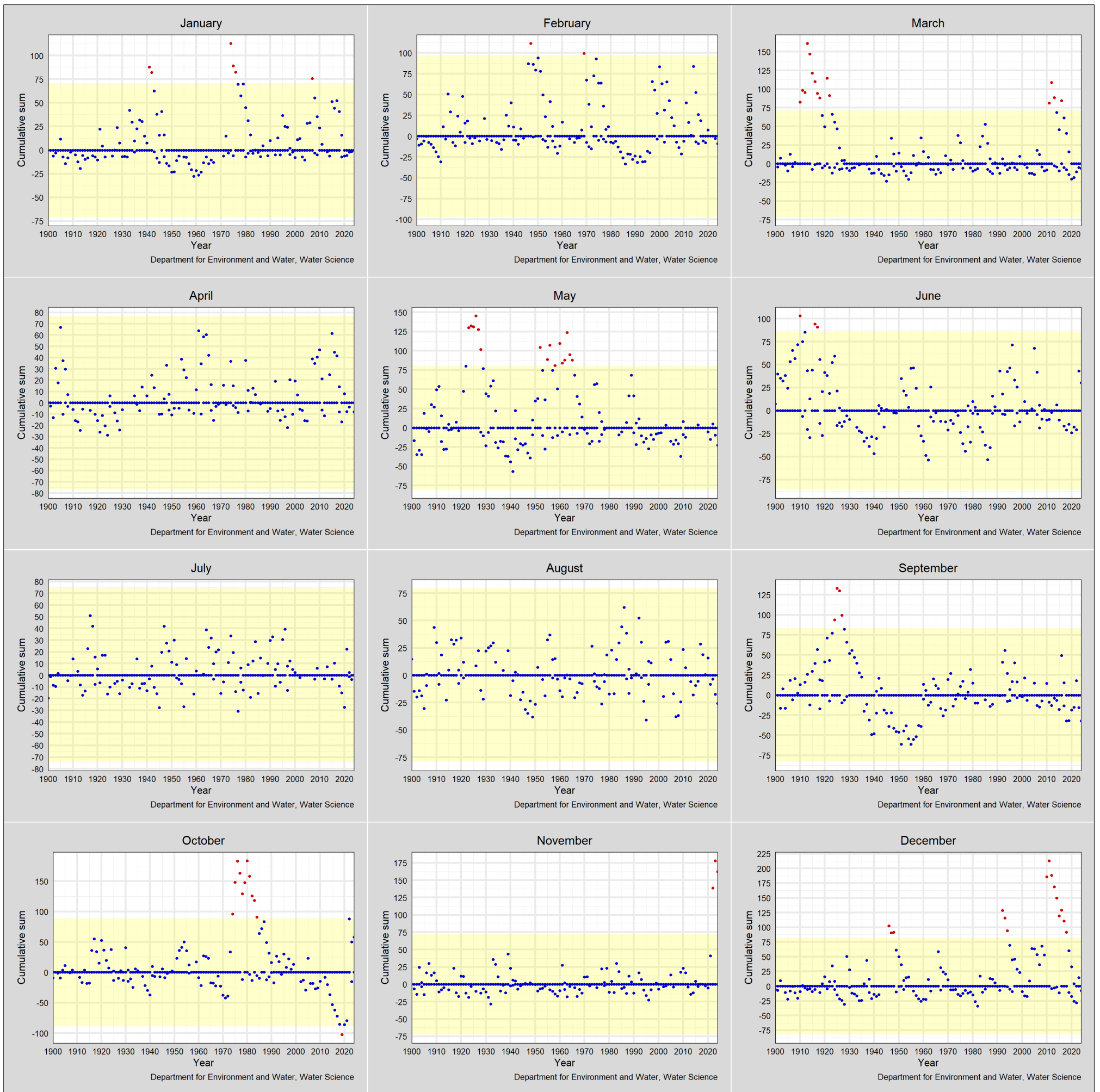


Figure 7.15. CUSUM charts of monthly rainfall (1900 to 2024) for Sedan (24531) Marne Saunders PWRA

