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Comparing drivers of hydrological shifts across regions: the case of southern Australia

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Abstract. Several regions globally have recently experienced persistent shifts in the relationship between rainfall and runoff, triggered by multi-annual drought. These regions are climatically diverse; however, few assessments have yet been undertaken to draw parallels (if any) between the processes responsible. We present a comparative analysis of these hydrological shifts between south-west Australia and south-east Australia, two regions separated by over 2,700 km (~1,700 miles). We apply existing methods based on Hidden Markov modelling to characterise shifts in rainfall-runoff relationships in 254 catchments in Eastern and 54 in Western Australia. Of the catchments analysed, 51% of Eastern and 63% of Western catchments displayed a movement away from the historical rainfall-runoff relationship to one of reduced flow generation following a multi-year period of drier climate. The reduced flow state persisted in 31% of catchments in Eastern Australia despite a return to near-normal climatic conditions after multi-year drought, whereas in Western Australia neither the climate nor the flow states have returned to earlier norms (i.e. nearly all shifted catchments have stayed shifted). Interestingly, some catchment characteristics that were correlated with shifts in one region were anticorrelated in the other, possibly indicative of different causative processes. For example, in Western Australia the shifted catchments are typically those that have not been cleared for agriculture and thus retain forest coverage; the opposite is true in Eastern Australia. We suggest a possible link to pre-existing trends in groundwater for cleared catchments, where those in Western Australia may have been experiencing rising groundwater levels due to clearing occurring recently (mid-1900s) relative to Eastern Australia (late-1800s). These findings suggest the importance of land use history when considering changes in rainfall-runoff relationship. We recommend further comparative studies be conducted to synthesise understanding across geographies and better inform water planning decisions under climate change.

1 Introduction

Prolonged periods of reduced precipitation, whether due to climate change or multi-year drought, present a challenge to water resource management through intensification of water scarcity. This is further exacerbated by shifts in the relationship between annual rainfall and annual runoff such that the runoff volume generated is lower than would have been expected historically (for a given annual rainfall). This behaviour, also referred to here as "hydrological shifts", has been noted globally at the catchment scale and has been afforded much attention in research, due in part to the vulnerability of downstream water systems with many dependent stakeholders (Garreaud et al., 2017; Fowler et al., 2022; Petrone et al. 2010). In Central Chile, persistent rainfall deficits of 25-45% since 2010 have reduced streamflow by up to 90% (Garreaud et al., 2017), while in China the runoff ratio on the Loess Plateau reduced 32% during 1991-1999 (Zhang et al., 2018). Several periods of severe drought in the late 20th and early 21st century in California and across Europe were shown to have caused reductions in streamflow of up to 51% and 85% respectively, when compared to what was predicted for a given rainfall based on the historic relationship (Avanzi et al., 2020; Massari et al., 2022). In Australia, this behaviour has been widespread in the south-east, triggered by periods of intense rainfall reduction, including the Millenium Drought (Saft et al., 2016b; Peterson et al., 2021; Fowler et al., 2022), and the subsequent Tinderbox Drought (Devanand et al., 2024). In Western Australia, shifts in rainfall-runoff relationship have been identified in a few well-studied catchments as a response to long-term drying trends in climate (Petrone et al. 2010; Kinal and Stoneman, 2012; Hughes et al. 2012). In cases where precipitation has returned to the historic average, shifts have been alleviated in some catchments, while in others persistence has been seen, meaning that a catchment may not recover from a multi-annual drought for years after it has ended (Peterson et al., 2021). Across Eastern Australia, strict water consumption restrictions were imposed during the Millenium Drought, and recovery of water storage was only achieved after anomalously high rainfall in early 2010 (van Dijk et al., 2013), despite continued hydrological shifts in some catchments. In south-west Western Australia, reduced precipitation has persisted (Hope et al., 2006; CSIRO and Bureau of Meteorology, 2020) and surface water catchments which were previously responsible for 88% of domestic water use in the 1960s (Gelsinari et al., 2024) have dramatically declined in their supply. Reliance has transitioned in some areas to groundwater, responsible for almost all private use in the Perth metropolitan region in 2008 (Water Corporation, 2009). Significant reductions in potential recharge of aquifers (McFarlane et al., 2012), has necessitated the construction of multiple desalination plants as a supplementary water source. While climate models disagree regarding the magnitude (and sometimes direction) of change in precipitation in south-eastern Australia (Potter et al., 2016), there is consensus predicting drying in Western Australia (Dawes et al., 2012). Understanding this hydrological behaviour is vital due to its impact on current and future water resources.

Because of incomplete understanding of the underlying causes of changes to rainfall-runoff relationships, predicting where this behaviour may arise is currently a challenge. Occurrences to date have been unexpected (Chiew and Vaze, 2015; Fowler et al., 2022), contributing to the severity of resultant impacts. This is because planning could not be undertaken in advance, meaning that mitigation measures could not be implemented, nor stakeholders properly prepared (Schofield, 2010; Grafton et al., 2014). Resource managers commonly explore future scenarios through simple conceptual rainfall-runoff models, many of which lack the ability to extrapolate to unforeseen conditions (which is key for systems experiencing rainfall-runoff shifts), leading to overestimation of runoff (Coron et al., 2012; Saft et al., 2016b). Attention has been given to enhancing extrapolative capacity through inclusion of long-term catchment storage (Grigg and Hughes, 2018; Deb et al., 2019), however, reviews of model performance suggest further revision of structures (e.g. Deb et al., 2019; Fowler et al., 2020) and calibration methods (Fowler et al., 2018) is required. Overall, despite some advances, we are far from being able to predict

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

shifts in catchment responses in advance, let alone codify this understanding in models suitable for decision making. A key step is to study the known cases of hydrological shifts globally, and attempt to synthesise a broader understanding that can be generalised across regions, even to regions that have not yet seen this behaviour.

Individual studies have hypothesised possible regional specific drivers. In Chile, Alvarez-Garreton et al. (2021) explained hydrological shifts in terms of accumulated deficit in hydrological storages with long-term memory, namely groundwater and snowpack. They emphasised the importance of interactions, with snowmelt recharging the groundwater that (pre-drought) sustained and buffered low flow regimes (see also Bruno et al., 2022). Álamos et al. (2024) reported that water extraction in Central Chile further contributed to streamflow reductions. In the south-west of the USA and in western Europe, increased partitioning of precipitation to evapotranspiration was an important factor (e.g. Massari et al., 2022), and in some locations drought was severe enough to cause tree mortality, giving an additional mode of system shifting (Avanzi et al., 2020; Bales et al., 2018). In south-eastern Australia, Saft et al. (2016a) found that drier and flatter catchments with shallower soils tended to be more susceptible, while Fowler et al. (2022) suggested groundwater processes were important drivers of long-term behaviour in these drier catchments. This aligns with Hughes et al. (2012) working in south-western Australia, who reported close correlations between the multi-annual dynamics of groundwater storage and streamflow, and Kinal and Stoneman (2012) who demonstrated that the timing of groundwater disconnection from the stream bed aligned with hydrological shifts presenting in a Western Australian catchment. Thus, groundwater storage is implicated in many, but not all cases of reported hydrological shifts, while evapotranspiration dynamics and human influences are often also implicated.

Despite the proliferation of studies examining shifts in rainfall-runoff relationship most studies are focussed on their own region, and comparisons of underlying processes across regions are rare. Through comparison of locations where this behaviour has already been seen, a more comprehensive understanding of drivers can be developed, leading to diagnosis of potentially vulnerable catchments. To begin to fill this gap, here we compare and contrast the hydrological shifts that have occurred in south-east Australia with that in the south-west, two regions separated by over 2,700 km (1,700 miles). We seek to answer the following research questions:

1. Where have shifts in rainfall-runoff relationship occurred throughout southern Australia, and are the temporal and spatial patterns similar between south-east and south-west?
2. Do catchments exhibiting these shifts across the study regions have similar characteristics?
3. Are the causal factors for these shifts the same across the study regions? As causal processes cannot directly be measured, we will discuss and try to infer them based on the outcomes of the previous questions.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

2 Methods

2.1 Study site selection

Catchments for this study were selected from the freely available CAMELS-AUS database, version 2 (Fowler et al., 2025). This dataset contains pre-processed information (see Section 2.2) for 561 catchments in Australia, but not all these catchments were included here. As mentioned, the study examines two distinct regions, the south-west and south-east of Australia (Fig. 1). Site selection is described for each region in turn, below.

Overall, the western half of Australia is very dry, but the south-west corner is a relatively small region sufficiently far south to receive rainfall from southerly cold fronts moving east from the Indian Ocean, typically in the colder months. For site selection, the intent was to adopt all CAMELS-AUS v2 catchments within this wetter region. The boundaries of this region are subjective; here we selected all catchments (n=54) with centroids west of 118° E and south of 30° S. Catchments further north than this are considered to be too arid to form part of this wetter region.

Unlike the west, eastern Australia is wet (humid grading to tropical) across the entire length of the eastern seaboard, so it is not immediately clear how to demarcate a set of catchments. Previous studies of hydrological shifts varied in this regard—for example, Peterson et al. (2021) studied only catchments south of 36° S, while Saft et al. (2015) studied catchments as far north as 28° S. However, the latter set includes catchments with summer-dominant rainfall, which contrasts with the winter-dominant regime in the south-west. Given the focus here is on comparing hydrological processes across regions, it is logical to select the regions to be relatively similar in other regards such as climatic conditions (as far as possible). Thus, the eastern catchments were selected with reference to a seasonality index—namely those with values greater than approximately 1.15 (see Appendix A, Fig. A1) in the moisture index seasonality measure used by Knoben et al. (2018). This tended to include catchments with winter-dominant rainfall (typically further south) and year-round rainfall but not summer dominant. The resulting set of eastern catchments (n=254) covered the Australian states of Victoria, New South Wales, and South Australia, plus the Australian Capital Territory.

The catchments selected in Western Australia cover a wide area, with the furthest catchments 630 km (~390 miles) apart. This region experiences an exceedingly seasonal climate, characterised by hot dry summers and wet winters. Long-term aridity (precipitation divided by potential evapotranspiration) is less than 0.50 in a number of catchments (Fig. 1(c)). Greater average annual rainfall occurs along the coast, progressively decreasing moving inland north and east.

In Eastern Australia, catchments also experience typically hot dry summers, with cool wet winters. These catchments are less seasonal and have a lower annual potential evapotranspiration demand relative to precipitation. Potential evapotranspiration exceeds precipitation in approximately three quarters of catchments and can be up to double (Fig. 1(c)). Rainfall is higher within the mountainous regions to the east of Victoria, and lower moving inland and to the west.

