Assessment of non-stationarity in the northern basin

Anjana Devanand, Michael Leonard and Seth Westra

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Contact

Intelligent Water Decisions research group
School of Civil, Environmental and Mining Engineering
University of Adelaide

Physical: Engineering North Building North Terrace Campus University of Adelaide, Adelaide. Postal:

University of Adelaide, Adelaide, 5005

Telephone: (08) 8313 5451

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Executive summary

The Department of Planning and Environment (DPE) has used a risk-based methodology to account for climate variability and change in developing its Regional Water Strategies (RWS), in which the climate risk assessment is informed by the use of stochastically generated long-term sequences that reflect potential climate patterns beyond those contained within the instrumental record. An independent expert panel review of this climate risk method commended many aspects of the methodology, but recommended further review of the potential non-stationarity of historical climate data used to inform the stochastic models, to determine whether changes in climate in recent decades affect estimates of present-day climate risk compared with climate risk based on the whole observed record, by (a) assessing non-stationarity of the historical record; and (b) split sample testing of the stochastic model.

These recommendations were addressed in the context of the key hydrological variables of rainfall, temperature and evapotranspiration for the southern basin, using a 'multiple lines of evidence' approach to determine the presence and potential causes of any non-stationarity. Multiple lines of evidence indicate the presence of non-stationarity in temperature and cool season rainfall totals in the southern basin. A similar assessment is undertaken for the northern basin in New South Wales. This report documents the results of this assessment and includes a review of literature documenting changes in rainfall in the region; a review of future climate projections; and trend analysis and split sample testing using data from pilot sites in the northern catchments.

The main findings are summarised as follows.

Stationarity of rainfall in the northern catchments

The multiple lines of evidence examined to assess non-stationarity are described as follows.

- Trends in literature and at the pilot sites: In the literature, there are no major trends reported in seasonal totals in the historical record in this region, although there is some consensus on short-term decreasing trends in the number of wet days in the region. In contrast, the analysis of pilot sites in the northern catchments reveals that there are significant trends in a number of different attributes of rainfall. The trends that are consistent in sign in both short-term (post-1950) and long-term (post-1890) trend analysis are:
  - decreasing JJA rainfall totals and number of heavy rainfall days in JJA at the Namoi-Gwydir-Border pilot sites
  - decreasing number of wet days in MAM and JJA at the Lachlan-Macquarie pilot sites.

  The discrepancy between findings from the literature and from the pilot sites are likely to be because of differences in definitions of the study region, period of record and/or trend detection methodology. Although this study does not seek to attribute trends to a cause, it is likely that the significant trends detected at the pilot sites consist of a combination of low-frequency variability and climate change signal.

  There is agreement between literature and the results from the pilot sites on a short-term (post-1950 or post-1970) decreasing trend in the annual number of wet days; there is no consensus on trends in other attributes and seasons. There are fewer significant trends in annual and seasonal totals in the northern pilot sites compared to the trends detected in the southern basin pilot sites documented in the previous report. However, the existing field significant trends are similar in magnitude to those in the southern pilot catchments. In these northern catchments, field significant trends are detected mainly in the number of wet days and number of heavy rainfall days, with fewer significant changes in the corresponding seasonal totals compared to the southern pilot catchments.

- Interpretation of recent droughts and role of natural climate variability: Climatic processes associated with low-frequency Interdecadal Pacific Oscillation (IPO) interact with higher frequency variability associated with El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM) to drive persistent wet–dry rainfall patterns in this region. The northern basin has experienced droughts in the recent past as well as in the first half of the 20th century prior to 1945. The observed rainfall during the Millennium Drought has been reported to be within the natural variability of the northern basin. The recent drought that started in 2017 has resulted in record low rainfall across much of the northern basin; however, definitive attribution of causes is not yet possible.
- Future projections: The projections indicate that the sign of near-term changes in annual total rainfall cannot be projected reliably; natural variability is expected to be the major driver in the short term. Towards the latter half of the 21st century, the projections report with higher confidence that winter and spring rainfall will decrease. Regional projections also indicate that autumn rainfall may increase in the longer term.

The importance of the stochastic generation calibration period for key statistics

The split sample tests do not show clear benefits from including or excluding the Millennium Drought in the calibration period. The differences between the simulations and the validation period are dependent upon how similar the calibration and validation periods themselves are for specific attributes and seasons. For example, in the Namoi-Gwydir-Border region, split sample simulations excluding (or including) the Millennium Drought in the calibration period show that the simulations overestimate the JJA total rainfall by a median of +23 (+10) mm/season. That is, there is a reduction in the biases in JJA total rainfall after inclusion of the drought in the calibration period. However, the same simulations show an increase in biases in simulations of DJF total rainfall from −4.4 to +22 mm/season after inclusion of the drought in the calibration period.

Overall, although there is some evidence of trends for several key attributes for the pilot sites, in aggregate the alternate lines of evidence do not converge to indicate the clear presence of non-stationarity in the historical record of the northern basin. Furthermore, although some trends are consistent with those anticipated from climate models over the 21st century, overall, it is likely that natural variability continues to play an important role. Thus, it is not yet possible to formally attribute historical trends to anthropogenic climate change.

1 Introduction

The Department of Planning and Environment (DPIE) has used a risk-based methodology to account for climate variability and change in developing the Regional Water Strategies (RWS). The method involves the use of stochastically generated long-term sequences of climate data to characterise the 'current' climate, and the application of scaling factors to the stochastic data to generate future climate projections. The stochastic modelling uses historical (observed and reconstructed) records of daily rainfall, evapotranspiration and temperature to generate synthetic data for 10,000 years that reflect variability over the instrumental record from 1889 to 2018. The stochastic sequences provide insights into natural climate variability beyond the available observations. The scaling factors for a future climate are derived based on projections from the New South Wales and Australian Regional Climate Modelling (NARCliM) project, and applied to the stochastic data to characterise future climate risk.

The stochastic data generation methodology has been applied to multiple basins across New South Wales using a multisite stochastic data generator conditioned on the Inter-decadal Pacific Oscillation (IPO) documented in Leonard & Westra (2020). An independent expert panel review of the DPIE climate risk method recommended that ongoing improvement of the stochastic generation methodology be given high priority. The panel recommended further work to understand the implications of the existence of non-stationarity in the instrumental record of the southern New South Wales region on stochastic time series generation. To address this question, a review of literature, future climate projections and analysis of pilot sites in southern New South Wales was undertaken to assess the presence of non-stationarity in this region. The results of this study are documented in the report entitled *Implications of Non-Stationarity for Stochastic Time Series Generation in the Southern Basins*. Multiple lines of evidence indicate the presence of non-stationarity in the historical record of the southeast Australia (south of 33°S and east of 135°E).

In this report, a similar analysis employing multiple lines of evidence is undertaken to assess the presence of non-stationarity in the historical record for the northern New South Wales basins comprising the Macquarie, Lachlan, Namoi, Gwydir and Border catchments. This report includes a review of the reported historical changes in rainfall in this region, regional future projections and analysis of pilot rainfall sites in the region to assess historical trends and perform split sample testing of the stochastic model. Figure 1 shows the northern catchments along with north–south basin divisions referred to by the Murray–Darling Basin Authority (MDBA), and sub-clusters used by the Climate Change in Australia (CCIA) for future projections. All the northern catchments under consideration, except Lachlan, are located in the northern basin and the CCIA Central Slopes sub-cluster. This report therefore reviews relevant MDBA reports and CCIA projections with specific focus on this basin and sub-cluster.

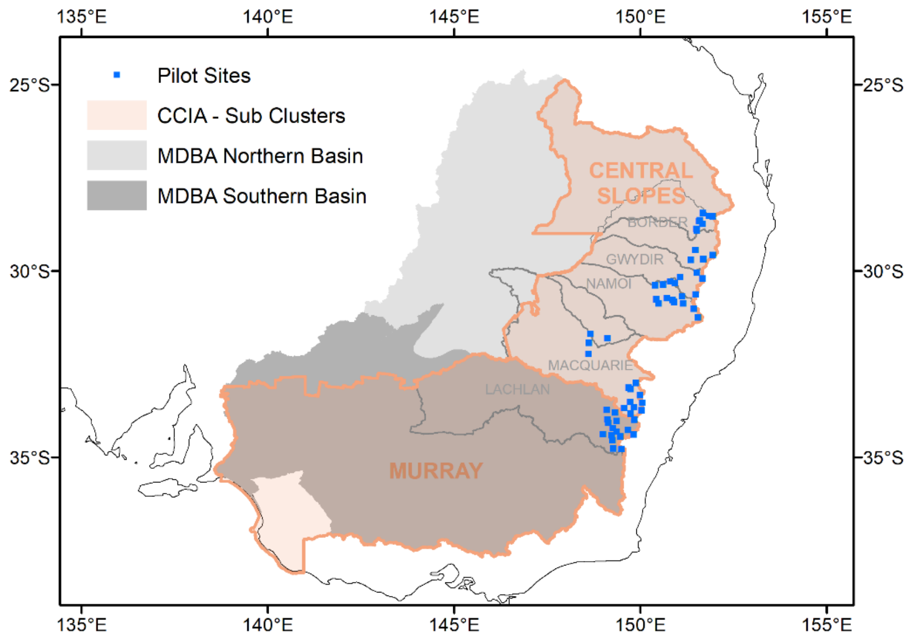


Figure 1 Location of northern catchments and pilot sites, northern and southern basins referred to in MDBA reports, and sub-clusters used by Climate Change in Australia

2 Historical rainfall record of the northern basin

2.1 Summary of rainfall patterns and teleconnections

The rainfall patterns in the northern basin are different from that in the southern basin of the MDB. The southern basin experiences a winter-dominated precipitation regime. In contrast, the northern basin receives more rainfall during the warm season. There is considerable spatial and seasonal variation in rainfall across the region. The eastern part of the northern basin experiences more rainfall and larger number of wet days (Ekström et al. 2015). The typical rainfall pattern averaged across the Central Slopes sub-cluster shows a drier winter and wetter summer (Ekström et al. 2015). The climate mechanisms that generate rainfall in the northern basin during the different seasons are different and more complex than those in the southern basin. As a result, the historical record of this region exhibits more variability. The northern basin has multiyear cycles of wetting and drying in the observed rainfall record (MDBA, 2018), which are linked to large-scale patterns of global ocean–atmosphere variability. The region experienced more variability in the second half of the 20th century, and this period contains individual wet years and multiyear periods of below-average rainfall (Ekström et al. 2015).

At decadal scales, this rainfall variability is related to oscillations of the conditions in the Pacific basin, which is described by an index known as the IPO. The negative phase of the IPO is associated with higher rainfall in the northern basin. At interannual and seasonal scales, the rainfall is also influenced by El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM); with varying influences during different seasons. The phases of the IOD are associated with the variability of winter and spring rainfall in this region. During negative phases of the IOD, the sea surface temperatures off the coast of northwest Australia are higher, and this phase enhances the winter and spring rainfall in eastern Australia (Verdon & Franks, 2005). SAM, which is the leading mode of extratropical variability in the southern oceans, modulates the westerlies and frontal systems that bring rainfall to the region during the cool season (Nicholls 2010).

The different scales of variability interact with each other. For example, negative IPO phase concurrent with conductive ENSO or IOD conditions are associated with summer floods in this region (Ekström 2015; CSIRO 2012). Moreover, the extent to which the IPO is a separate mode of variability or simply the low-frequency representation of the ENSO phenomenon is still debated in the literature (Westra et al. 2015). The low-frequency (15–35 years) pattern of variability of the IPO appears to modulate the intensity and frequency of the ENSO events; a positive IPO phase is associated with enhanced El Niño events and lower rainfall in the northern basins and vice versa (Verdon et al. 2004). The stochastic model used to generate synthetic time series in the northern basin (Leonard & Westra 2020) is conditioned on the IPO. Based on the full dataset (years 1890 to 2018) originally used for stochastic simulations in the Namoi-Gwydir-Border catchments (Leonard & Westra 2020), the mean differences in regional rainfall between the positive and negative phases of the IPO amount to 47–74 mm in this region (Table 1).

Table 1 Differences in average annual totals of rainfall in the northern catchments with respect to the state of the IPO

Catchment	Number of rainfall sites	Annual rainfall (mm) IPO –ve minus IPO +ve
Namoi	68	74
Gwydir	24	66
Border	93	47

The interactions of climatic processes associated with IPO, ENSO, IOD and SAM drive persistent wet–dry patterns of rainfall in this region (Verdon-Kidd & Kiem, 2009).

2.2 Historical changes and trends in rainfall

Similar to the southern basin, the northern basin experienced the Millennium Drought in the beginning of the 21st century. The Millennium Drought in the northern basin was not as pronounced and started post-2000s, that is, later compared to the southern basin (Chiew et al. 2009). The average annual rainfall in the northern basin during the Millennium Drought is similar to the observed rainfall in the historical record before 1945 (MBDA 2018). A seasonal reduction in rainfall during the cool season was observed during the drought. Specifically, the Millennium Drought was associated with decreases in winter and spring rainfall in the northern region. It is reported that there are more days with less intense rainfall such that rainfall from heavy intensity events makes up a lower proportion of the annual totals in the recent historical record (MDBA 2018). But due to the higher variability in this region, these rainfall declines during the Millennium Drought lie within natural variability and are not at the extreme end of the historical rainfall distribution (Chiew et al. 2009).

The northern basin entered into another multiyear meteorological drought in 2017, and most of the basin has experienced record low rainfall at timescales of 18 months to 3 years during this recent period. The rainfall during the current drought is substantially lower than the previous records (BoM 2019). The IOD and SAM conditions during specific seasons within the past three years have been conducive for the sustenance of drought conditions (BoM 2019). The reasons behind the ongoing drought have not been definitively identified.