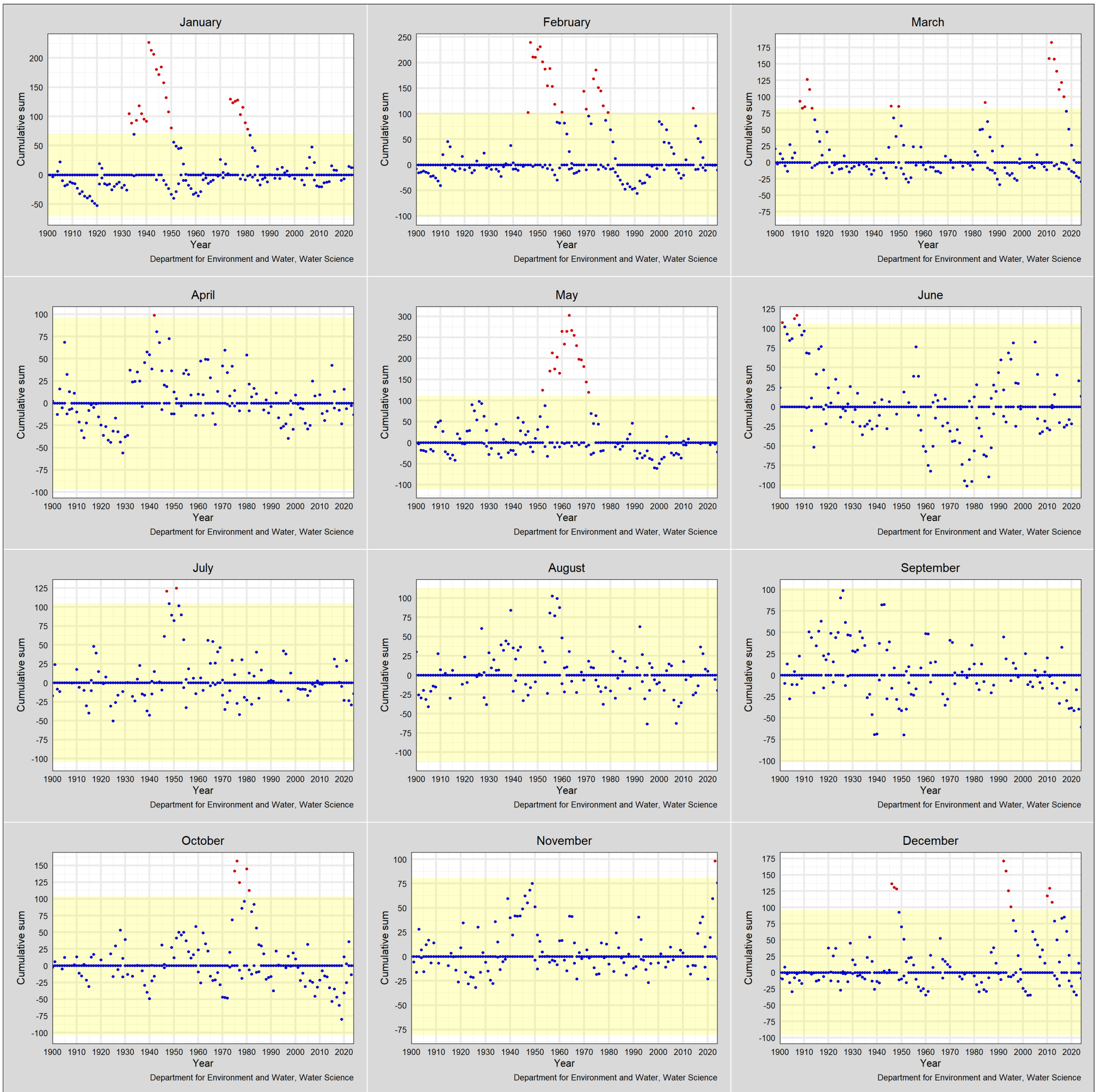


Figure 7.16. CUSUM charts of monthly rainfall (1900 to 2024) for Palmer (24525) Marne Saunders PWRA

## 7.8. Monthly streamflow totals for Saunders Creek catchment (2010 – 2024)



Figure 7.17. Monthly streamflow totals for Saunders Creek catchment (2010 – 2024)

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