While all selected catchments have no large reservoirs and are not urbanised, most catchments have been subject to land clearing, typically in the mid-1900s and the late 1800s for the south-west and south-east, respectively. In addition to this, many catchments are affected by small private dams (farm dams), which intercept runoff before it reaches larger streams and

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

rivers. Earlier analysis suggests that those dams are not sufficient in number or magnitude to cause observed hydrological shifts at the catchment scale (Fowler et al., 2022).

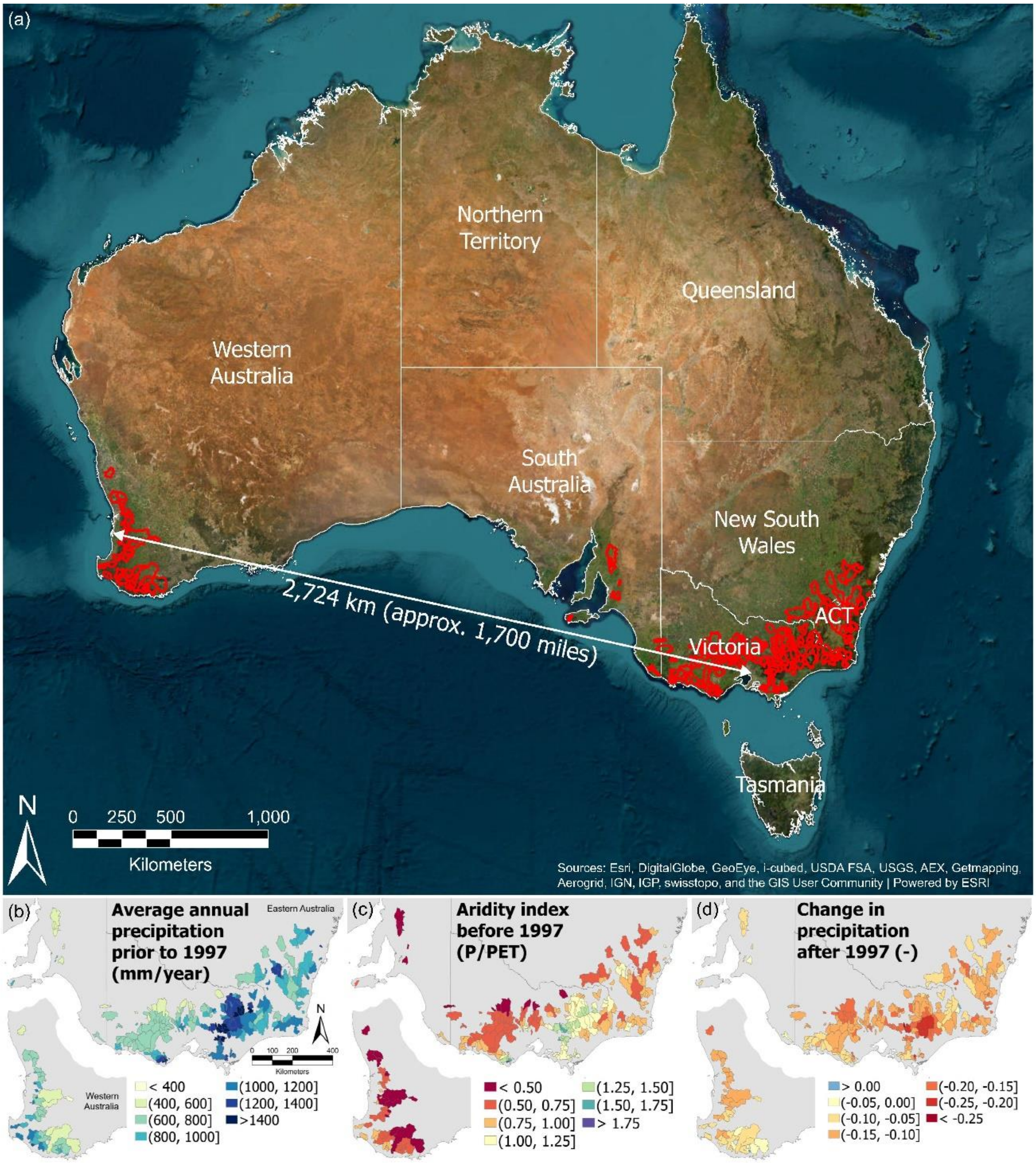


Figure 1: (a) Location of the two study areas, with catchments marked in red (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community | Powered by ESRI); (b) annual average precipitation (1950-1997) for Western and Eastern Australia; (c) the aridity index prior to 1997, calculated as precipitation divided by potential evapotranspiration; and (d) the change in annual average precipitation post 1997 as a proportion of the historic average.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

2.2 Data sources and preparation

As mentioned, timeseries data were obtained from the CAMELS-AUS v2 database (Fowler et al. 2025). This included both daily streamflow and daily precipitation, with the latter originally from the SILO database (http://www.longpaddock.qld.gov.au/silo) and supplied with CAMELS-AUS v2. As explained below, the methods required data on an annual timestep, which meant infilling was required for gaps present in daily streamflow data prior to aggregation to annual. Infilling was undertaken by fitting a linear relationship between daily flows at the catchment of interest and the nearest neighbouring catchment with flow data on that day.

Data were aggregated to the annual timestep, based on the water year of May to April of the following year. This choice of water year was intended to include the majority of flows triggered by the start of the seasonally high streamflow (typically commencing in May-June).

Later aspects of the analysis required information on catchment attributes such as slope, vegetation, and climatic conditions. For this, we adopted the attributes provided with the CAMELS-AUS v2 dataset, which cover a wide range of catchment properties.

2.3 Analysis of shifts in rainfall-runoff relationship

2.3.1 Detection

As mentioned above, the essence of this hydrological behaviour is not that streamflow exhibits variability (e.g. droughts and floods), but rather that the relationship between (annual) precipitation and streamflow itself changes with time. In the hydrological literature, several different methods have been developed to determine whether this behaviour is evident in a given record. One common method is to plot annual sums of the two variables in a bi-variate plot (Saft et al., 2015; Kinal and Stoneman, 2012). In this case, a shift in relationship can be discerned subjectively, via visual inspection, or objectively using a statistical test such as the one proposed by Saft et al. (2015).

However, a limitation of this statistical test is that the period subject to the hydrological shift must be assumed a priori, a limitation overcome by our adopted method, originally proposed by Peterson et al. (2021). This method uses Hidden Markov Modelling, a statistical method which assumes that there is a hidden state that explains the response (here, streamflow) of a system to its inputs (here, precipitation), with changes in this state being inferred from the data. The existence (or otherwise) of such changes is determined by testing models with more than one state (and thus more parameters) and using the Akaike Information Criterion (Akaike, 1973) to determine whether the increase in performance justifies the additional model complexity of multiple states. If not, the catchment is deemed to be without hydrological shifts; otherwise, the method directly outputs both the magnitude and timing of onsets of shifts in hydrological state. This information can also be used to characterise hydrological recovery or non-recovery following multi-year drought (Peterson et al. 2021).

To apply this method, the infilled and aggregated streamflow data for each catchment were input into the open-source R package, HydroState (Peterson et al., 2021). The structure selected was a linear model with no serial correlation, where

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

streamflow was transformed using the Box-Cox transform (Box and Cox, 1964) and a gamma distribution was used for each Markov state. We defined a "normal" flow state as the state seen in the year 1975, or in the earliest year of flow recorded thereafter. This model structure was tested over four combinations of flow state: one-state, two-state, three-state and three-state unstructured (the last option permitting that the states may change from the highest to lowest of the three states (or vice-versa) without going via the middle state). Following on from the earlier definition, our analysis is concerned with catchments which exhibit flow states lower than normal, representing less water being produced as runoff annually for a given rainfall, when compared to what historically would have been expected.

2.3.2 Quantifying hydrological shifts

To enable quantitative tests to understand the drivers of hydrological shifts, the extent by which a catchment shifted required quantification. The primary output of the HydroState package is categorical – i.e. catchments can be categorised according to whether or not hydrological shifts occurred. However, for the purpose of exploring relationships with possible co-variates, it is useful to quantify, rather than merely categorise, the shifts.

For this purpose, we transformed streamflow using the Box-Cox (Box and Cox, 1964) transform such that the relationship between rainfall and runoff became approximately linear. Values of lambda used in the transforms varied from -0.23 to 1.50 and were chosen individually for each catchment such that the skew magnitude was minimised. A line of best fit was then constructed using linear regression between the precipitation and the transformed streamflow. This was across all data points leading up to 1997—a year that was chosen because the results indicated it was prior to any widespread shifts in rainfall-runoff relationship, in both regions. The residuals from this relationship were then used to quantify the shift in subsequent rainfall-runoff responses. The residuals were averaged and standardised by dividing them by the average annual streamflow between 1991 and 1996. This gave an approximate proportion by which a catchment shifted relative to the historical (pre-1997) flow.

2.3.3 Investigation of correlation with catchment attributes

To explore causation, we investigate correlation between the changes in the flow regime and various catchment attributes, by computing Kendall's τ correlation coefficient. This rank-based measure was selected due to the skewed nature of some land coverage data, meaning linear (least-squares) regression techniques could not be used without violating assumptions. Kendall's τ was calculated using the MATLAB function corr with 'Kendall' selected as the 'Type,' which also provides p values quantifying the likelihood of the result arising by chance. A selection of 118 metrics were tested for correlation. This covered all quantitative attributes included within the CAMELS-AUS database, in addition to metrics calculated based on average precipitation and potential evapotranspiration over a number of periods and how these averages changed over those periods. Refer to the Appendix B for a complete list of all metrics assessed for correlation.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

3 Results

The analysis revealed a shift to a lower rainfall-runoff relationship in 63% (34 out of 54) of Western Australian catchments, with only 3 of these catchments reverting to a normal flow state by the end of their streamflow record. Conversely in Eastern Australia, 51% of catchments shifted (129 out of 254), but some of these (45) subsequently recovered. Figure 2 depicts how changes to the flow regime presented in individual catchments. For example, in the Ovens River, the analysis did not identify hydrological shifts, and this is reflected in the consistency of data points congregated around the line representing the pre-1997 relationship. Contrastingly, the remaining catchments show that the streamflow for a given rainfall was greater in previous years (blue to green) compared to more recently (yellow points).