The long-term rainfall in the Central Slopes sub-cluster is not reported to exhibit any significant trends in the literature (Ekström et al. 2015). To our knowledge, trends analysis studies on smaller spatial scales focused on specific catchments in this region are not available in literature. Hence, we collate the available information using country-wide studies, specifically focusing on the results for the northern basin in Table 2.

Table 2 Summary of reported rainfall trends in the historical record of the northern basins

Authors	Dataset	Period	Region	Index type	Findings
Gallant et al. (2007)	Stations (95 across Australia)	1910–2005 1950–2005	Six regions in Australia. The Western Tablelands cover parts of the northern basin	• Total rain • Rain days (threshold = 1 mm) • Mean rain per rain day • Extreme intensity, frequency, and proportion of the total (95th and 99th percentile thresholds)	The Western Tablelands do not exhibit many significant trends. There are no long-term or medium-term trends in annual and seasonal total rainfall. In the long term (1910–2005), the number of wet days in SON shows an increasing trend. In the medium term (1950–2005), the annual number of wet days shows a decreasing trend.
Taschetto & England, (2009)	Gridded BoM rainfall data at 0.5° resolution	1970–2006	Whole country	• Annual and seasonal total rainfall • Frequency of moderate (up to 1 SD from the mean), heavy (from 1 to 2 SD from mean), very heavy (more than 2 SD from mean) rainfall events	There are no major trends in the northern basin. The DFJ total rainfall shows significant decreasing trends over some parts of the region. The annual frequency of moderate rainfall events also shows decreasing trends over part of the northern basin.
Ukkola et al. (2019)	Area average records from BoM for 6 regions across Australia	1900–2018	Whole country	• Annual and seasonal totals	The DJF total rainfall shows significant increasing trends over some parts of the northern basin. There are no other significant trends.

2.2.1 Historical changes in the context of the Basin Plan

The recent changes in the Murray–Darling Basin led to discussions about appropriate historical baselines to be used for planning future water use. The Murray–Darling Basin Plan implemented in 2012 considered baselines to be used for hydrological modelling and adopted the full record from 1895 to 2009 based on input from CSIRO (Chiew et al. 2009). The report (Chiew et al. 2009) notes that the use of the full historical record in the northern basin is appropriate for planning given the large historical variability in this region. The report mentions that the question of baseline is only relevant for the southern basin as the observed drying in the southern basin is at least partly attributed to climate warming. But since it is difficult to separate the global warming signal from underlying natural variability, it was recommended at the time to use the full historical record for formulation of the basin plan in the southern basin as well. In addition, it was suggested that a short-term drier scenario (based on the past 10–20 years in 2009) may be useful for developing short-term and medium-term basin plans in the southern basin, given that the drier conditions are expected to continue (Chiew et al. 2009). This suggestion was not pursued in the development of the Basin Plan implemented in 2012.

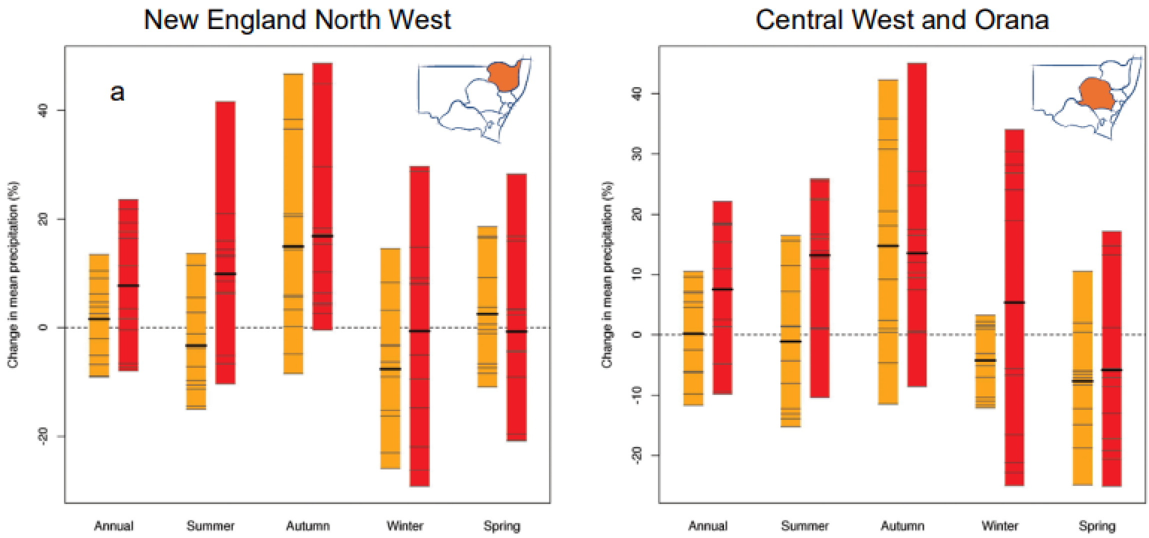
A recent discussion paper published by the MDBA (MDBA 2019) reiterates that climate change and natural variability are jointly responsible for the changes in the Murray–Darling Basin, and it is as yet difficult to separately quantify the timing and magnitude of long-term climate change. The Murray–Darling Basin Plan that was implemented in 2012 addresses the risks of climate change. However, it is noted that further work is needed to deal comprehensively with a changing climate, and there may be a need to adapt the implemented policies for scenarios with even less water than what was planned in 2012 (MDBA 2019).

3 Future climate projections for the northern basin

A brief summary of future climate projections for the northern basin is included here as an alternative line of investigation of non-stationarity in the historical record. Based on the physical processes that lead to rainfall in the different regions (including the role of relevant climate modes), climate change is expected to influence the weather systems differently in the northern basin compared to the southern basin.

The New South Wales and Australian Regional Climate Modelling (NARCliM) project provides regional climate projections over New South Wales. NARCliM projections indicate that a small increase in total annual rainfall in the northern basin is more likely by 2070s relative to the 1990–2009 baseline. The current version of the regional projections (Evans et al. 2014) is based on regional climate simulations using four Coupled Model Intercomparison Project phase 3 (CMIP3) GCMs forced with higher emission scenarios and three model configurations forming a 12-member model ensemble. NARCliM projections are reported over 12 regions in New South Wales. Two regions (the New England North West region and Central West and Orana region) cover a major part of the northern basins investigated in this assessment.

The NARCliM projections of annual and seasonal rainfall in these regions are shown in Figure 2 below (see also the OEH, 2014 Climate Change snapshots for these regions). In the New England North West region, most models agree that the autumn rainfall will increase (10 out of 12 models), and the winter rainfall will decrease (8 out of 12 models). In the Central West and Orana region, spring rainfall will decrease (9 and 8 out of 12 models for 2030 and 2070, respectively), and autumn rainfall will increase (10 and11 out of 12 models for 2030 and 2070, respectively). The projected changes annually and during the other seasons exhibit larger model spreads across positive and negative ranges.



Source: NARCliM, AdaptNSW snapshots for New England North West and Central West and Orana regions, OEH
The bars (2030 yellow; 2070 red) show the spread of 12 model results, the light grey lines within the bars are the individual models. The inlay plots show the New South Wales regions.

Figure 2 Projected changes in average rainfall annually and by season in New England North West region and the Central West and Orana region

Future projections of drought intensity are examined from 50 km resolution NARCliM outputs (available for the entire country) using the Standardised Precipitation-Evaporation Index (Herold et al. 2018). Significant changes are not projected in the drought index for near and far futures (2030s and 2070s) in the northern basin region (Herold et al. 2018). In the far future (2070s), droughts are projected to intensify in spring in areas south of the northern basin (roughly covering the southern basin shown in Figure 1).

The CCIA project that provides projections for the Central Slopes cluster (Figure 1) is another source of information available for future rainfall projections in this region. The CCIA report (Ekström et al. 2015) notes that the sign of changes in annual rainfall cannot be projected reliably in this region due to the complexity in rain-producing systems and large spread in the simulated results, consistent with the NARCliM projections shown in Figure 2. CCIA Central Slopes climate projections for 20-year mean rainfall around 2030 indicate that natural variability is the major driver. The projected change in annual rainfall is about +/− 10% annually relative to the climate of 1986–2005 using results from 39 CMIP5 models. There is more confidence in the long-term (2090s) seasonal changes during winter and spring from the CCIA projections. The analysis by Ekstrom et al (2015) shows that decreases in winter rainfall are projected by the end of the 21st century with high confidence, and spring with medium confidence. The changes in seasonal rainfall in other seasons cannot be projected reliably due to the large spread in modelling results (Ekström et al. 2015).

Future projections of drought are estimated using the Standardized Precipitation Index for the Central Slopes cluster and reports a low confidence in projecting the frequency and duration of extreme meteorological droughts, but there is medium confidence that the time spend in drought will increase over the course of the 21st century under the high emissions (RCP8.5) scenario (Ekström et al. 2015).

The strength of projected changes in the annual mean and the spread of modelling results in the northern basins contrasts with the consistent projections of declines in annual total rainfall in catchments in the southern system (based on Victoria Climate Projections, VCP19, Clarke et al. 2019). However, future regional projections based on the new suite of global model experiments performed for CMIP6 are reported to show higher model agreement over Australia. It is reported that the recent CMIP6 products exhibit more model agreement and consistent regional patterns of meteorological drought (defined based on 15th percentile monthly thresholds of 3-month running mean rainfall) in simulations using low and high emission scenarios, compared to CMIP5.

Southern Australia is one of the regions where robust increases in drought duration are projected (Ukkola et al. 2020). However, the definition of 'Southern Australia' used in this study refers to a larger region consisting of the southern and northern basins based on the figures presented in this global analysis. The CMIP6 rainfall projections during winter in Southern Australia also have a narrower range compared to the CMIP5 projections. Thus, it is likely that future regional projections over Australia associated with CMIP6 would have improved confidence (Grose et al. 2020), although the full suite of CMIP6 models has yet to be comprehensively analysed.

To summarise, the sign of changes in annual rainfall in the northern basin cannot be projected reliably, and natural variability is the major driver in the short term. There is higher confidence in seasonal rainfall changes towards the end of the 21st century. The NARCliM projections indicate that the autumn rainfall will increase, and the winter or spring rainfall will decrease (depending on the specific region). The global projections from CCIA report that winter rainfall will decrease with high confidence, and spring rainfall will decrease with medium confidence in 2090s.

4 Analysis of pilot sites

4.1 Data

Analysis of the historical trends in pilot sites in the northern catchments and split sample testing of the stochastic model are presented in this section. We use data from pilot sites located in the northern basins, shown in Figure 3. All data were sourced from the SILO database. The data consist of rainfall time series that span ~130 years from 1 January 1889 to 31 December 2018 or 31 December 2019, with the end date depending on the specific catchment (Table 3). There were no missing values (owing to pre-determined infilling methods used to construct the data).

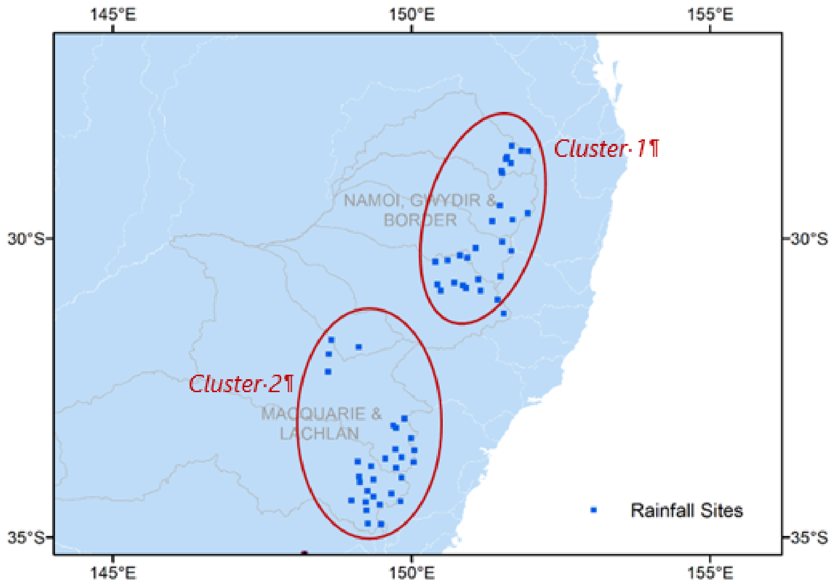


Figure 3 Division of pilot rainfall sites into clusters for trend analysis and split sample testing

Table 3 provides a summary of the rainfall time series from the pilot sites. The analysis was performed for two clusters of sites: Cluster 1 consists of sites in the Namoi, Gwydir and Border (29 no.) regions, and Cluster 2 consists of sites in the Macquarie and Lachlan regions (30 no.). The sites were divided into 2 clusters since these pilot sites span a larger area across eastern New South Wales. Some of the sites in Cluster 2 (Lachlan-Macquarie region) are located south of 33°S, which is generally delineated as 'southeast' Australia and reported to exhibit non-stationarity in the historical record.

Table 3 Summary of observation rainfall timeseries used for the analysis

Cluster	Region	Catchment	Number of sites	Period
Cluster 1	Namoi	Keepit	13	01/01/1890 to 31/12/2018
Cluster 1	Gwydir	Copeton	4	01/01/1890 to 31/12/2019
Cluster 1	Borders	Pindari & Glenlyon	12	01/01/1890 to 31/12/2019
Cluster 2	Macquarie	Burrendong	14	01/01/1890 to 31/12/2018
Cluster 2	Lachlan	Wyangala	16	01/01/1890 to 31/12/2018

4.2 Methodology

4.2.1 Trend detection

The statistical significance of temporal trends in various attributes of the time series are assessed using a non-parametric Mann Kendall test at two-sided 5% significance level. The Mann Kendall test is a well-established technique employed for assessment of hydroclimatic time series (Lavender & Abbs 2013; Theobald et al. 2016; Ukkola et al. 2019). The magnitude of significant trends is quantified using least square regression, similar to the analysis performed by Theobald et al. (2016).