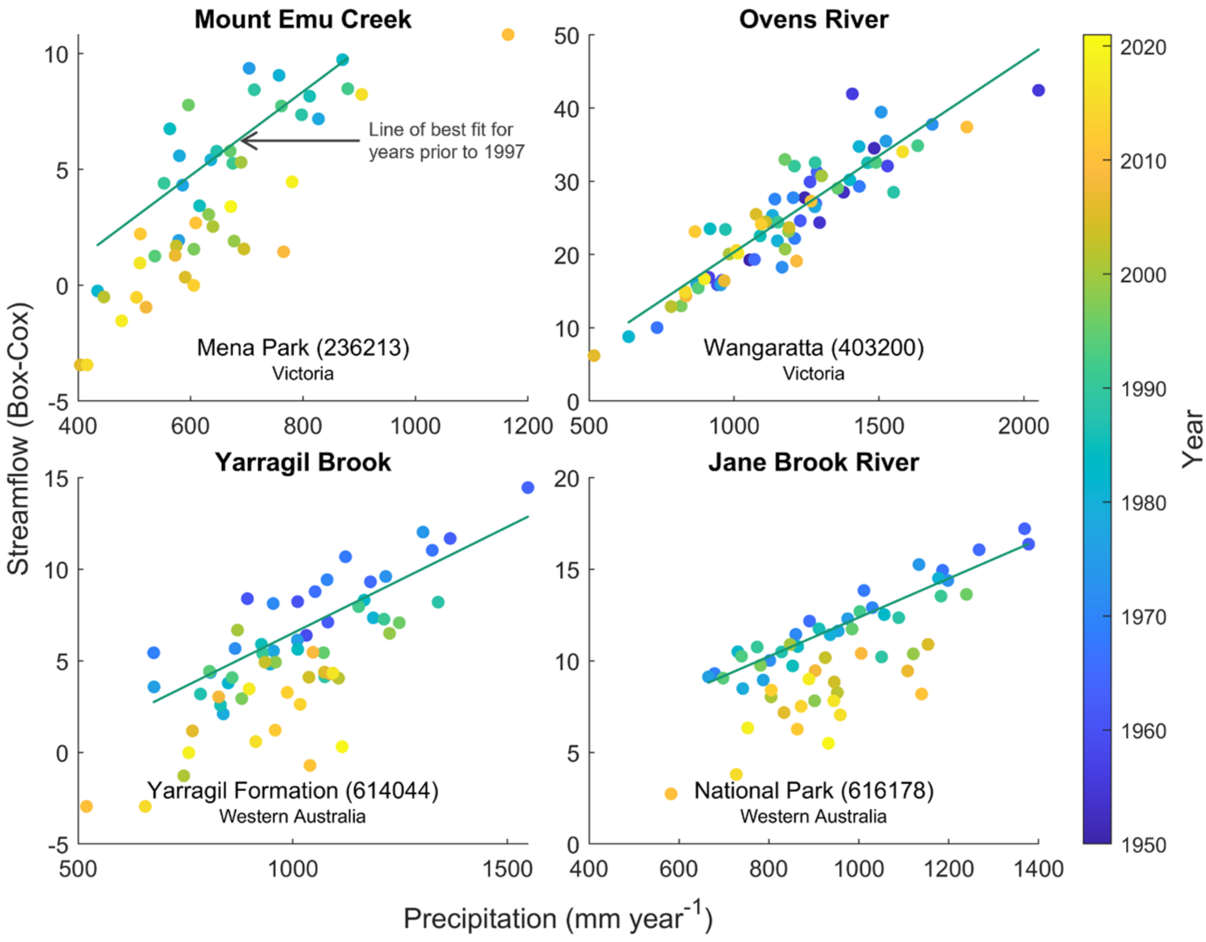


Figure 2: Annually aggregated and transformed streamflow data plot against annual precipitation for a selection of catchments across the study region, with each year of data coloured according to the legend displayed. A line of best fit has been plot for each catchment representing the estimated relationship between rainfall and runoff prior to 1997. Note that these plots are not an output of HydroState and are shown only for illustrative purposes.

In Western Australia, some general spatial patterns exist (Fig. 3), with the majority of catchments displaying hydrological shifts along the coast and towards the south of the region. The coastal catchments to the east have seen a relatively minor

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

reduction in rainfall (Fig. 1(d)), which may help to explain why they did not show shifts in relationships. In Eastern Australia, there is a variety of behaviour within New South Wales and South Australia. In Victoria, however, the previously reported concentration of hydrological shifts towards the west of the state is apparent (Peterson et al., 2021), and less change in rainfall-runoff relationship within the alpine catchments to the east.

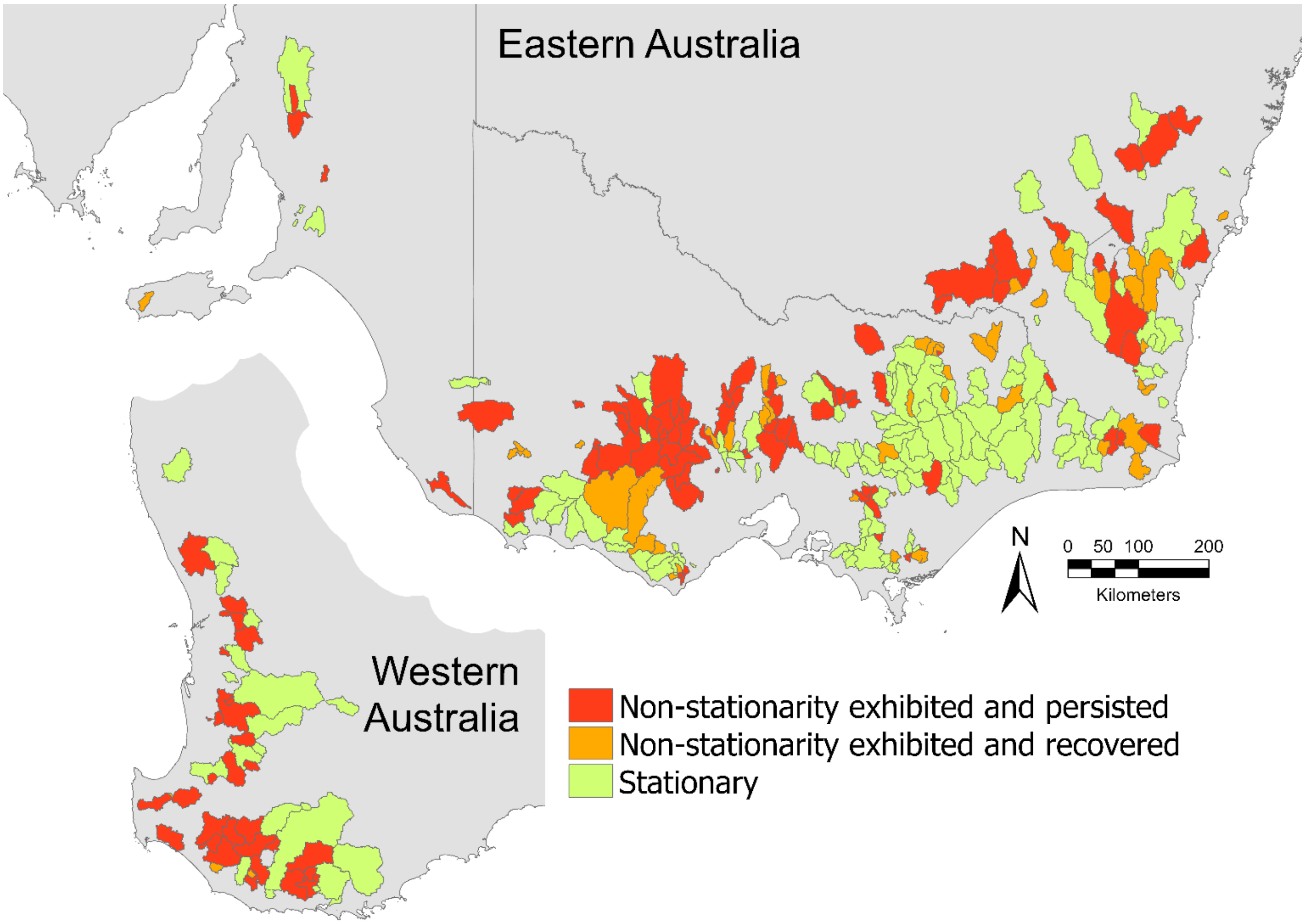


Figure 3: Spatial distribution of catchments which experienced hydrological shifts towards a lower flow state during their streamflow record and in which catchments this state persisted until the end of their streamflow record.

In Western Australia, the majority of catchment shifts occurred just after the year 2000 (Fig. 4), followed by some subsequent increases in the number of shifted catchments, particularly in 2010. Interestingly, the documented change in climate which began in the mid-1970s did not elicit a change in rainfall-runoff relationship, despite this change reducing inflows into municipal dams by more than half (McFarlane et al., 2012). Eastern Australia displayed a clear peak in shifted catchments immediately prior to the end of the Millenium drought in 2010. This was followed by a period where some catchments exhibited recovery and another less defined peak during the Tinderbox drought (2017-19).

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

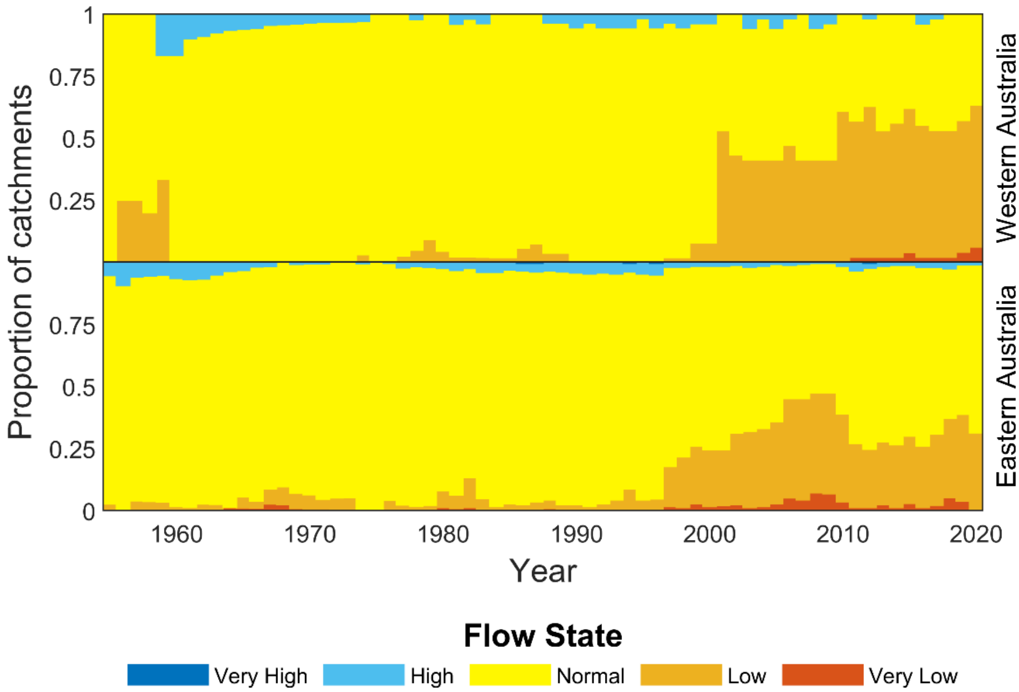
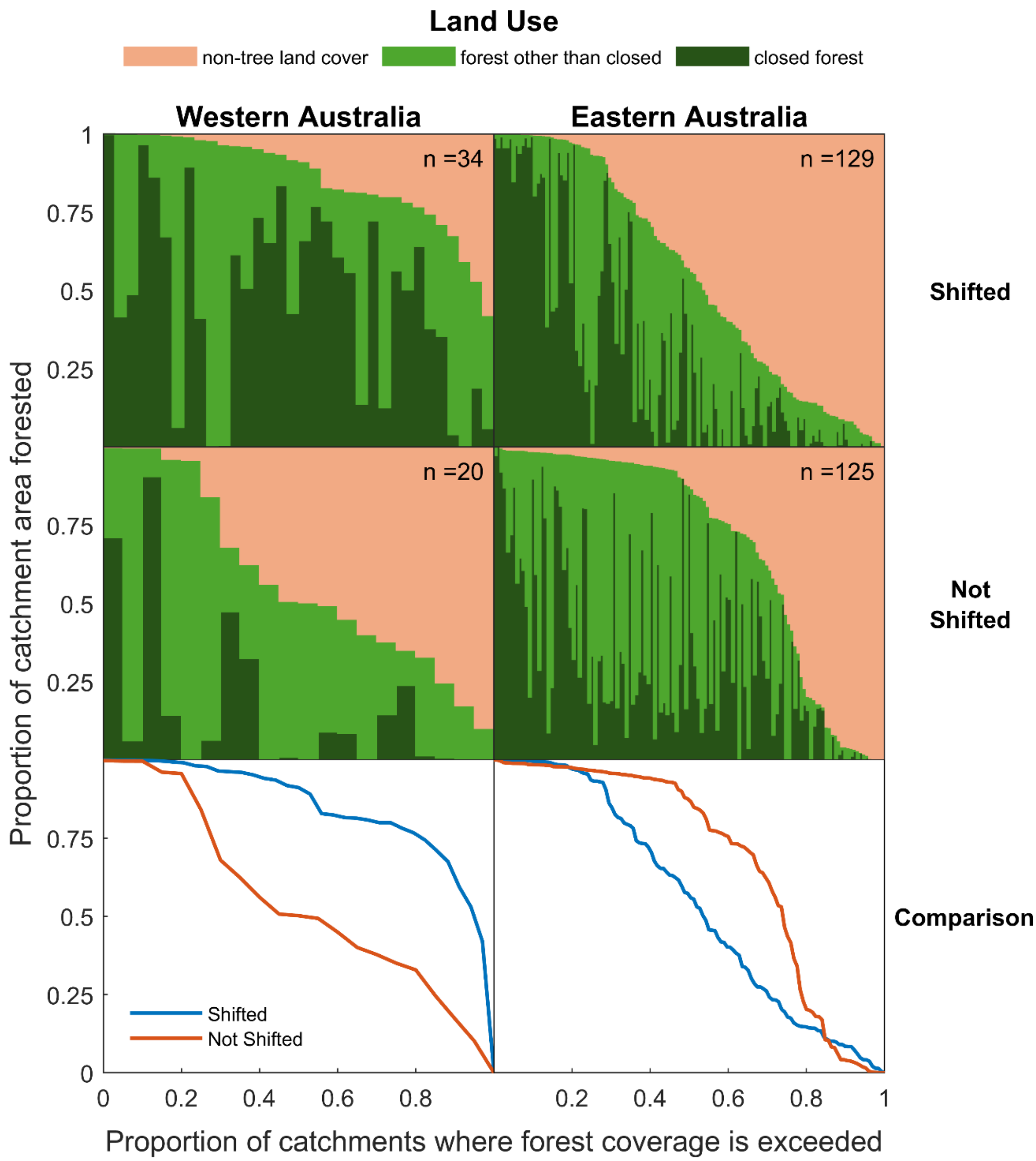


Figure 4: Proportion of catchments in each flow state over time in the two regions. Note that the number of catchments in the regions varies over time in line with gauging commencement at each site (leading to less catchments in the sample in the 1960s and 1970s compared to 1990s and 2000s).

Figure 5 compares the land use of catchments within each region, with catchments categorised according to the presence or absence of hydrological shifts (whether they saw a low flow state at some point in their streamflow record). It is seen that the shifted catchments in Western Australia tended to be those with greater forest coverage. In contrast, the forested catchments in Eastern Australia tended to be the least susceptible to shifts in rainfall-runoff relationship, as previously reported (e.g. Saft et al. 2015; 2016b). Thus, the pattern in the west is reversed in the east.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

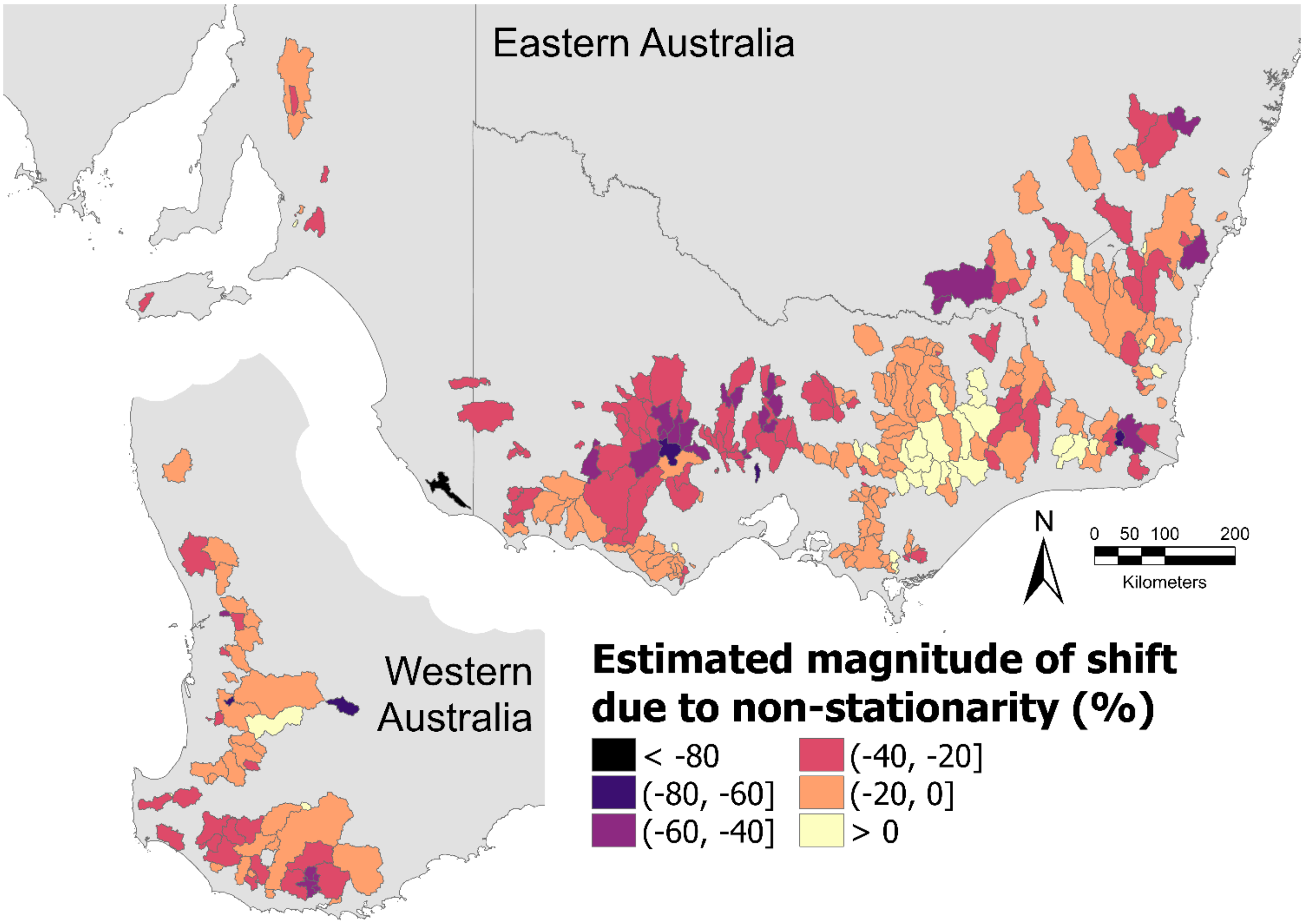


235 **Figure 5: Distributions of land use coverage across all catchments (each column represents one catchment) separated by region and by whether they experienced hydrological shifts towards a lower flow state during their streamflow record. The bottom panel compares the shifted and non-shifted distributions for the same region.**

When looking at the differences in residuals around the pre-1997 rainfall-runoff relationship (as described in Section 2.3.2), some key areas of concentration can be seen (Fig. 6). The greatest estimated proportion of water loss in Western Australia
240 can be seen further west and south. In Eastern Australia, the largest concentration of loss occurs to the north-west of

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

Victoria, with greater variation seen in southern New South Wales. The catchments which displayed generally lower losses were found in eastern Victoria.



245 **Figure 6: Average percentage difference between observed streamflow and approximate streamflow based on residuals around the pre-1997 rainfall-runoff relationship.**

When analysing the correlation between the magnitude of shift and the selection of 118 metrics, some categories showed significant correlation. These categories included land use type, climate and those associated with catchment topography.