While this approach can assess whether individual sites exhibit statistically significant trends, in multisite analyses there is often a non-negligible probability of detecting one or more individual sites with significant trends even under the null hypothesis of no trends (for example, at the 5% significance level, one would expect an average of 5 out of every 100 sites to experience statistically significant trends under the null hypothesis that there is no trend). As such, a 'field significance' test is used to determine whether the number of stations experiencing statistically significant trends is more than would be expected under the null hypothesis. The field significance of the trends is assessed in this study using a bootstrap resampling procedure (e.g. Do et al. (2017)). The bootstrap procedure uses resampled data to obtain an estimate of the 95th percentile value of the percentage of significant sites that may occur due to chance. If the percentage of sites exhibiting significant trends in the historical record exceeds this estimate, then the trends are considered field significant. The methodology used for the analysis of trends consists of the following steps:

1 The significance of site level trends are estimated using the Mann Kendall test. The proportion of sites that exhibit significant positive and negative trends in the historical record are calculated.

2 The entire dataset is randomly resampled in time while preserving the spatial structure. The new resampled data therefore contains a new sequence of years (for example: {1967, 1954, 2003, 1895, 1920…}). The site level significant trends in the resampled dataset are estimated using the Mann Kendall test and the proportion of sites that exhibit positive and negative trends are calculated as done in step A.

3 A bootstrapping procedure is used to repeat step B 1000 times. The samples are used to create a distribution of percentage of significant sites that may occur in the region due to chance. If the proportion of significant sites in the historical data (step A) is higher than the 95th percentile value of the proportion of significant sites that may occur due to chance, the historical trend is considered to be field significant.

The attributes of rainfall used for the trend analyses are listed in Table 4. These attributes are selected to comprise 'hydrologically relevant' features of the respective variables, which may have a bearing on hydrological response of the respective catchments. The trend analysis is performed using the entire dataset of 130 years (1890 to 2018–19) as well as a recent subset of the dataset (1950 to 2018–19), similar to the analysis performed for the southern basin.

Table 4 Attributes of rainfall variables and the time periods used for trend analyses

Attribute	Definition
Total	Total annual and seasonal (DJF, MAM, JJA & SON) rainfall (mm)
Wet day rainfall	Mean annual and seasonal wet day (P >= 1 mm) rainfall (mm/day)
Number of wet days	Annual and seasonal number of wet days (P >= 1 mm) (days)
Heavy day rainfall	Annual and seasonal heavy day (P >= 10 mm) rainfall (mm/day)
Number of heavy rainfall days	Mean annual and seasonal heavy day (P >= 10 mm) rainfall (mm/day)
Mean dry spell duration	Annual mean number of consecutive days with rainfall less than 1 mm (days)
Maximum dry spell duration	Annual maximum number of consecutive days with rainfall less than 1 mm (days)
Extreme intensity	Annual mean rainfall during days with rainfall greater than the 95th percentile (mm/day)
Extreme frequency	Annual mean number of days with rainfall greater than the 95th percentile (days)

4.2.2 Split sample stochastic simulations

We assess the potential implications of non-stationarity on the results of stochastic analyses using split sample tests. This is achieved using a split sample methodology, in which the stochastic generation model is calibrated to one part of the time series (usually the earlier part of the record) and then validated on the other part of the record. This split sample approach provides an analogy for possible issues that could arise by calibrating a stochastic model to the full historical record and assuming it is representative of current or future conditions. We perform split sample stochastic simulations using the precipitation from the pilot sites to assess the ability of a stochastic model calibrated on the earlier part of the record to capture statistics corresponding to the later part of the record. The split sample tests are designed based on the recommendations of the independent review panel and consist of '1990 reference' and 'drought reference' experiments. These are defined as follows:

- **1990 reference:** The experiment uses data up to year 1990 to calibrate the stochastic model, and data after year 1990 to validate stochastic simulations.
- **Drought reference:** The experiment includes data up to the end of the Millennium Drought (year 2009) to calibrate the model, and the remaining period data to validation the simulations.

We perform the calibration-validation tests using the full record (1889 to 2018–19, 130 years) as well as a shorter recent period of data (1950 to 2018–19, 69 years) to assess the performance of the stochastic model while calibrated using different record lengths. Note that the year 1950 used here is selected arbitrarily to consider the potential of a using a shorter baseline (for example, corresponding to the NARCliM 1.5 baseline starting in 1950). In total, the experiment suite consists of the four experiments shown in Figure 4.

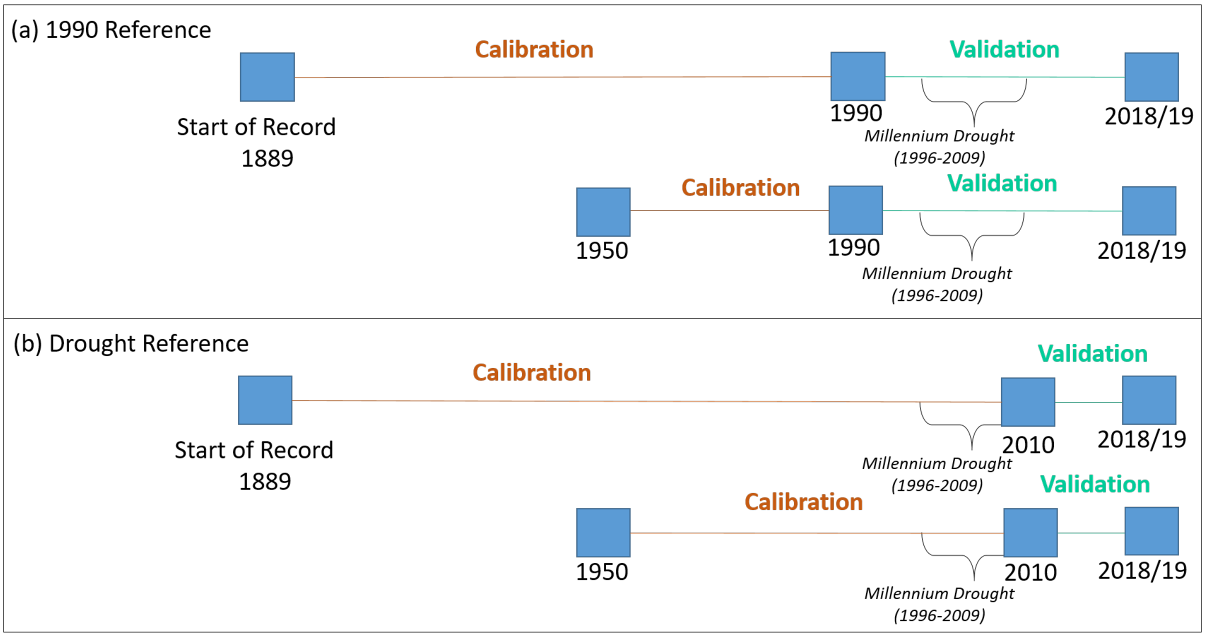


Figure 4 Schematic of split sample experiments

The stochastic model used for the experiments is based on the latent variable model formulation documented in Bennett et al. (2018). The model implemented for this pilot study is not conditioned on the IPO and is a single-site version of the spatial field rainfall model used for stochastic time series generation in the northern New South Wales basins (Leonard & Westra 2020). The model is calibrated site-wise using observations from the calibration time period and used to generate stochastic time series. Time series are generated for 100 replicates of data length corresponding to the validation time period.

The simulated data is compared to observations during both the calibration and validation time periods for assessment of the split sample experiments. The comparison is based on the attributes of hydroclimatic time series that show major trends in the historical record identified using non-parametric trend testing at the pilot sites. The mean values of the attributes from the simulated data are compared to the mean values of observations from the calibration and validation periods at site level. The results are presented using histograms of the differences between the observations and simulations across all the pilot sites.

4.3 Results of non-parametric trend testing

4.3.1 Trends in rainfall attributes

Tables 5 and 6 summarise the number of sites that exhibit significant trends in rainfall attributes in Cluster 1 (Namoi-Gwydir-Border regions) and Cluster 2 (Macquarie-Lachlan regions) during the 2 different time periods analysed. The number of sites exhibiting significant trends are presented in Tables A1 and A2 in Appendix A. The trends in the attributes of rainfall that are significant in both long-term (1890 to 2018–19, with the final year of record depending on the catchment being analysed as reported in Table 3) and short-term (1950 to 2018–19) analyses are:

- Namoi-Gwydir-Border shows decreasing trends in JJA rainfall totals and the number of heavy rainfall days in JJA
- Lachlan-Macquarie shows decreasing trends in the number of wet days in MAM and JJA

Based on these results presented in Tables 5 and 6, the trends in the various rainfall attributes are summarised as follows.

Cluster 1: Namoi-Gwydir-Border

- **Annual and seasonal totals:** Both long-term (1890 to 2018-19) and short-term (1950 to 2018-19) analysis shows decreasing trends in the JJA total rainfall. In the short-term (1950 to 2018-19) analysis, the decreasing trends are significant at the annual scale as well. But there are no significant trends in the remaining seasons (DJF, MAM, SON), and in the annual total in the long term.
- **Mean wet day rainfall:** The short-term and long-term analyses show opposing trends in this attribute. In the long-term analysis, positive trends in the mean wet day rainfall are dominant and field significant at the annual scale as well during DJF, MAM and SON seasons. Few sites also exhibit negative trends in MAM and at the annual scale in the long-term analysis. In the short-term analysis, only the negative trends are significant – during annual values as well as during DJF, MAM and JJA seasons.
- **Number of wet days:** In the long-term analyses, negative trends are significant at both annual and seasonal scales. Some sites also exhibit increasing trends at annual scale, and in DJF and SON seasons. In the short term, only the annual decreasing trends are significant, and the seasonal scale trends are insignificant.
- **Mean heavy day rainfall days:** The trends in mean heavy day rainfall vary between the analyses performed at long and short time scales. In the long-term analysis, there is an increasing trend in the number of heavy rainfall days annually and in DJF. In the short-term analysis, there are decreasing trends in the same. There are no significant trends in MAM, JJA and SON seasons.
- **Number of heavy rainfall days**: The number of heavy rainfall days shows decreasing trends in JJA in both the short-term and long-term analysis. In the short term, the decreasing trends are also significant at the annual scale. At the long-term annual scale, and in DJF, MAM and SON seasons, the trends are insignificant.
- **Intensity and frequency of extreme rainfall days:** Long-term analysis shows an increase in the annual intensity of extreme rainfall days; the trends are not significant in the short term. The short-term analysis shows decreasing trends in the annual frequency of extreme rainfall days; the trends are not significant in the long term.
- **Dry spell durations:** Long-term analysis shows increasing trends in the mean and maximum dry spell durations. In the short-term analysis the trends are of mixed sign or insignificant.

Cluster 2: Lachlan-Macquarie

- **Annual and seasonal totals:** Long-term analysis does not show significant trends at annual or seasonal scales. In the short term (1950 to 2018), annual and SON total rainfall shows decreasing trends. In the remaining seasons, DJF, MAM and JJA, there are no significant short-term trends.

- **Mean wet day rainfall:** This attribute shows a reversal of trends at the annual scale between the long and short time period analyses. The mean wet day rainfall shows increasing trends in the long term annually and during all four seasons. In the short term, the significant trends are only at the annual scale – the sign of trends is reversed to show a decreasing trend. In the short term, the seasonal trends are insignificant.
- **Number of wet days:** The number of wet days show decreasing trends annually and during the cool season in the long-term (during MAM & JJA) and short-term (during MAM, JJA and SON) analysis. In the long term, there is an increasing trend in the number of wet days in DJF.
- **Mean heavy day rainfall:** The annual mean heavy day rainfall shows a reversal of trends between the short-term and long-term analysis. In the long term, the annual trends and the trends during DJF and SON are positive (increasing trend). In the short term, the annual mean heavy day rainfall shows a decreasing trend. There are no significant seasonal trends in the short term.
- **Number of heavy rainfall days:** At annual scale, the number of heavy rainfall days show a reversal of trends between the short-term and long-term analysis. In the long term, there are increasing trends in DJF and SON. The trends are insignificant in other seasons and scales.
- **Intensity and frequency of extreme rainfall days:** There are no significant trends in extreme rainfall intensity. The frequency of extreme rainfall events show reversal between the short-term and long-term analyses. In the short-term analysis, there are significant decreasing trends, and in the long term the trends are positive (increasing).
- **Dry spell durations:** The annual average dry spell duration shows an increasing trend only in the short-term analysis; trends in maximum dry spell duration are insignificant. In the long term, trends in maximum and mean dry spell durations are insignificant.

Tables 5 and 6 include trends reported in literature. The comparison is based on summarising results from the northern basin as distinct from the larger-scale analysis documented in these studies. There are no major trends reported in this region. There are some significant trends that vary based on the season and time period under consideration. There is little consistency between the significant trends identified at the pilot sites and those reported in the literature. The only consistent signal is a short-term (post-1950 or post-1970) decreasing trend in the number of wet days. The general understanding of rainfall patterns in the region summarised in Section 2 indicates that there is a large variability in rainfall in this region, with wet–dry patterns that persist across years. Hence it is possible that the Mann Kendall tests performed under independent and identically distributed assumptions could reflect either low-frequency natural variability, anthropogenic climate change, or a combination of both drivers of change.

Table 5 Trends in rainfall attributes in the pilot sites in Namoi-Gwydir-Border regions

Attribute	Study or publication	Period	Annual	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Total rainfall[1]	Pilot study long	1889–2018	N	N	N	N	N	N	N	WD	WD	WD	N	N	N
Total rainfall[1]	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Ukkola et al. (2019)	1910–2018	N	WI	WI	WI	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Pilot study short	1950–2018	D	N	N	N	N	N	N	D	D	D	N	N	N
Total rainfall[1]	Taschetto & England (2009)	1970–2006	N	WD	WD	WD	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Gallant et al. (2007)	1950–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean wet day rainfall	Pilot study long	1889–2018	I/D	I	I	I	I/D	I/D	I/D	N	N	N	I	I	I
Mean wet day rainfall	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean wet day rainfall	Pilot study short	1950–2010	D	WD	WD	WD	D	D	D	WD	WD	WD	N	N	N
Mean wet day rainfall	Gallant et al. (2007)	1950–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Number of wet days[2]	Pilot study long	1889–2018	WD	WD	WD	WD	WD	WD	WD	WD	WD	WD	WD	WD	WD
Number of wet days[2]	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	I	I	I
Number of wet days[2]	Pilot study short	1950–2018	D	N	N	N	N	N	N	N	N	N	N	N	N
Number of wet days[2]	Taschetto & England (2009)	1970–2006	WD	N	N	N	N	N	N	N	N	N	N	N	N
Number of wet days[2]	Gallant et al. (2007)	1950–2005	WD	N	N	N	N	N	N	N	N	N	N	N	N
Heavy day rainfall	Pilot study long	1889–2018	I	I	I	I	N	N	N	N	N	N	N	N	N
Heavy day rainfall	Pilot study short	1950–2018	D	D	D	D	N	N	N	N	N	N	N	N	N
Number of heavy rainfall days[3]	Pilot study long	1889–2018	N	N	N	N	N	N	N	WD	WD	WD	N	N	N
Number of heavy rainfall days[3]	Pilot study short	1950–2018	WD	N	N	N	N	N	N	WD	WD	WD	N	N	N
Number of heavy rainfall days[3]	Taschetto & England (2009)	1970–2006	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean dry spell duration	Pilot study long	1889–2018	WI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Attribute	Study or publication	Period	Annual	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Mean dry spell duration	Pilot study short	1950–2018	I/D	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Maximum dry spell duration	Pilot study long	1889–2018	I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Maximum dry spell duration	Pilot study short	1950–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity[4]	Pilot study long	1889–2018	I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity[4]	Gallant et al. (2007)	1910–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity[4]	Pilot study short	1950–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity[4]	Gallant et al. (2007)	1950–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Pilot study long	1889–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Gallant et al. (2007)	1910–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Pilot study short	1950–2018	D	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Gallant et al. (2007)	1950–2005	-	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

1 T&E (2009) & Ukkola et al. (2019) used gridded data; the comparison is based on approximately locating the pilot region from their figures. Gallant et al. (2007) performed analysis over a narrower Western Tablelands regions that extends from Macquarie to Border

2 T&E (2009) analysed moderate rainfall events as events within one SD of the mean

3 T&E (2009) analysed the number of heavy (1 to 2 SD from mean) and very heavy (more than 2 SD from mean) rainfall events

4 Gallant (2007) defined extreme rainfall as the 95th percentile of rainfall

N = no significant trends

I = increase

WI = widespread increase (trends that are present at more than 25% of the sites)

D = decrease

WD = widespread decrease (trends that are present at more than 25% of the sites)

N/A = analyses for the attribute or season are not available

Table 6 Trends in rainfall attributes in the pilot sites in Macquarie-Lachlan regions

Attribute	Study or publication	Period	Annual	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Total rainfall[1]	Pilot study long	1889–2018	N	N	N	N	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Ukkola et al. (2019)	1910–2018	N	WI	WI	WI	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Pilot study short	1950–2018	WD	N	N	N	N	N	N	N	N	N	WD	WD	WD
Total rainfall[1]	Taschetto and England (2009)	1970–2006	N	WD	WD	WD	N	N	N	N	N	N	N	N	N
Total rainfall[1]	Gallant et al. (2007)	1950–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean wet day rainfall	Pilot study long	1889–2018	WI	WI	WI	WI	I	I	I	I	I	I	WI	WI	WI
Mean wet day rainfall	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean wet day rainfall	Pilot study short	1950–2010	D	N	N	N	N	N	N	N	N	N	N	N	N
Mean wet day rainfall	Gallant et al. (2007)	1950–2005	N	N	N	N	N	N	N	N	N	N	N	N	N
Number of wet days[2]	Pilot study long	1889–2018	WD	I	I	I	D	D	D	WD	WD	WD	N	N	N
Number of wet days[2]	Gallant et al. (2007)	1910–2005	N	N	N	N	N	N	N	N	N	N	WI	WI	WI
Number of wet days[2]	Pilot study short	1950–2018	WD	N	N	N	WD	WD	WD	WD	WD	WD	WD	WD	WD
Number of wet days[2]	Taschetto and England (2009)	1970–2006	WD	N	N	N	N	N	N	N	N	N	N	N	N
Number of wet days[2]	Gallant et al. (2007)	1950–2005	WD	N	N	N	N	N	N	N	N	N	N	N	N
Heavy day rainfall	Pilot study long	1889–2018	I	N	N	N	N	N	N	N	N	N	N	N	N
Heavy day rainfall	Pilot study short	1950–2018	WD	N	N	N	N	N	N	N	N	N	N	N	N
Number of heavy rainfall days[3]	Pilot study long	1889–2018	I	WI	WI	WI	N	N	N	N	N	N	WI	WI	WI
Number of heavy rainfall days[3]	Pilot study short	1950–2018	WD	N	N	N	N	N	N	N	N	N	N	N	N
Number of heavy rainfall days[3]	Taschetto and England (2009)	1970–2006	N	N	N	N	N	N	N	N	N	N	N	N	N
Mean dry spell duration*	Pilot study long	1889–2018	WI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Attribute	Study or publication	Period	Annual	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Mean dry spell duration	Pilot study short	1950–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Maximum dry spell duration	Pilot study long	1889–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Mean dry spell duration	Pilot study short	1950–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity	Pilot study long	1889–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity	Gallant et al. (2007)	1910–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity	Pilot study short	1950–2018	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall intensity	Gallant et al. (2007)	1950–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Pilot study long	1889–2018	WI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Gallant et al. (2007)	1910–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Pilot study short	1950–2018	WD	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Extreme rainfall frequency[4]	Gallant et al. (2007)	1950–2005	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

1 T&E (2009) & Ukkola et al. (2019) used gridded data; the comparison is based on approximately locating the pilot region from their figures. Gallant et al. (2007) performed analysis over a narrower Western Tablelands regions that extends from Macquarie to Border.
2 T&E (2009): Analysed moderate rainfall events as events within one SD of the mean.
3 T&E (2009) analysed the number of heavy (1 to 2 SD from mean) and very heavy (more than 2 SD from mean) rainfall events.
4 Gallant (2007) defined extreme rainfall as the 95th percentile of rainfall.

N = no significant trends
I = increase
WI = widespread increase (trends that are present at more than 25% of the sites)
D = decrease
WD = widespread decrease (trends that are present at more than 25% of the sites)
N/A = analyses for the attribute or season are not available

Having examined the statistical significance of trends, we now turn to an examination of the magnitude of trends for cases that are field significant in the northern pilot sites. The magnitude of trends is estimated site-wise using linear least squares regression. The median absolute value of the trends and the median percentage of trends in Lachlan-Macquarie (30 sites) and Namoi-Gwydir-Border (30 sites) are presented in Tables 7a–c.

Table 7a Median magnitude of trends in total rainfall in mm/decade (%/decade) at the pilot sites

Region	Time period	Median trends ANN	Median trends DJF	Median trends MAM	Median trends JJA	Median trends SON
Namoi-Gwydir-Border	1889–2019	x	x	x	−3.5 (−2.1%)	x
Namoi-Gwydir-Border	1950–2019	−12.6 (−1.7%)	x	x	−3.7 (−2.8%)	x
Lachlan-Macquarie	1889–2018	x	x	x	x	x
Lachlan-Macquarie	1950–2018	−27.4 (−3.4%)	x	x	x	−7.2 (−3.3%)

Table 8b Median magnitude of trends in number of wet days in days/decade (%/decade)at the pilot sites

Region	Time period	Median trends ANN	Median trends DJF	Median trends MAM	Median trends JJA	Median trends SON
Namoi-Gwydir-Border	1889–2019	−1.5 (−2%)	−0.2 (−1%)	-0.3 (-2.4%)	−0.6 (−2.9%)	−0.3 (−1.2%)
Namoi-Gwydir-Border	1950–2019	−1.2 (−1.6%)	x	x	x	x
Lachlan-Macquarie	1889–2018	−0.4 (−0.5%)	0.1 (0.6%)	−0.1 (−0.8%)	−0.4 (−1.5%)	x
Lachlan-Macquarie	1950–2018	−2.3 (−2.6%)	x	−0.9 (−4.5%)	−0.6 (−2.3%)	−0.8 (−3.1%)

Table 9c Median magnitude of trends in number of heavy rainfall days in days/decade (%/decade)at the pilot sites

Region	Time period	Median trends ANN	Median trends DJF	Median trends MAM	Median trends JJA	Median trends SON
Namoi-Gwydir-Border	1889–2019	x	x	x	−0.1 (−2%)	x
Namoi-Gwydir-Border	1950–2019	−0.5 (−1.9%)	x	x	−0.2 (−4.7%)	x
Lachlan-Macquarie	1889–2018	0.2 (0.9%)	0.1 (2%)	x	x	0.1 (1.8%)
Lachlan-Macquarie	1950–2018	−0.7 (−2.7%)	x	x	x	x

Absolute trends per decade are presented first, followed by percentage change per decade in parentheses; x marks trends that are not field significant.

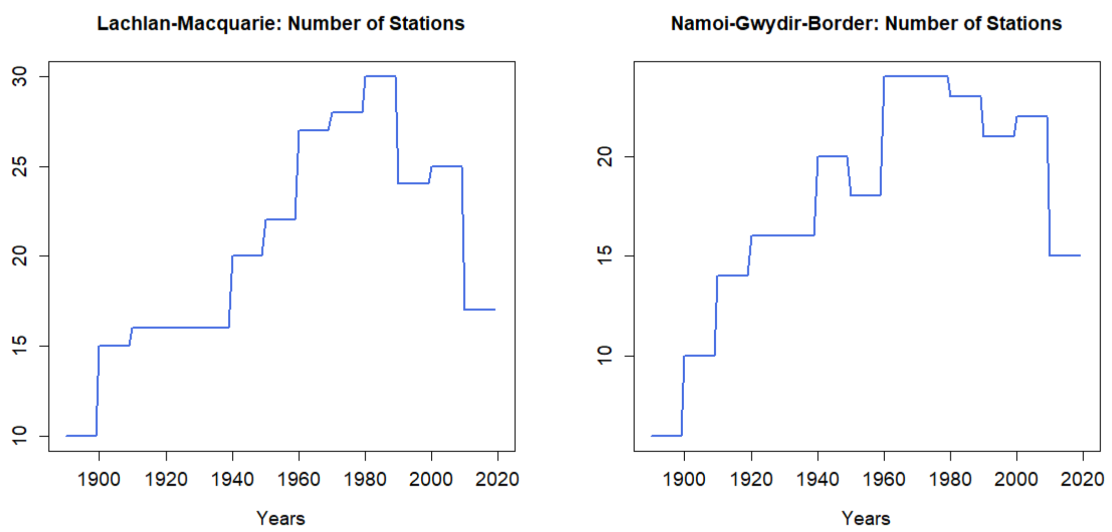
Namoi-Gwydir-Border

The analysis shows field significant trends in the winter (JJA) total rainfall of −2.1% per decade over the long term and −2.8% per decade over the short term. At the annual scale, the short-term decreasing trends (−1.7%/decade) are weaker than in the Lachlan-Macquarie region. The number of heavy rainfall days show stronger trends in this region in JJA (−2% per decade over 130 years and −4.7% per decade over 70 years).

Lachlan-Macquarie

The short-term decreasing trends in annual totals amount to a median of −27.4 mm per decade (−3.4% per decade). The decreasing trends in annual total occur due to changes in MAM, JJA and SON. But the decreasing trends are field significant only in SON (magnitude of −7.2 mm or -3.3% per decade). The field significant trends in annual and seasonal number of wet days amount to −0.4 days per decade in the long term (over 129 years) and −2.3 days per decade in the short term (69 years).

To summarise, there are fewer significant trends in annual and seasonal totals in the northern pilot sites compared to the trends detected in the southern basin pilot sites documented in the previous report. However, the existing field significant trends are similar in magnitude to those in the southern pilot catchments. In the northern catchments, field significant trends are detected mainly in the number of wet days and number of heavy rainfall days, with fewer significant changes in the corresponding seasonal totals. The threshold-based attributes (number of wet days and number of heavy rainfall days) could potentially be influenced by interpolation in the earlier parts of the record when observed data from fewer stations are available. Figure 5 shows the number of pilot sites at which actual observed data are available during the years 1890 to 2019 based on the SILO database, with the remainder being interpolated.



Sites that have more than 75% of data availability during the decade are considered available. The earlier part of the record contains more interpolated data, which may affect threshold-based rainfall attributes number of wet days and number of heavy rainfall days.