As expected, given Fig. 5, in Western Australia, percentage coverage by closed forest (τ = -0.3138, p = 0.0008310) (Fig. 7) was significantly negatively correlated with the rainfall-runoff residuals and similar negative correlations were found with other metrics related to forest coverage (proportion of catchment forested and, natural and extant national vegetation information system (NVIS)). Conversely, sparse woodlands and cropping coverage were negatively correlated with closed forest coverage and positively associated with lowered water loss. Regarding metrics associated with climate, shifts in rainfall-runoff relationship were most significantly negatively associated with the recent average annual catchment rainfall (1997-2021, τ = -0.2886, p = 0.002114), and most significantly positively associated with the average annual potential

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

evapotranspiration prior to 1997 (1950-1996, τ = 0.2006, p = 0.03287). Average annual rainfall was also closely correlated with percentage coverage of closed forest (τ = 0.6394, p = 9.180E-12), which makes it difficult to isolate driving variables from covariates. Regarding metrics associated with catchment topography, these had a comparatively small influence on the estimated magnitude of shift for Western Australia, possibly because the catchments selected in Western Australia have little variation in slope and elevation relative to Eastern Australia.

In Eastern Australia, forest coverage contrastingly had a positive relationship with the estimated magnitude of shift, meaning less hydrological shifts in forested areas. The relationship with closed forest coverage, however, was weaker than in Western Australia (τ = 0.1753, p = 3.266E-05). With regards to climatic metrics, the most significant period of precipitation relative to the magnitude of shift was that prior to 1997 (1950-1996, τ = 0.4015, p = 1.563E-21). Interestingly, the catchments estimated to have lost the greatest proportion of streamflow had the lowest change in precipitation, with a significant negative correlation between the magnitude of shift and the difference between the average annual rainfall before and after 1997 (τ = -0.3409, p = 5.765E-16). This study region has greater variability in the landscape, as such a significant positive relationship is found between the shift magnitude and the mean slope in a catchment (τ = 0.3778, p = 3.030E-19). There is a significant negative relationship between shift magnitude and the average Multi-Resolution Valley Bottom Flatness (MRVBF; indicative of the extent of areas subject to deposition within the landscape) (τ = -0.3617, p = 9.038E-18).

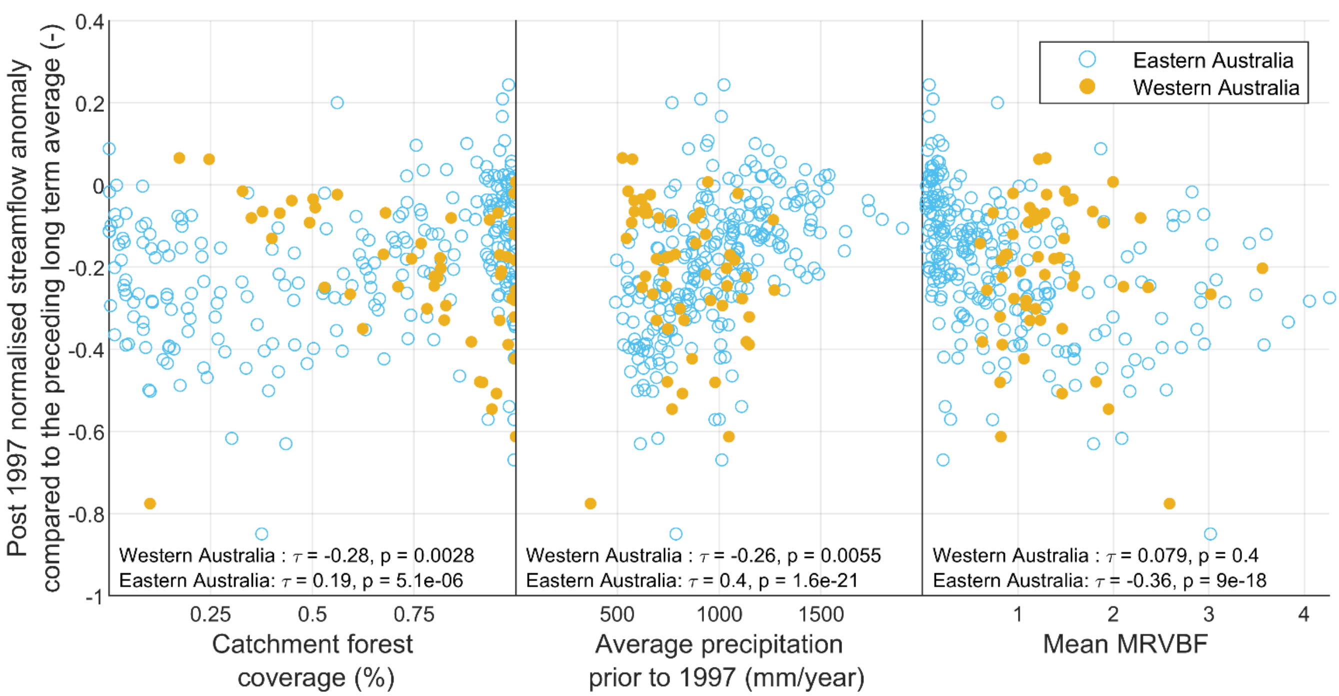


Figure 7: Correlation between the estimated magnitude of shift and a) the percentage of catchment area covered by closed forest, b) the average annual precipitation prior to 1997, and c) the mean Multi-Resolution Valley Bottom Flatness (MRVBF) within the catchment.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

3 Discussion

3.1 Identifying hydrological shifts

We are now able to answer the research questions posed in Section 1, the first of which was Where have hydrological shifts occurred throughout southern Australia, and are the temporal or spatial patterns similar between south-east and south-west? As expected, the results reveal hydrological shifts are widespread across both study regions. In south-western Australia, shifting catchments were in the majority, with coverage of most parts of the study area, but exceptions were found in the most inland catchments and those towards the south-east of the state, with the latter being subject to less change to rainfall over time. Overwhelmingly, the onset of shifts in the south-west was in or around the year 2000. This timing does not directly mirror the reported commencement of rainfall decline beginning in the 1970s (Hope et al. 2006), however, it does align with the study of Petrone et al. (2010) which found change points in streamflow in the early 2000s which were not reflected by change points in precipitation. This suggests that, despite the initial reductions in streamflow, the rainfall-runoff relationship remained consistent even with the changes in rainfall regime.

Comparatively, there were strong contrasts in both temporal and spatial patterns when comparing Eastern and Western Australia. In the east, the timing of shift lined up more closely with climatic forcing, with a large number of catchments shifting in response to the commencement of the Millennium Drought (in 1997) or drier years later in the same drought such as 2006. Likewise, the results showed stronger spatial patterns, with a large area in the east of the state of Victoria conspicuously lacking any hydrological shifts. As mentioned, these areas are the most mountainous, typically wetter and without significant land clearing, which is discussed further below. Both the temporal and spatial patterns reported here for the east region are consistent with Peterson et al. (2021), although the present study extends much further north and later in time.

3.2 Catchment characteristics

We now consider the second question, asking whether shifting catchments have common characteristics, and the last question, regarding causal processes. Firstly, let us consider forest cover. The results suggest that in Eastern Australia, forested catchments are less likely to experience hydrological shifts, while the opposite is true in Western Australia, where the forested catchments are more susceptible to shifts. Similarly, areas with lower annual average rainfall in Western Australia have a generally smaller shift magnitude, while the reverse is again true in Eastern Australia, where areas with lower annual average rainfall have a higher concentration of hydrological shifts. These two observations are linked, since forested catchments in both regions receive higher average annual rainfall. These results may appear contradictory initially, however, it is important to consider the correlation coefficient only reports how strongly associated two variables are, which may not denote cause. Thus, careful consideration is needed to unpack these apparent contradictions. We propose trends in groundwater levels and their interaction with surface water as an underlying driver of hydrological shifts in both regions, as

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

discussed below. This hypothesis, however, does not abandon the key role of land use in hydrological behaviour; indeed, the hypothesis can only explain the observations if the timing of historic land use changes is accounted for.

3.2.1 Climate and land-clearing-induced groundwater trends as a clue to causation

Both regions saw significant and widespread historic land clearing, and in both cases, this has led to significant salinity problems due to rising water tables (Gill et al., 2012; Raper et al., 2024; Caccetta et al., 2022). However, there are some key differences between the two regions. Cleared areas in Western Australia saw a rising groundwater trend throughout the 1980s, 90s and 2000s, despite significant (and mostly monotonic) climatic drying since the 1970s. Only recently have we seen a plateau or slow in the rise of the groundwater levels. Before we unpack the cause of this contradictory behaviour, we first consider Eastern Australia. Figure 8 shows that groundwater began a long decline in the 1990s, and remained low throughout the Millennium Drought, with an increase in 2010 with the floods that ended the drought. Broadly, the patterns follow periods of drought and wet across Eastern Australia, not only the Millenium Drought but also the Tinderbox Drought (2017-19) and wet years since. Note that these at-site measurements are broadly consistent in Eastern Australia with satellite gravity data (Leblanc et al., 2009; Fowler et al., 2020).

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

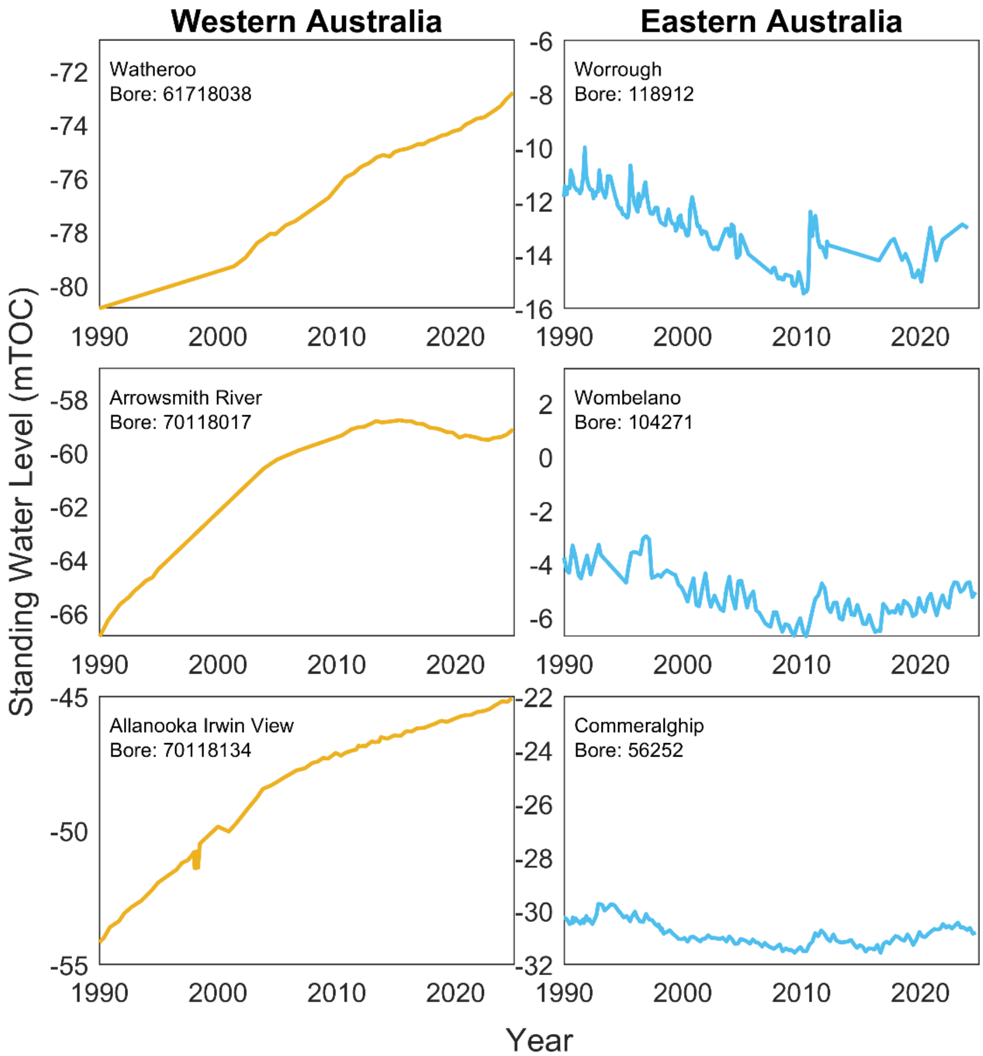


Figure 8: Groundwater bore records across catchments cleared for agriculture within the study region (Department of Energy, Environment and Climate Action, 2025; Department of Water and Environmental Regulation, 2025). The x and y axes have been equalised, with standing water level ranging across 10 metres and dates ranging from 1990 to 2024.

We propose that the timing in which land was cleared is responsible for these differing groundwater trends. Land clearing in Victoria began relatively early, prior to 1860, and reached a peak around 1900 (Table 1), according to the study by Sinclair et al. (2012), who constructed digital historic time slices of land use from primary resources, and the study of Bradshaw (2012) who conducted a review of relevant literature surrounding land use patterns in Australia. In contrast, land clearing in Western Australia did not start in earnest until the 20th century—for example, in 1890 less than 1% of clearing for agriculture had been completed (Table 1; Saunders, 1989). A key impetus for land clearing in the west was the return of World War 2 soldiers in the mid-1940s, who were given uncleared land to settle on, with the expectation they would clear it for agriculture. Thus, groundwater systems in Victoria had considerably more time to reach an equilibrium prior to the onset

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

of multi-annual drought in the 1990s than did western catchments, which explains why the groundwater trends in the east largely follow climate signals. In Western Australia, however, where groundwater tables were on an upward trajectory due to the later land clearing, it would appear that the reduced rainfall and pre-existing groundwater trend acted contrary to one another and may have partly or fully cancelled each other out. This would explain why we saw no apparent change in the rainfall-runoff relationship in the cleared catchments of Western Australia. In summary, it is hypothesised that a pre-existing rising trend in groundwater in Western Australian catchments acted contrary to the drying climate, meaning they appeared to remain stationary; whereas the eastern Australian catchments saw no such buffering and thus saw a change in rainfall-runoff relationship.

Table 1: Development of land clearing in South-west Western Australia and Victoria, Eastern Australia (developed using the data sources described in Appendix C).

	Year	*Western Australia*	*Eastern Australia*
Land cleared (as a % of total land cleared as at 1982)	1890	<1%	72.3%
	1945	46%	99.2%
	1982	100%	100%

While the impact of groundwater on streamflow generation varies based on local conditions (Stokes and Loh, 1982; Turner et al., 1987), existing research in our study area indicates it is a significant factor in the runoff generation process (Grigg and Kinal, 2020; Hughes and Vaze, 2015). Where the groundwater table is sufficiently high, contributions are provided not only directly through the stream but through the development of a variable source area, meaning less rain is required for saturation of the soil prior to runoff (Dunne and Black, 1970; Raiter, 2012). Clearing of land for agricultural purposes increases the apportioning of precipitation to recharge, as crops and pasture have less interception capacity than higher density vegetation (Schofield and Ruprecht, 1989) and have a reduced evapotranspiration demand (McFarlane et al., 1993). In Western Australia, the areas in which clearing has occurred are relatively homogeneous, and groundwater has been described as moving slowly (Sharafi et al., 2005), consistent with the remnant rise in groundwater table.

3.2.2 Extending causative analysis to forested catchments

The above hypothesis only covers cleared catchments and only partly explains why tree cover and hydrological shifts were correlated in the west and anti-correlated in the east. In Western Australia, the result is consistent with findings that deep rooted vegetation may continue to draw water needed for growth from the soil or groundwater table where precipitation in that year was not sufficient – findings supported both locally (Petrone et al., 2010; Smettem et al., 2013) and abroad (e.g. Avanzi et al., 2020).

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Preprint. Discussion started: 16 February 2026

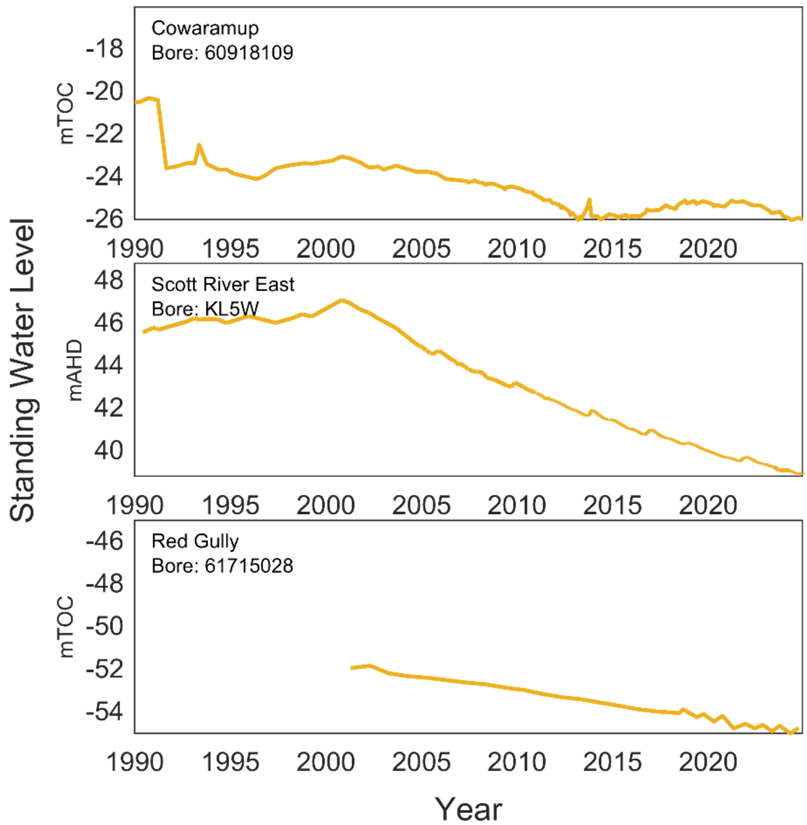


Figure 9: Groundwater bore records across forested catchments within Western Australia (Department of Water and Environmental Regulation, 2025).

Given these processes influencing streamflow generation in forested catchments in Western Australia, why are those in Eastern Australia not exhibiting the same behaviour? Firstly, we have comparatively good groundwater monitoring records in Western forested catchments showing declining trends (Fig. 9), but this is a knowledge gap for most forested catchments in the East, which are in a spatial gap in groundwater monitoring. Nonetheless, it is possible to gain a qualitative understanding of groundwater processes by considering the physical properties of these catchments. Compared to non-forested catchments in the east, forested catchments tend to:

- span a much higher elevation range, with many including alpine areas (>1,500 m elevation),
- have higher precipitation,
- be steeper, and
- be erosional (V-shaped valley bottoms), lacking the depositional locations which may facilitate interactions between surface and groundwater (Stein et al., 2021; Tetzlaff et al., 2009).

Due to the erosional characteristics of these landscapes, soils can be shallower, which further aids in permeability and the speed of drainage. This is reflected in Saft et al. (2016a) who (working in our east region) found catchments with a greater mean solum thickness had a greater magnitude of shift.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

If this is the case, this means the mechanisms related to groundwater which amplify or diminish streamflow may not be as significant in these steeper catchments of eastern Australia. As such, any declines in groundwater storage linked to rainfall reduction may not have triggered the same response in streamflow.

It is important to note, however, that some studies have demonstrated the significance of groundwater contributions in alpine catchments specifically (Frisbee et al. 2011). Fujino et al. (2023) support this theory in particular for vegetated catchments, where groundwater constituted a higher contribution in catchment runoff compared to those which were cleared. However, such studies typically examine the role of groundwater in seasonal flow dynamics rather than the multi-annual dynamics in focus here, and further research is recommended.

3.3 Limitations

As noted already, there are limitations to our study, with one of the most significant being the lack of groundwater bore data available within our catchments. We have presented a selection of groundwater bores and studies which observe general groundwater patterns within these regions, however, groundwater data are not available for all of our study catchments, particularly in mountainous catchments.

Further data is lacking in the timing of clearing. While satellite imagery or remote sensing data on land clearing are currently available and span wide regions, they are limited in their historic coverage. The historic land use changes in the east were inferred from a dataset that covers only a portion of the area (namely, the state of Victoria); while a similar dataset is not available for Western Australia across the periods of interest, forcing us to rely on disparate sources of information that state land clearance proportions at different points in time.

While we propose that the declining trend in groundwater storage is directly related to changes in climate and land use, it is worth noting that studies have proposed additional external factors, including human factors such as small private dams (e.g. Morden et al., 2024) and farming practices in agricultural areas (e.g. Yihdego and Webb, 2010). While these influences may be relatively minor compared to the magnitude of hydrological shifts at the catchment scale, they are examples of plausible minor changes to flow patterns which may also be present. Lastly, further work could examine the role of greening on the runoff behaviour of forested catchments (e.g. Ukkola et al., 2016; Ajami et al., 2017) and particularly whether any physiological differences between greening effects in the eastern versus western forests may contribute to the patterns seen here.