Figure 5 Number of stations at which actual observed data is available during 1890 to 2019, based on the SILO database

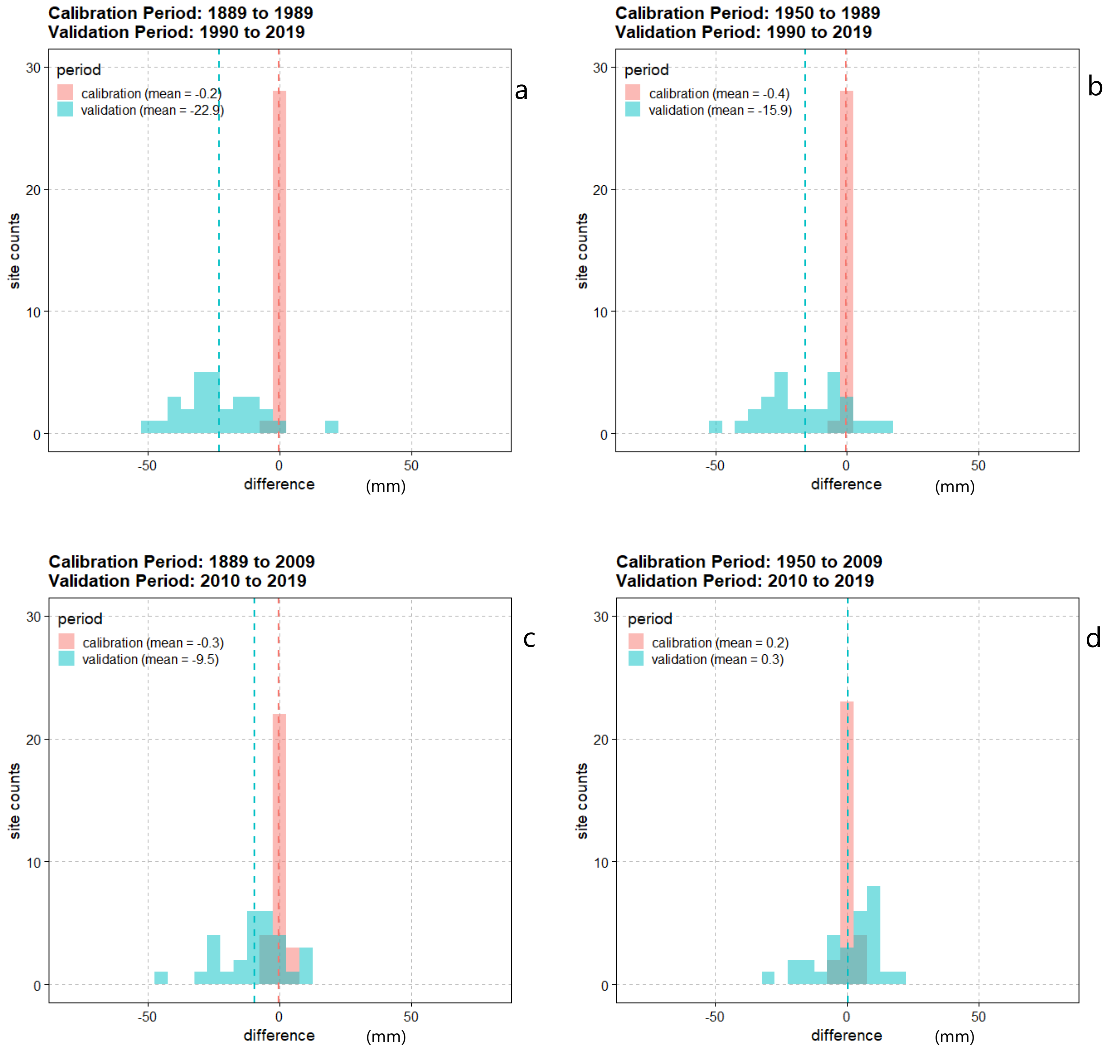
4.4 Results of split sample testing

Four split sample simulations are performed using the historical data from the pilot sites to assess the ability of the stochastic model to capture the attributes of rainfall in recent observations, following the methodology outlined in section 4.2.2. The split sample tests consist of the 1990 reference and drought reference experiments. The 1990 reference experiment uses data up to year 1990 to calibrate the stochastic model, and data after year 1990 to validate stochastic simulations. The drought reference experiment includes data up to the end of the Millennium Drought (year 2009) to calibrate the model, and the remaining period data to validate the simulations. The mean attributes of the simulated data are compared with the mean attributes of observations during the calibration and validation time periods in the subsections below.

4.4.1 Namoi-Gwydir-Border

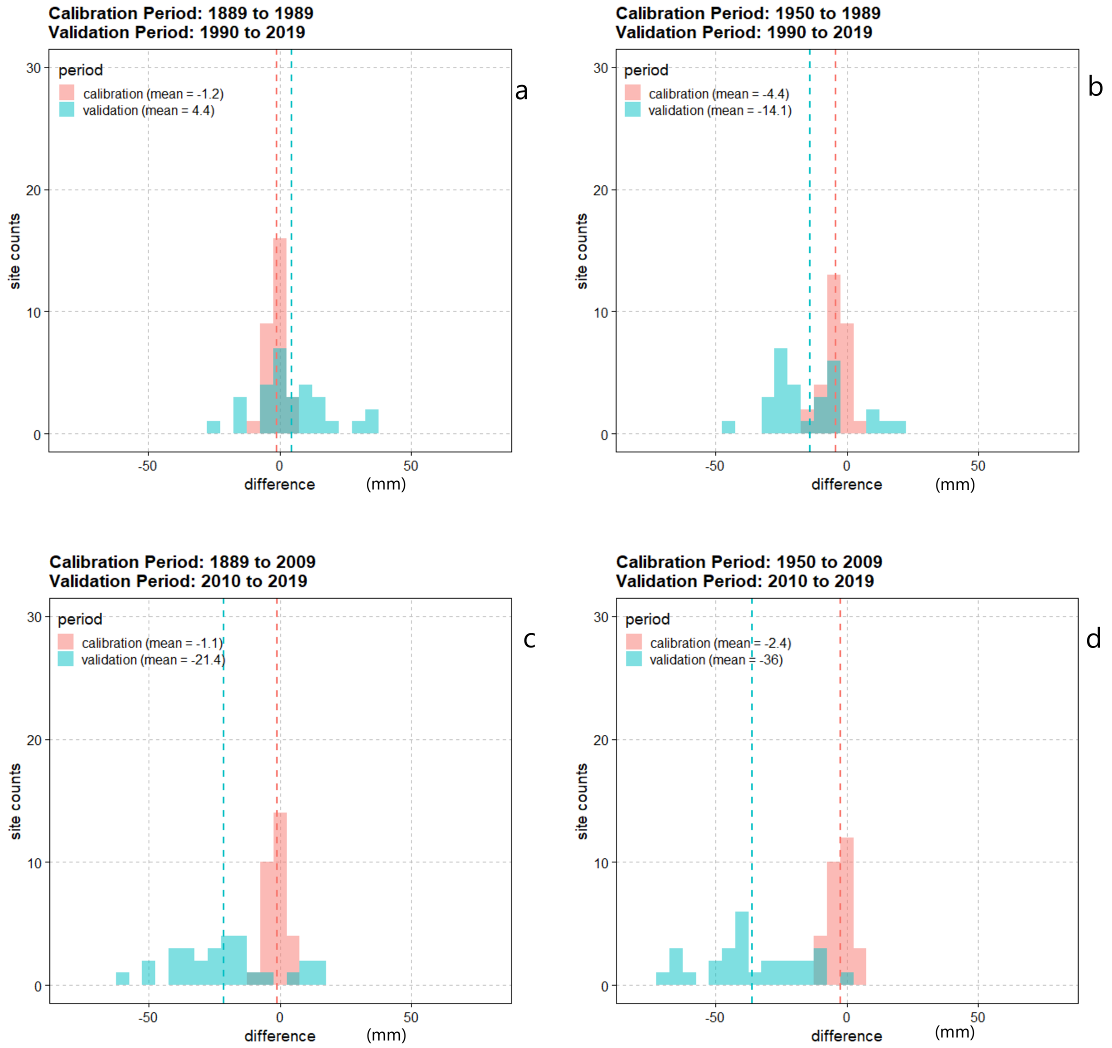
There are significant trends in JJA total rainfall at the pilot sites, as shown in Table 4. The histograms of the site-wise biases in JJA total rainfall during the calibration and validation time periods are shown in Figure 6. The drought reference experiments show lower biases in JJA rainfall totals during the validation period in the 1990 reference experiments. The results are similar for experiments using long and short calibration time periods. The rainfall during MAM also shows a similar behaviour (not shown). However, in the case of the total rainfall during DJF (Figure 7), the drought reference experiments show larger biases during the validation period. The results for SON are similar to DJF (not shown).

To summarise, the seasonal rainfall totals from the simulations are close to the mean rainfall during the calibration period in all experiments. The performance with respect to the validation period depends upon how similar the seasonal totals during the calibration and validation periods themselves are.



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period.
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

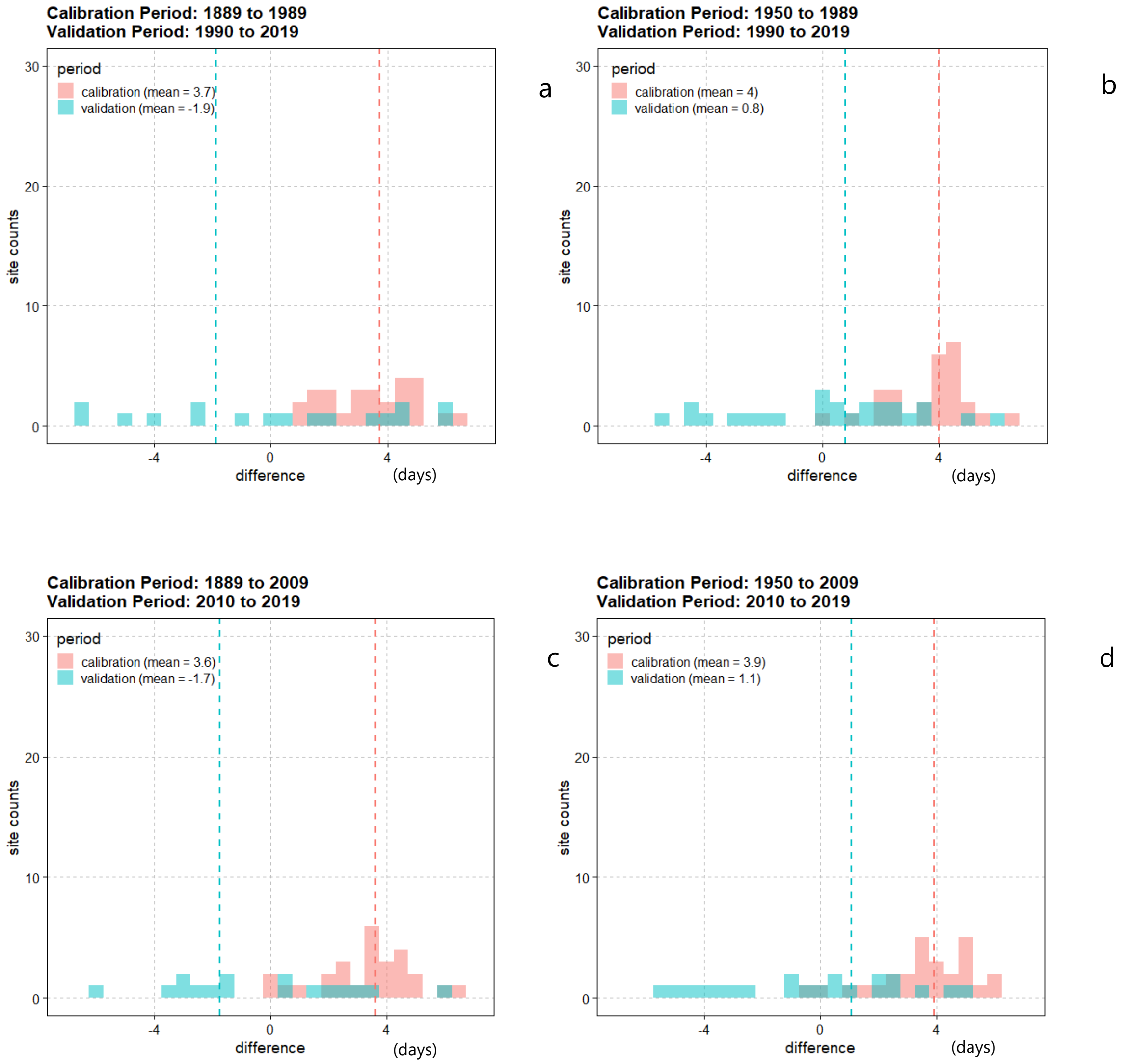
Figure 6 Histograms of the mean differences in total rainfall in JJA during the calibration and validation time periods from stochastic simulations at 29 pilot sites in Namoi-Gwydir-Border



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

Figure 7 Histograms of the mean differences in total rainfall in DJF during the calibration and validation time periods from stochastic simulations at 29 pilot sites in Namoi-Gwydir-Border

Figure 8 shows the histograms of the annual number of wet days in the simulation and the biases in the corresponding calibration and validation time periods. In general, the simulations underestimate the number of wet days during the calibration period. The number of wet days during the validation period are lower than during the calibration period, consistent with the decreasing trends in this statistic. As a result, there are lower biases during the validation period in this statistic.



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

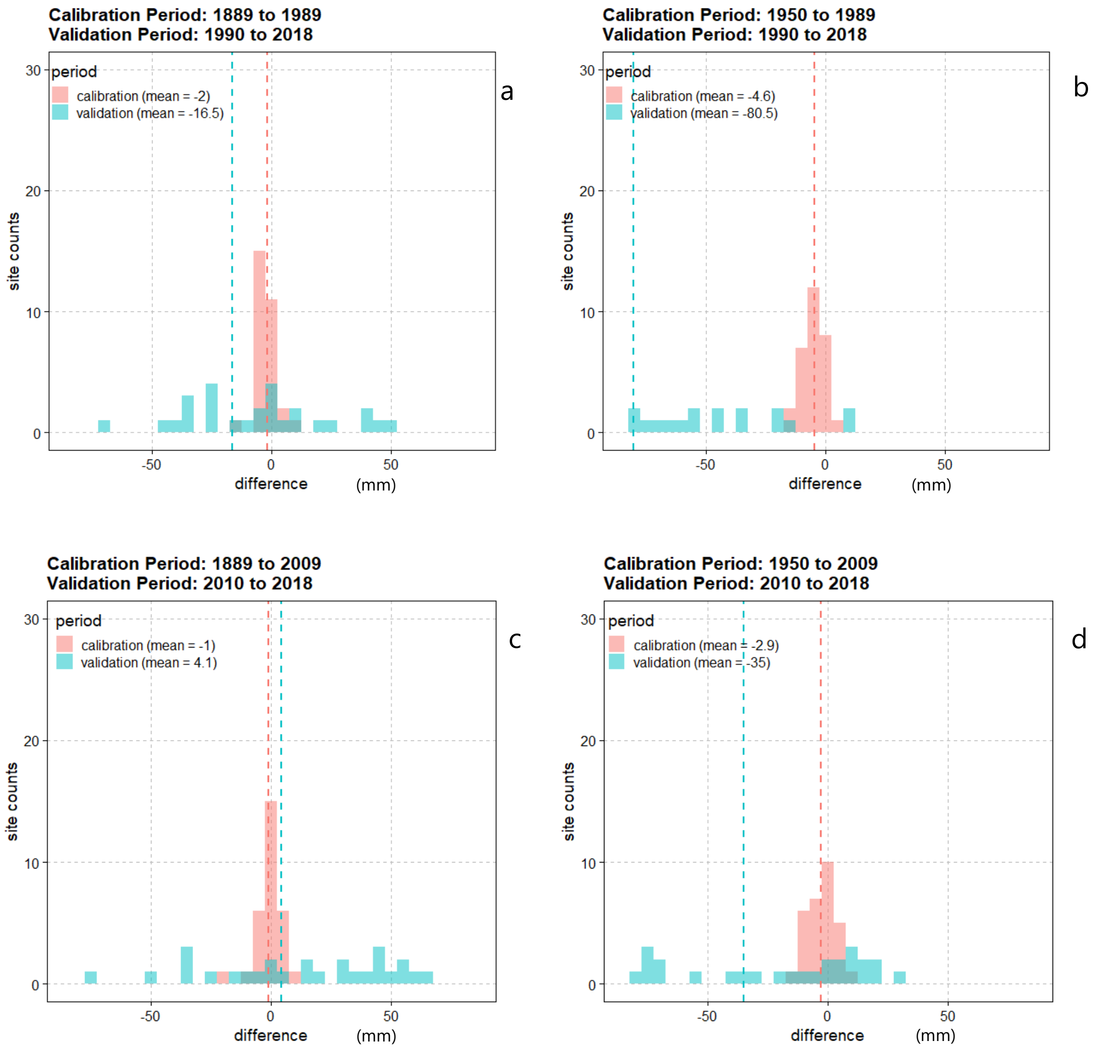
Figure 8 Histograms of the mean differences in the number of wet days during the calibration and validation time periods from stochastic simulations at 29 pilot sites in Namoi-Gwydir-Border

4.4.2 Lachlan-Macquarie

The differences in annual and seasonal totals exhibited by the simulations in this region are influenced by the calibration period as well as the inclusion or exclusion of the Millennium Drought in the calibration period. Figure 9 shows the histograms of the annual total rainfall in the simulation and the biases in the corresponding calibration and validation time periods. When the drought period until year 2009 is included in the calibration period, the biases during the validation period are reduced; the magnitude of reduction is smaller for simulations using the long calibration period. The differences during the validation period are higher when a shorter time period (1950 to 1989 or 1950 to 2009) is used to calibrate the stochastic model. These differences are due to changes in the pattern of biases in seasonal rainfall totals when the model is calibrated using the long-term (1890 to

1989 or 2009) versus short-term (1950 to 1989 or2009) observed records. There are two factors that affect this behaviour:

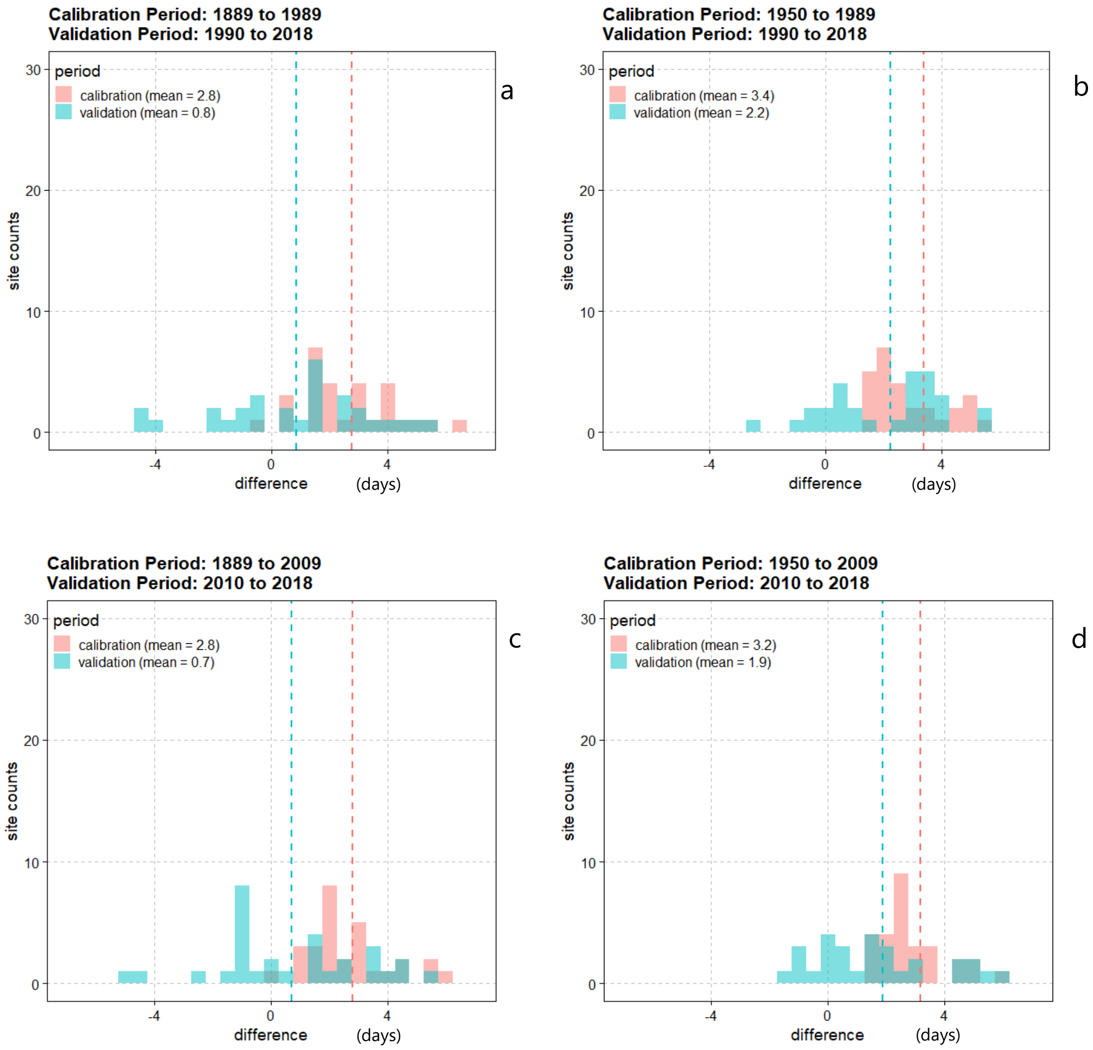
- In general, the simulations overestimate the seasonal total rainfall during the MAM, JJA and SON seasons. During SON, the overestimation is higher when a shorter observed record post-1950 is used to calibrate the model (Appendix A, Figure A1).
- During DJF, the biases are of opposite sign, that is, the simulations underestimate the seasonal total rainfall during DJF in the validation period. The magnitude of this bias is larger in the simulations calibrated using the longer period, resulting in net lower biases in annual total from these experiments. The histograms of the differences in DJF total rainfall are shown in Appendix A, Figure A2.



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

Figure 9 Histograms of the mean differences in annual total rainfall during the calibration and validation time periods from stochastic simulations at 30 pilot sites in Lachlan-Macquarie

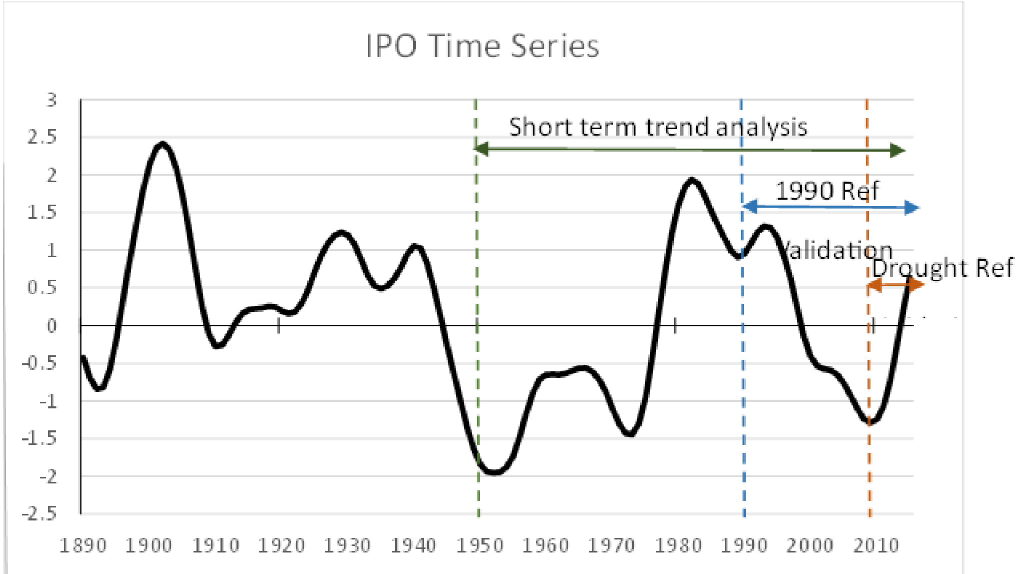
The trend analysis showed negative trends in the number of wet days during JJA and MAM (Table 5). As seen in the Namoi-Gwydir-Border regions, the simulations underestimate the number of wet days compared to the calibration period. Since the number of wet days during the validation period are lower than during the calibration period (owing to the decreasing trend in this attribute), the simulations show lower biases with respect to the validation period. The histograms showing the differences in the number of wet days during JJA are shown in Figure 10.



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the in plot legends.

Figure 10 Histograms of the mean differences in number of wet days in JJA during the calibration and validation time periods from stochastic simulations at 30 pilot sites in Lachlan-Macquarie

The significant trends detected at the pilot sites and the results of the split sample tests may be influenced by low-frequency natural variability associated with the IPO, which affects the rainfall in this region as summarised in Section 2.1. Figure 11shows the 11-year filtered historical time series of the IPO from 1890 to 2015 (obtained from Folland, 2017) calculated using the UK Met Office Hadley Centre sea surface temperatures. The analysis of short-term (post-1950) trends at the pilot sites show significant decreasing trends in annual total rainfall in both Cluster 1 and Cluster 2. These trends may be associated with change in the phase of the IPO from negative (associated with higher rainfall) to positive (associated with lower rainfall) in the mid-1970s.



Source: Folland (2017)

Figure 11 IPO time series from 1890 to 2015 showing the periods used for short-term trend analysis and validation of split sample stochastic simulation

5 Summary of key findings from assessment of non-stationarity

The assessment of multiple lines of evidence presented in this report consists of a review of available literature, future projections, and assessment of pilot sites in Lachlan, Macquarie, Namoi, Gwydir and Border catchments using Mann Kendall and split sample tests. The key findings are summarised below.

- **Trends in literature and at the pilot sites**: In the literature, are no reports of major trends in seasonal totals in the historical record in this region, although there is some consensus on short-term decreasing trends in the number of wet days in the region. In contrast, the analysis of pilot sites in the northern catchments reveal that there are significant trends in a number of different attributes of rainfall. The trends that are consistent in sign in both short-term (post-1950) and long-term (post-1890) trend analysis are:
  - decreasing trends in JJA rainfall totals and the number of heavy rainfall days in JJA at pilot sites in Namoi-Gwydir-Border
  - decreasing trends in the number of wet days in MAM and JJA at pilot sites in Lachlan-Macquarie.

  There is agreement between literature and the results from the pilot sites on a short-term (post-1950 or post-1970) decreasing trend in the annual number of wet days; there is no consensus on trends in other attributes or seasons. The discrepancy between findings from the literature and from the pilot sites is likely to be because of differences in definitions of the study region, period of record and/or trend detection methodology. Although this study does not seek to attribute trends to specific causes, it is likely that the significant trends detected at the pilot sites consist of a combination of low-frequency variability and climate change signal.

  There are fewer significant trends in annual and seasonal totals in the northern pilot sites compared to the trends detected in the southern basin pilot sites documented in the previous report. However, the existing field significant trends are similar in magnitude to those in the southern pilot catchments. In these northern catchments, field significant trends are detected mainly in the number of wet days and number of heavy rainfall days, with fewer significant changes in the corresponding seasonal totals compared to the southern pilot catchments.

- **Interpretation of recent droughts and role of natural climate variability**: Climatic processes associated with low-frequency IPO interact with higher-frequency variability associated with ENSO, IOD, and SAM to drive persistent wet–dry rainfall patterns in this region. The northern basin has experienced droughts in the recent past as well as in the first half of the 20th century prior to year 1945. The observed rainfall during the Millennium Drought has been reported to be within the natural variability of the northern basin. The recent drought that started in 2017 has resulted in record low rainfall across much of the northern basin; however, definitive attribution of causes is not yet possible.