4 Conclusion

Although many studies have characterised shifts in rainfall-runoff relationship for individual regions, this study is the first to consider differences in driving processes across regions. The process of comparison yielded a greater level of understanding that could be gained from considering the regions separately, because the apparently contradictory results were ultimately instructive and prompted deeper consideration of causative factors. Specifically, the analysis indicated that forested catchments tended to be more susceptible to shifts in rainfall-runoff relationship in West Australia, yet less susceptible in

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

south-east Australia. We hypothesise that this is because western catchments were still equilibrating to mid-1900s land clearing, with groundwater levels still rising when the climate began to dry in the 1970s. Importantly, this suggests that these apparently stable catchments may be vulnerable to shifts in rainfall-runoff relationship once they fully equilibrate—a crucial insight that may not have occurred without the comparison across regions. Overall, this study suggests the importance of intercomparison and generalisations to develop richer and more insightful hypotheses to explain hydrological change, ultimately providing more robust and defensible projections of future water availability from rivers.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

Appendix A: Aridity index and seasonality of CAMELS-AUS catchments

The method of Knoben et al. (2018) was applied to calculate both the Moisture Index Seasonality and Annual Average Moisture Index of all CAMELS-AUS v2 catchments, with the equations as follows:

$$MI(t) = \begin{cases} 1 - \frac{E_p(t)}{P(t)}, & P(t) > E_p(t) \\ 0, & P(t) = E_p(t) \\ \frac{P(t)}{E_p(t)} - 1, & P(t) < E_p(t) \end{cases} \tag{A1}$$

$$Annual\ Average\ Moisture\ Index;\ I_m = \frac{1}{12}\sum_{t=1}^{t=12} MI(t) \tag{A2}$$

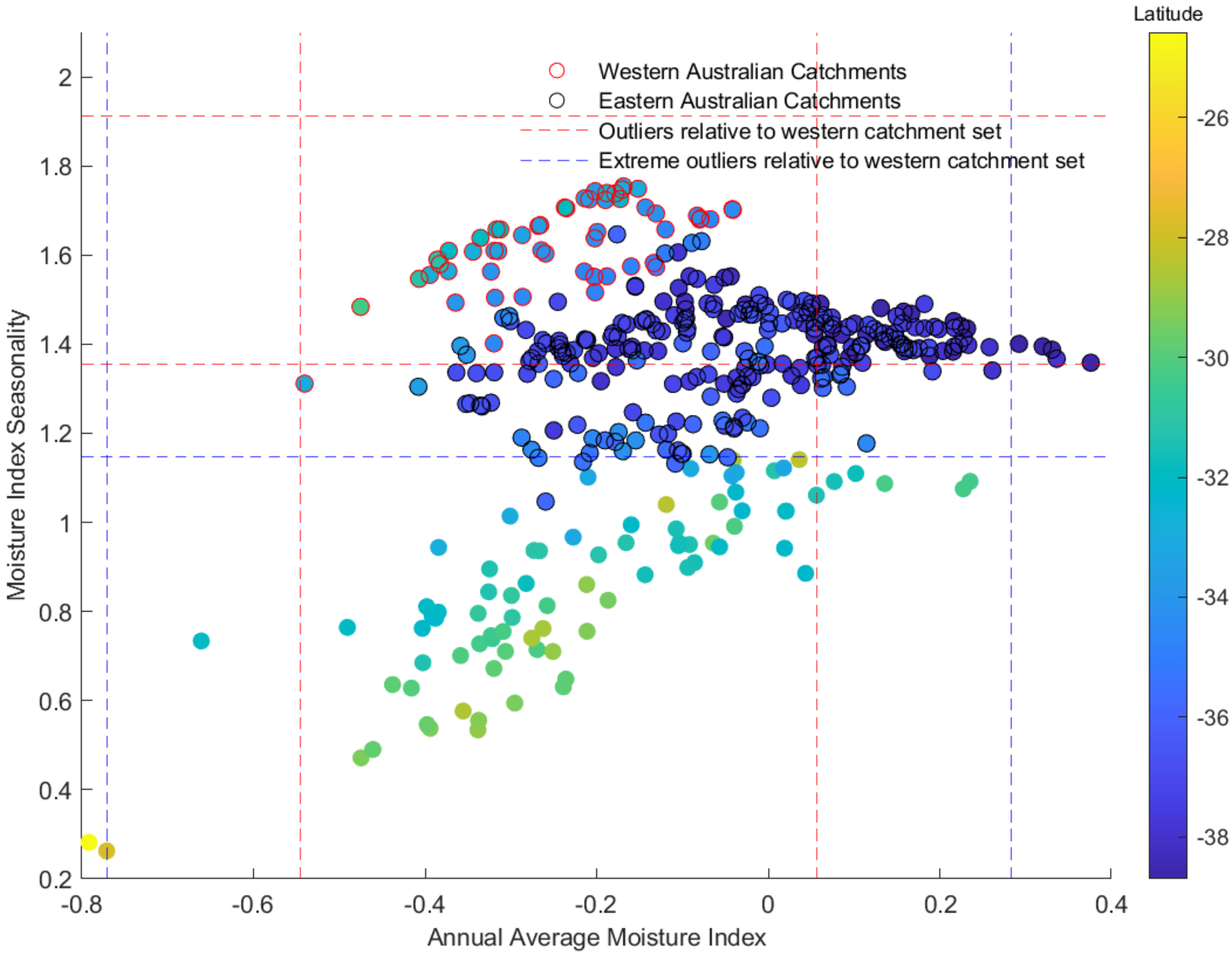
$$Moisture\ Index\ Seasonality;\ I_{m,r} = \max\big(MI(1,2,\dots 12)\big) - \min\big(MI(1,2,\dots 12)\big) \tag{A3}$$

Where $P(t)$ is the precipitation, $E_p(t)$ is the potential evapotranspiration and MI is the moisture index calculated separately for t, each month of the year from 1950 to 2021. Resulting metrics from Eastern Australia were then compared to those in Western Australia through calculating at what value the metric became an extreme outlier, where:

$$Extreme\ outliers = \begin{cases} Q1 - 3 * IQR \\ Q3 + 3 * IQR \end{cases} \tag{A4}$$

Extreme outliers were selected to ensure a sufficiently large sample size, rather than what was afforded by determining outliers alone. Following from this, it was found that the Moisture Index Seasonality was the main separating factor (Fig. A1), as such, catchments below a seasonality of approximately 1.15 were excluded.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026



425 **Figure A1: Scatter plot of annual average moisture index versus moisture index seasonality for every CAMELS-AUS v2 catchment in the south-eastern states (Victoria, New South Wales, Australian Capital Territory and South Australia), with points coloured according to latitude. Catchments in Western Australia are outlined in red. Since the intent with selection of eastern catchments was to ensure they were not too different from western catchments, the plot also quantifies the degree of difference by showing the 'outliers' and 'extreme outliers' defined according to the above equations (dashed red and blue lines). The catchments then**
430 **selected for the analysis from the south-eastern states are outlined in black.**

Appendix B: Metrics assessed for correlation

Table B1: Metrics assessed for correlation taken from CAMELS-AUS v2 (Fowler et al., 2025). Refer to the CAMELS-AUS v2 data description for further information on these values and their original sources.

Metric name	***Metric name***	***Metric name***	***Metric name***
elev_min	lc15_alpineg	nvis_nodata_n	leveebank_fac

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

elev_max	lc16_openhum	nvis_nodata_e	infrastruc_fac
elev_mean	lc18_opentus	geol_prim_prop	settlement_fac
elev_range	lc19_shrbsca	geol_sec_prop	extract_ind_fac
mean_slope_pct	lc24_shrbden	unconsoldted	landuse_fac
upsdist	lc25_shrbope	igneous	catchment_di
strdensity	lc31_forclos	silicsed	flow_regime_di
strahler	lc32_foropen	carbnatesed	river_di
elongratio	lc33_woodope	othersed	pop_mean
relief	lc34_woodspa	metamorph	pop_max
reliefratio	lc35_urbanar	sedvolc	pop_gt_1
confinement	nvis_grasses_n	oldrock	pop_gt_10
lc01_extracti	nvis_grasses_e	claya	erosivity
lc03_waterbo	nvis_forests_n	clayb	anngro_mega
lc04_saltlak	nvis_forests_e	sanda	anngro_meso
lc05_irrcrop	nvis_shrubs_n	solum_thickness	anngro_micro
lc06_irrpast	nvis_shrubs_e	ksat	gromega_seas
lc08_rfcropp	nvis_woodlands_n	solpawhc	gromeso_seas
lc09_rfpastu	nvis_woodlands_e	distupdamw	gromicro_seas
lc11_wetlands	nvis_bare_n	impound_fac	npp_ann
lc14_tussclo	nvis_bare_e	flow_div_fac	

435 **Table B2: Metrics assessed for correlation and calculated as part of the analysis.**

Metric name	***Meaning***	***Metric name***	***Meaning***
mrvbf	Average Multi-Resolution Valley Bottom Flatness of the catchment calculated from mrvbf_prop_0 – mrvbf_prop_9.	1975_2021_PET_ltac	Difference between the average annual potential evapotranspiration (PET) after 1975 (1975-2010) and the average annual PET across the streamflow record (1950-2021) (mm).
prop_forested	Combination of all land coverage categories associated with forestry (lc31 – 34).	1975_2021_PET_ltac_perc	Difference between the average annual PET after 1975 (1975-2010) and the average annual

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

Metric name	***Meaning***	***Metric name***	***Meaning***
			PET across the streamflow record (1950-2021) as a percentage of the average annual PET across the streamflow record (%).
prop_forested_except_closed	Combination of all land coverage categories associated with forestry, except closed (lc32 – 34).	1975_2021_PET_ltac_spring	Same as above, calculated for spring months only (September, October, November) (mm).
prop_past_crop	Combination of all land coverage categories associated with pasture and cropping (lc05, lc06, lc08, lc09).	1975_2021_PET_ltac_spring_perc	Same as above, calculated for spring months only (September, October, November) (%).
prop_non_forested	Combination of all land coverage categories not associated with forestry (1 – prop_forested).	1950_1996_P_av	Average annual rainfall from 1950 to 1996 (mm).
seasonal_aridity_index	Moisture index seasonality, as per Knoben et al. (2018).	1997_2021_P_av	Average annual rainfall from 1997 to 2021 (mm).
aridity_index	Annual average moisture index, as per Knoben et al. (2018).	1950_1996_PET_av	Average annual PET from 1950 to 1996 (mm).
Mill_P_ltac	Difference between the average annual rainfall during the Millenium Drought (1997-2010) and the average annual rainfall across the streamflow record (1950-2021) (mm).	1997_change_prop	Difference between the average annual rainfall before and after 1997 as a proportion of the rainfall prior to 1997 (-).
Mill_P_ltac_perc	Difference between the average annual rainfall during the Millenium Drought (1997-2010) and the average annual rainfall across the streamflow record (1950-2021) as a percentage of	1997_change_mm	Difference between the average annual rainfall before and after 1997 (mm).

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

Metric name	***Meaning***	***Metric name***	***Meaning***
	the average annual rainfall across the streamflow record (%).		
Mill_P_ltac_winter	Same as above, calculated for winter months only (June, July, August) (mm).	aridity_P_over_PET_pre1997	Rainfall divided by PET from 1950 to 1996 (-).
Mill_P_ltac_winter_perc	Same as above, calculated for winter months only (June, July, August) (%).	1950_1974_P_av	Average annual rainfall from 1950 to 1974 (mm).
1975_2021_P_ltac	Difference between the average annual rainfall after 1975 (1975-2010) and the average annual rainfall across the streamflow record (1950-2021) (mm).	1975_2021_P_av	Average annual rainfall from 1975 to 2021 (mm).
1975_2021_P_ltac_perc	Difference between the average annual rainfall after 1975 (1975-2010) and the average annual rainfall across the streamflow record (1950-2021) as a percentage of the average annual rainfall across the streamflow record (%).	1975_change_prop	Difference between the average annual rainfall before and after 1975 as a proportion of the rainfall prior to 1975 (-).
1975_2021_P_ltac_winter	Same as above, calculated for winter months only (June, July, August) (mm).	1950_2021_P_av	Average annual rainfall from 1950 to 2021 (mm).
1975_2021_P_ltac_winter_perc	Same as above, calculated for winter months only (June, July, August) (%).	1950_2021_PET_av	Average annual PET from 1950 to 2021 (mm).
Mill_PET_ltac	Difference between the average annual potential evapotranspiration (PET) during the Millenium Drought (1997-2010) and the average annual	aridity_P_over_PET	Rainfall divided by PET from 1950 to 2021 (-).

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

Metric name	***Meaning***	***Metric name***	***Meaning***
	PET across the streamflow record (1950-2021) (mm).		
Mill_PET_ltac_perc	Difference between the average annual PET during the Millenium Drought (1997-2010) and the average annual PET across the streamflow record (1950-2021) as a percentage of the average annual PET across the streamflow record (%).	saft_mag_shift_av	Standardised differences in residuals around the pre-1997 rainfall-runoff relationship (as described in Section 2.3.2).
Mill_PET_ltac_spring	Same as above, calculated for spring months only (September, October, November) (mm).	saft_mag_shift	Average magnitude of differences in residuals around the pre-1997 rainfall-runoff relationship (as described in Section 2.3.2).
Mill_PET_ltac_spring_perc	Same as above, calculated for spring months only (September, October, November) (%).		

Appendix C: Land use cover change

C1 Eastern Australia

The dataset used as an analogy for change in land use throughout Eastern Australia is the Land Use History data (1837-2005) dataset (Sinclair et al., 2012; Department of Energy, Environment and Climate Action, 2021) which depicts the land use coverage information for Victoria within time slices ranging from 1837 to 2005 through compilation of primary historical sources. To determine the percentage of land cleared each year, we combined all coverage types associated with clearing, including irrigated, built and cropping land types. To align with the points in which data is available in Western Australia, a linear relationship was fit between the years on either side of 1890, 1945 and 1982, and the percentage cleared was estimated for this relationship.

This dataset is only representative of Victoria, however, as the majority of the catchments being analysed are in Victoria (75%), including those cleared catchments most impacted by the Millenium drought, we propose this is a suitable indicator

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

of land clearing trends for our study area. This is supported by Bradshaw (2012), who suggests that a large proportion of clearing happened during the 19th century in NSW as a result of it being the earliest settled state.

We present end points in 1982 for both regions of Australia as the dataset suggests only minor increases in land clearing after this time (Fig. C1), while other studies (e.g. Fowler et al., 2022) suggest that salinity remediation works resulted in revegetation in some areas.

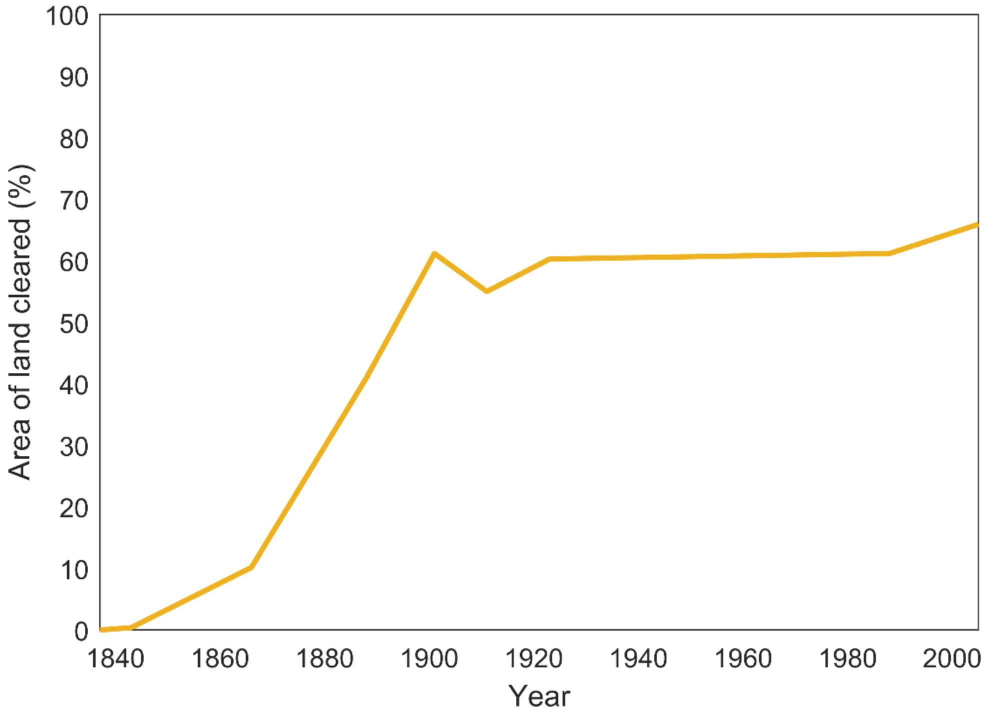


Figure C1: Land clearing timeseries across the state of Victoria (land use information obtained from Department of Energy, Environment and Climate Action (2021) dataset).

C2 Western Australia

In south-west Western Australia, land use coverage data is rare and systematic change through time is typically not reported. As such, in lieu of a dataset, we use Saunders (1989, p. 3) who reports that "*54% of all land developed for agriculture was cleared between 1945 and 1982*". Saunders also reports that only 500 km² had been cleared by 1890 compared to 130,000 km² by 1968. As such it can be deducted that the total cleared area in 1982 was greater than 130,000 km^2, meaning in 1890, less than 1% of the total land area that was to be cleared had been.

Regarding clearing patterns post 1982, we refer to Caccetta et al. (2001) and Western Australian Government (2025) which have information regarding vegetation coverage from 1972 onwards. Woody coverage from the period 1982 to 2022 appears to remain constant or slightly increase.

https://doi.org/10.5194/egusphere-2026-378
Preprint. Discussion started: 16 February 2026

As per Andrich and Imberger (2013) the area of land being farmed for wheat can also be used as analogy for the amount of land cleared. Figure C2 reinforces the above understanding that the majority of clearing occurred within the second half of the twentieth century.

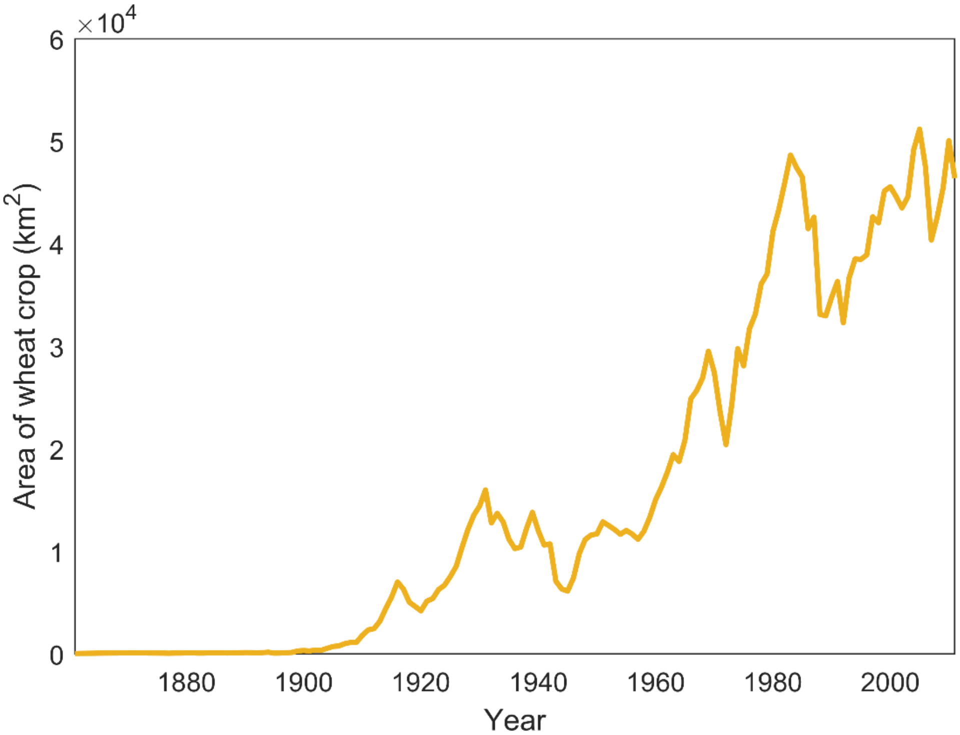


Figure C2: Area of land being farmed for wheat in Western Australia (land use information obtained from Australian Bureau of Statistics (2013) dataset).

Code and data availability

Hydroclimatic data used in this study are freely available as part of the CAMELS-AUS v2 database (Fowler et al. 2025), found at https://doi.org/10.5281/zenodo.12575680. Groundwater data for Victoria and Western Australia are also freely available and can be found at https://data.water.vic.gov.au/WMIS and http://wir.water.wa.gov.au/, respectively.
The R-package, hydroState (Peterson et al., 2021), used to perform Hidden Markov Modelling, is open source and can be found at https://github.com/peterson-tim-j/HydroState.

Author contributions

KF conceptualized this article, supervised its execution and conducted project administration. NC curated the data, undertook the formal analysis, visualized the outcomes and prepared the original draft. All parties contributed to the reviewing & editing of the transcript, in addition to development of the methodology.

Competing interests

At least one of the (co-)authors is a member of the editorial board of *Hydrology and Earth System Sciences.*

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