- **Future projections**: The projections indicate that the sign of near-term changes in annual total rainfall cannot be projected reliably; natural variability is expected to be the major driver in the short term. Towards the latter half of the 21st century, the projections report with higher confidence that winter and spring rainfall will decrease. Regional projections also indicate that autumn rainfall may increase in the longer term.

- **Results from split sample stochastic simulations**: The split sample tests do not show clear benefits of including or excluding the Millennium Drought in the calibration period. The differences between the simulations and the validation period are dependent upon how similar the calibration and validation periods themselves are for specific attributes and seasons. For example, in the Namoi-Gwydir-Border region, split sample simulations excluding (or including) the Millennium Drought in the calibration period show that the simulations overestimate the JJA total rainfall by a median of +23 (+10) mm/season. That is, there is a reduction in the biases in JJA total rainfall after inclusion of the drought in the calibration period. However, the same simulations show an increase in biases in simulations of DJF total rainfall from −4.4 to +22 mm/season after inclusion of the drought in the calibration period.

Overall, although there is some evidence of trends for several key attributes for the pilot sites, in aggregate the alternative lines of evidence do not converge to indicate the clear presence of non-stationarity in the historical record of the northern basin. Furthermore, although some trends are consistent with those anticipated from climate models over the 21st century, overall it is likely that natural variability continues to play an important role and thus it is not yet possible to formally attribute historical trends to anthropogenic climate change.

7 References

Bennett B, Thyer M, Leonard M, Lambert M and Bates B (2018) 'A comprehensive and systematic evaluation framework for a parsimonious daily rainfall field model', *Journal of Hydrology* 556:1123–1138, doi:10.1016/j.jhydrol.2016.12.043

BoM (Bureau of Meteorology) (2019) *Special Climate Statement 70 update—drought conditions in Australia and impact on water resources in the Murray–Darling Basin*, BoM.

Chiew FHS, Cai W and Smith IN (2009) *Advice on defining climate scenarios for use in the Murray–Darling Basin Authority Basin Plan modelling*, CSIRO report for the Murray–Darling Basin Authority, MDBA, Canberra.

Clarke J, Grose M, Thatcher M, Hernaman V, Heady C, Round V, Rafter T, Trenham C and Wilson L (2019) *Victorian Climate Projections 2019 Technical Report,* CSIRO, Melbourne.

CSIRO (Commonwealth Scientific and Industrial Research Organisation) (2012) *Climate and water availability in south-eastern Australia A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI)* (Vol. 41), CSIRO, Australia.

Do HX, Westra S and Leonard M (2017) 'A global-scale investigation of trends in annual maximum streamflow', *Journal of Hydrology* 552:28–43, doi:10.1016/j.jhydrol.2017.06.015

Ekström M and others (2015) *Central Slopes Cluster Report: Climate Change in Australia Projections for Australia's Natural Resource Management Regions*, CSIRO and Bureau of Meteorology, Australia.

Evans JP, Ji F, Lee C, Smith P, Argüeso D and Fita L (2014) 'Design of a regional climate modelling projection ensemble experiment – NARCliM', *Geoscientific Model Development* 7(2):621–629, doi:10.5194/gmd-7–621–2014

Folland C (2017) *Interdecadal Pacific Oscillation Time Series (updated August 2017)*, Met Office Hadley Centre for Climate Change and Services, doi:10.1029/2001GL014201

Gallant AJE, Hennessy KJ and Risbey J (2007) 'Trends in rainfall indices for six Australian regions: 1910–2005', *Australian Meteorological Magazine*, 223–239, https://www.researchgate.net/publication/242601092

Grose MR, Narsey S, Delage FP, Dowdy AJ, Bador M, Boschat G, Chung C, Kajtar JB, Rauniyar S, Freund MB, Lyu K, Rashid H, Zhang X, Wales S, Trenham C, Holbrook NJ, Cowan T, Alexander L, Arblaster JM and Power S (2020) 'Insights From CMIP6 for Australia's future climate', *Earth's Future* 8(5), doi:10.1029/2019EF001469

Herold N, Ekström M, Kala J, Goldie J and Evans JP (2018) 'Australian climate extremes in the 21st century according to a regional climate model ensemble: Implications for health and agriculture', *Weather and Climate Extremes* 20:54–68, doi:10.1016/j.wace.2018.01.001

Lavender SL and Abbs DJ (2013) 'Trends in Australian rainfall: Contribution of tropical cyclones and closed lows', *Climate Dynamics* 40(1–2):317–326, doi:10.1007/s00382–012–1566-y

Leonard M and Westra S (2020) *Methodology report for multisite rainfall and evaporation data generation of the Northern Basin*.

MDBA (Murray–Darling Basin Authority) (2018) *Hydrologic assessment of flow changes in the northern Basin* (Issue October), https://www.mdba.gov.au/sites/default/files/pubs/1209-Hydrologic-assessment-of-flow-changes-in-the-northern-basin.pdf

MDBA (Murray–Darling Basin Authority) (2019) *Climate change and the Murray–Darling Basin Plan: MDBA Discussion Paper*, MDBA, Canberra.

New South Wales Office of Environment and Heritage, 2014, *Central West and Orana Climate Change Snapshot.*

New South Wales Office of Environment and Heritage, 2014, New England North West Climate Change Snapshot.

Nicholls N (2010) 'Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007', *Climate Dynamics* 34(6):835–845, doi:10.1007/s00382–009–0527–6

Taschetto AS and England MH (2009) 'An analysis of late twentieth century trends in Australian rainfall', *International Journal of Climatology* 29(6):791–807, doi:10.1002/joc.1736

Theobald A, McGowan H and Speirs J (2016) 'Trends in synoptic circulation and precipitation in the Snowy Mountains region, Australia, in the period 1958–2012', *Atmospheric Research* 169:434–448, doi:10.1016/j.atmosres.2015.05.007

Ukkola AM, Roderick ML, Barker A and Pitman AJ (2019) 'Exploring the stationarity of Australian temperature, precipitation and pan evaporation records over the last century', *Environmental Research Letters* 14: 124035, doi:10.1088/1748–9326/ab545c

Ukkola AM, De Kauwe MG, Roderick ML, Abramowitz G and Pitman AJ (2020) 'Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation', *Geophysical Research Letters* 47(11), doi:10.1029/2020GL087820

Verdon DC, Wyatt AM, Kiem AS and Franks SW (2004) 'Multidecadal variability of rainfall and streamflow: Eastern Australia', *Water Resources Research* 40(10), doi:10.1029/2004WR003234

Verdon DC and Franks SW (2005) 'Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia', *Water Resources Research* 41(9):1–10, doi:10.1029/2004WR003845'

Verdon-Kidd DC and Kiem AS (2009) 'Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts' *Geophysical Research Letters* 36(22), doi:10.1029/2009GL041067

Westra S, Renard B and Thyer M (2015) 'The ENSO-precipitation teleconnection and its modulation by the interdecadal pacific oscillation', *Journal of Climate* 28(12):4753–4773, doi:10.1175/JCLI-D-14–00722.1

Appendix A – Supplementary material

Table A1 Number of sites that exhibit significant trends in annual and seasonal attributes of rainfall in the Namoi-Gwydir-Border pilot sites

Attribute	Trend	Periods, 1889–2019 Annual	Periods, 1889–2019 Dec–Feb	Periods, 1889–2019 Mar–May	Periods, 1889–2019 Jun–Aug	Periods, 1889–2019 Sep–Nov	Periods, 1950–2019 Annual	Periods, 1950–2019 Dec–Feb	Periods, 1950–2019 Mar–May	Periods, 1950–2019 Jun–Aug	Periods, 1950–2019 Sep–Nov
Total rainfall (mm)	pos	1 (3%)	1 (3%)	0 (0%)	0 (0%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total rainfall (mm)	neg	2 (7%)	0 (0%)	1 (3%)	20 (69%)	0 (0%)	5 (17%)	2 (7%)	0 (0%)	6 (21%)	0 (0%)
Total rainfall (mm)	none	26 (90%)	28 (97%)	28 (97%)	9 (31%)	28 (97%)	24 (83%)	27 (93%)	29 (100%)	23 (79%)	29 (100%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	pos	16 (55%)	13 (45%)	9 (31%)	4 (14%)	13 (45%)	1 (3%)	0 (0%)	1 (3%)	2 (7%)	1 (3%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	neg	5 (17%)	4 (14%)	5 (17%)	2 (7%)	3 (10%)	7 (24%)	9 (31%)	5 (17%)	9 (31%)	5 (17%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	none	8 (28%)	12 (41%)	15 (52%)	23 (79%)	13 (45%)	21 (72%)	20 (69%)	23 (79%)	18 (62%)	23 (79%)
Number of wet (P >= 1 mm) days	pos	5 (17%)	7 (24%)	1 (3%)	0 (0%)	4 (14%)	4 (14%)	3 (10%)	2 (7%)	1 (3%)	3 (10%)
Number of wet (P >= 1 mm) days	neg	17 (59%)	11 (38%)	12 (41%)	23 (79%)	8 (28%)	6 (21%)	3 (10%)	2 (7%)	4 (14%)	0 (0%)
Number of wet (P >= 1 mm) days	none	7 (24%)	11 (38%)	16 (55%)	6 (21%)	17 (59%)	19 (66%)	23 (79%)	25 (86%)	24 (83%)	26 (90%)
Mean heavy day (P >= 10 mm) rainfall (mm/day)	pos	8 (28%)	5 (17%)	3 (10%)	0 (0%)	2 (7%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Mean heavy day (P >= 10 mm) rainfall (mm/day)	neg	3 (10%)	0 (0%)	0 (0%)	0 (0%)	3 (10%)	7 (24%)	5 (17%)	3 (10%)	0 (0%)	1 (3%)
Mean heavy day (P >= 10 mm) rainfall (mm/day)	none	18 (62%)	24 (83%)	26 (90%)	29 (100%)	24 (83%)	22 (76%)	24 (83%)	26 (90%)	29 (100%)	28 (97%)

Attribute	Trend	Periods, 1889–2019 Annual	Periods, 1889–2019 Dec–Feb	Periods, 1889–2019 Mar–May	Periods, 1889–2019 Jun–Aug	Periods, 1889–2019 Sep–Nov	Periods, 1950–2019 Annual	Periods, 1950–2019 Dec–Feb	Periods, 1950–2019 Mar–May	Periods, 1950–2019 Jun–Aug	Periods, 1950–2019 Sep–Nov
Number of heavy rainfall (P >= 10 mm) days	pos	0 (0%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Number of heavy rainfall (P >= 10 mm) days	neg	0 (0%)	0 (0%)	0 (0%)	13 (45%)	0 (0%)	8 (28%)	1 (3%)	0 (0%)	9 (31%)	0 (0%)
Number of heavy rainfall (P >= 10 mm) days	none	29 (100%)	28 (97%)	29 (100%)	16 (55%)	29 (100%)	21 (72%)	28 (97%)	29 (100%)	20 (69%)	29 (100%)
Mean extreme (P > 95th percentile) rainfall (mm/day)	pos	6 (21%)	NA	NA	NA	NA	0 (0%)	NA	NA	NA	NA
Mean extreme (P > 95th percentile) rainfall (mm/day)	neg	2 (7%)	NA	NA	NA	NA	3 (10%)	NA	NA	NA	NA
Mean extreme (P > 95th percentile) rainfall (mm/day)	none	21 (72%)	NA	NA	NA	NA	26 (90%)	NA	NA	NA	NA
Frequency of extreme (P > 95th percentile) rainfall days	pos	4 (14%)	NA	NA	NA	NA	0 (0%)	NA	NA	NA	NA
Frequency of extreme (P > 95th percentile) rainfall days	neg	3 (10%)	NA	NA	NA	NA	9 (31%)	NA	NA	NA	NA

Attribute	Trend	Periods, 1889–2019 Annual	Periods, 1889–2019 Dec–Feb	Periods, 1889–2019 Mar–May	Periods, 1889–2019 Jun–Aug	Periods, 1889–2019 Sep–Nov	Periods, 1950–2019 Annual	Periods, 1950–2019 Dec–Feb	Periods, 1950–2019 Mar–May	Periods, 1950–2019 Jun–Aug	Periods, 1950–2019 Sep–Nov
Frequency of extreme (P > 95th percentile) rainfall days	none	22 (76%)	NA	NA	NA	NA	20 (69%)	NA	NA	NA	NA
Maximum dry (P < 1 mm) spell duration (days)	pos	5 (17%)	NA	NA	NA	NA	2 (7%)	NA	NA	NA	NA
Maximum dry (P < 1 mm) spell duration (days)	neg	0 (0%)	NA	NA	NA	NA	2 (7%)	NA	NA	NA	NA
Maximum dry (P < 1 mm) spell duration (days)	none	24 (83%)	NA	NA	NA	NA	25 (86%)	NA	NA	NA	NA
Average dry (P < 1 mm) spell duration (days)	pos	8 (28%)	NA	NA	NA	NA	5 (17%)	NA	NA	NA	NA
Average dry (P < 1 mm) spell duration (days)	neg	1 (3%)	NA	NA	NA	NA	4 (14%)	NA	NA	NA	NA
Average dry (P < 1 mm) spell duration (days)	none	20 (69%)	NA	NA	NA	NA	20 (69%)	NA	NA	NA	NA

pos = significant positive trend; neg = significant negative trend; none = no significant trends; NA = not applicable
The value in brackets indicate the number of sites as a percentage of the total number of sites (29 sites). Shading indicates trends that are field significant (at 5% level), darker shading marks trends that are present at more than 25% of the sites.

Table A2 Number of sites that exhibit significant trends in annual and seasonal attributes of rainfall in the Macquarie-Lachlan pilot sites

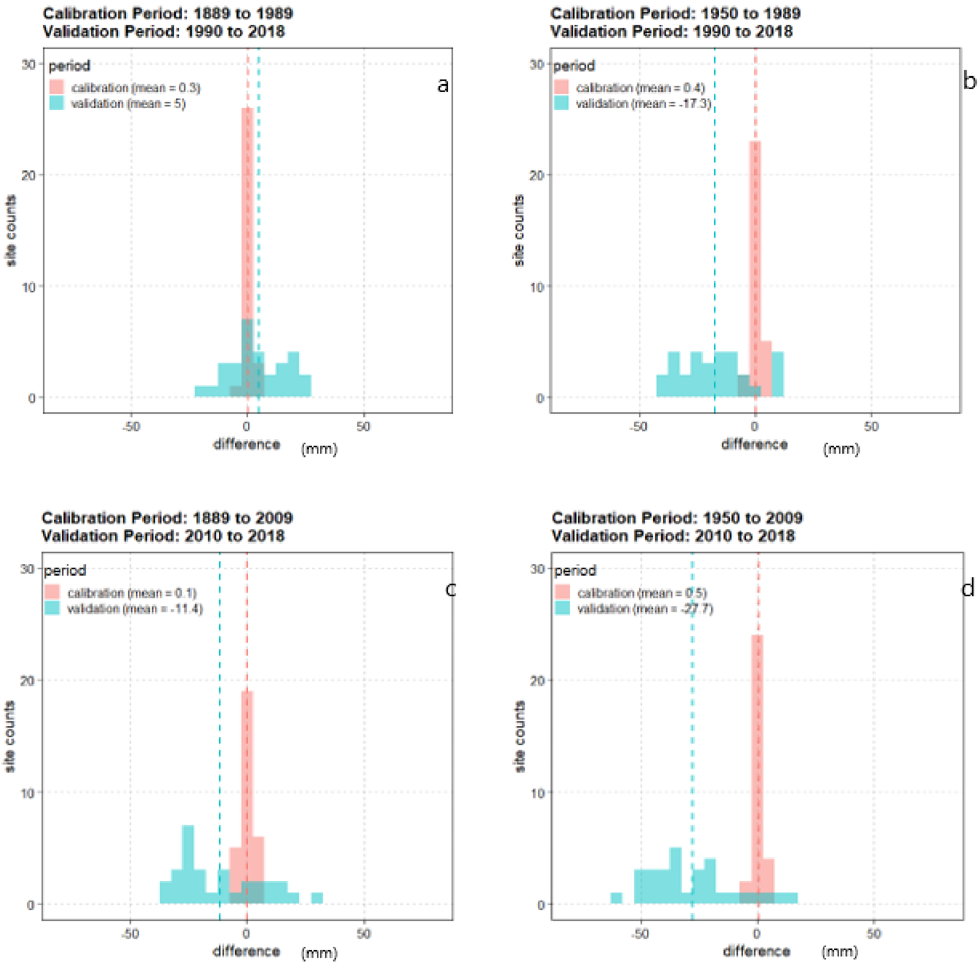
Attribute	Trend	Periods, 1889–2018 Annual	Periods, 1889–2018 Dec–Feb	Periods, 1889–2018 Mar–May	Periods, 1889–2018 Jun–Aug	Periods, 1889–2018 Sep–Nov	Periods, 1950–2018 Annual	Periods, 1950–2018 Dec–Feb	Periods, 1950–2018 Mar–May	Periods, 1950–2018 Jun–Aug	Periods, 1950–2018 Sep–Nov
Total rainfall (mm)	pos	1 (3%)	1 (3%)	0 (0%)	1 (3%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total rainfall (mm)	neg	1 (3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	15 (50%)	1 (3%)	4 (13%)	2 (7%)	8 (27%)
Total rainfall (mm)	none	28 (93%)	29 (97%)	30 (100%)	29 (97%)	29 (97%)	15 (50%)	29 (97%)	26 (87%)	28 (93%)	22 (73%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	pos	17 (57%)	15 (50%)	6 (20%)	6 (20%)	15 (50%)	2 (7%)	4 (13%)	1 (3%)	3 (10%)	2 (7%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	neg	1 (3%)	0 (0%)	1 (3%)	2 (7%)	1 (3%)	7 (23%)	2 (7%)	4 (13%)	3 (10%)	2 (7%)
Mean wet day (P >= 1 mm) rainfall (mm/day)	none	12 (40%)	15 (50%)	23 (77%)	22 (73%)	14 (47%)	21 (70%)	24 (80%)	25 (83%)	24 (80%)	26 (87%)
Number of wet (P >= 1 mm) days	pos	4 (13%)	7 (23%)	0 (0%)	0 (0%)	4 (13%)	0 (0%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)
Number of wet (P >= 1 mm) days	neg	10 (33%)	3 (10%)	6 (20%)	13 (43%)	3 (10%)	18 (60%)	2 (7%)	12 (40%)	8 (27%)	11 (37%)
Number of wet (P >= 1 mm) days	none	16 (53%)	20 (67%)	24 (80%)	17 (57%)	23 (77%)	12 (40%)	27 (90%)	18 (60%)	22 (73%)	19 (63%)

Attribute	Trend	Periods, 1889–2018 Annual	Periods, 1889–2018 Dec–Feb	Periods, 1889–2018 Mar–May	Periods, 1889–2018 Jun–Aug	Periods, 1889–2018 Sep–Nov	Periods, 1950–2018 Annual	Periods, 1950–2018 Dec–Feb	Periods, 1950–2018 Mar–May	Periods, 1950–2018 Jun–Aug	Periods, 1950–2018 Sep–Nov
Mean heavy day (P >= 10 mm) rainfall (mm/day)	pos	7 (23%)	4 (13%)	1 (3%)	4 (13%)	4 (13%)	1 (3%)	1 (3%)	1 (3%)	1 (3%)	1 (3%)
Mean heavy day (P >= 10 mm) rainfall (mm/day)	neg	1 (3%)	0 (0%)	3 (10%)	1 (3%)	1 (3%)	9 (30%)	2 (7%)	1 (3%)	2 (7%)	0 (0%)
Mean heavy day (P >= 10 mm) rainfall (mm/day)	none	22 (73%)	26 (87%)	26 (87%)	25 (83%)	25 (83%)	20 (67%)	27 (90%)	28 (93%)	27 (90%)	29 (97%)
Number of heavy rainfall (P >= 10 mm) days	pos	7 (23%)	12 (40%)	0 (0%)	0 (0%)	8 (27%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Number of heavy rainfall (P >= 10 mm) days	neg	0 (0%)	0 (0%)	0 (0%)	1 (3%)	0 (0%)	11 (37%)	0 (0%)	5 (17%)	1 (3%)	3 (10%)
Number of heavy rainfall (P >= 10 mm) days	none	23 (77%)	18 (60%)	30 (100%)	29 (97%)	22 (73%)	19 (63%)	30 (100%)	25 (83%)	29 (97%)	27 (90%)
Mean extreme (P > 95th percentile) rainfall (mm/day)	pos	3 (10%)	NA	NA	NA	NA	0 (0%)	NA	NA	NA	NA

Attribute	Trend	Periods, 1889–2018 Annual	Periods, 1889–2018 Dec–Feb	Periods, 1889–2018 Mar–May	Periods, 1889–2018 Jun–Aug	Periods, 1889–2018 Sep–Nov	Periods, 1950–2018 Annual	Periods, 1950–2018 Dec–Feb	Periods, 1950–2018 Mar–May	Periods, 1950–2018 Jun–Aug	Periods, 1950–2018 Sep–Nov
Mean extreme (P > 95th percentile) rainfall (mm/day)	neg	0 (0%)	NA	NA	NA	NA	3 (10%)	NA	NA	NA	NA
Mean extreme (P > 95th percentile) rainfall (mm/day)	none	27 (90%)	NA	NA	NA	NA	27 (90%)	NA	NA	NA	NA
Frequency of extreme (P > 95th percentile) rainfall days	pos	9 (30%)	NA	NA	NA	NA	0 (0%)	NA	NA	NA	NA
Frequency of extreme (P > 95th percentile) rainfall days	neg	0 (0%)	NA	NA	NA	NA	9 (30%)	NA	NA	NA	NA
Frequency of extreme (P > 95th percentile) rainfall days	none	21 (70%)	NA	NA	NA	NA	21 (70%)	NA	NA	NA	NA
Maximum Dry (P < 1 mm) Spell Duration (days)	pos	2 (7%)	NA	NA	NA	NA	1 (3%)	NA	NA	NA	NA
Maximum Dry (P < 1 mm) Spell Duration (days)	neg	1 (3%)	NA	NA	NA	NA	1 (3%)	NA	NA	NA	NA

Attribute	Trend	Periods, 1889–2018 Annual	Periods, 1889–2018 Dec–Feb	Periods, 1889–2018 Mar–May	Periods, 1889–2018 Jun–Aug	Periods, 1889–2018 Sep–Nov	Periods, 1950–2018 Annual	Periods, 1950–2018 Dec–Feb	Periods, 1950–2018 Mar–May	Periods, 1950–2018 Jun–Aug	Periods, 1950–2018 Sep–Nov
Maximum Dry (P < 1 mm) Spell Duration (days)	none	27 (90%)	NA	NA	NA	NA	28 (93%)	NA	NA	NA	NA
Average Dry (P < 1 mm) Spell Duration (days)	pos	3 (10%)	NA	NA	NA	NA	14 (47%)	NA	NA	NA	NA
Average Dry (P < 1 mm) Spell Duration (days)	neg	3 (10%)	NA	NA	NA	NA	0 (0%)	NA	NA	NA	NA
Average Dry (P < 1 mm) Spell Duration (days)	none	24 (80%)	NA	NA	NA	NA	16 (53%)	NA	NA	NA	NA

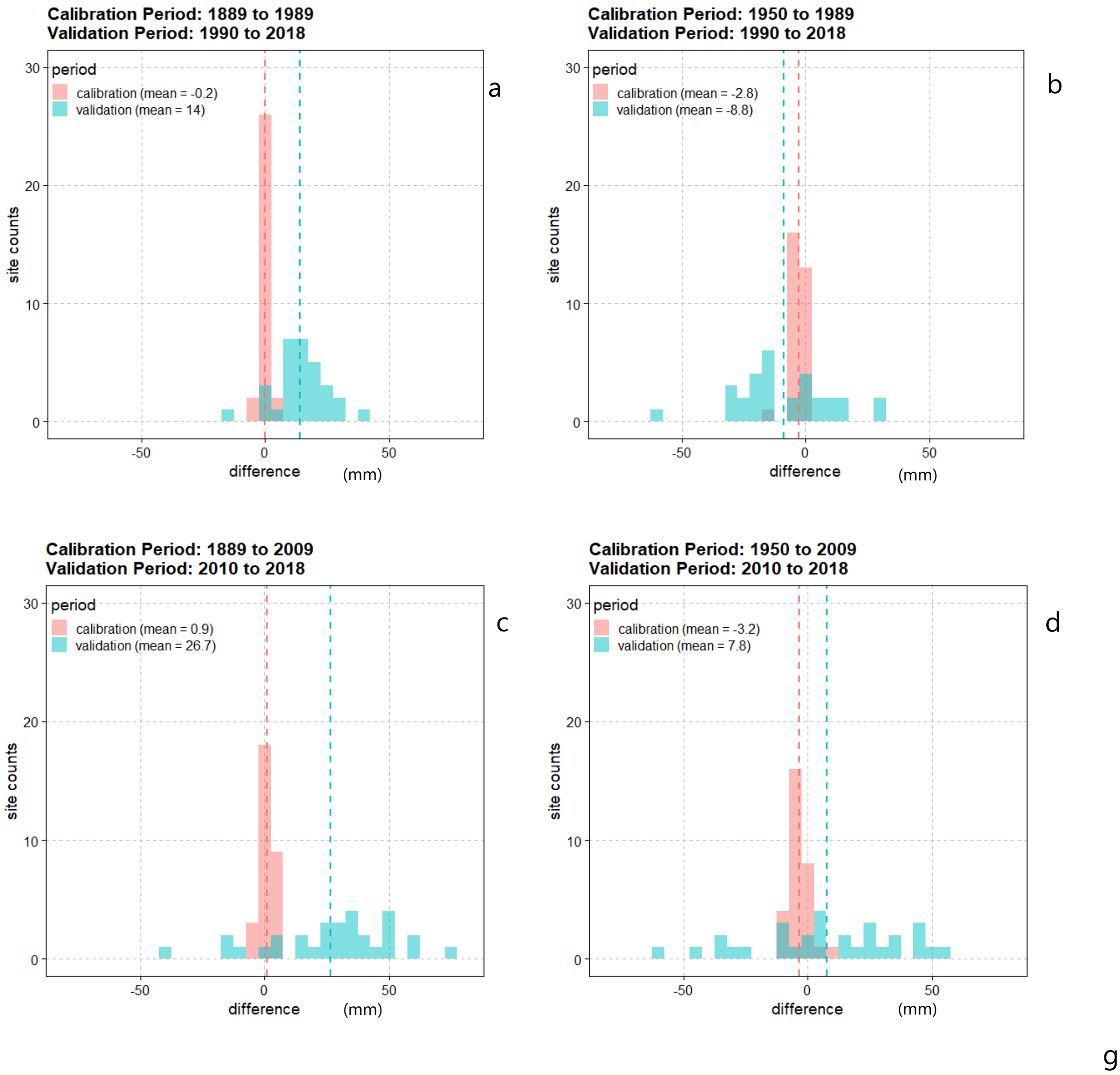
pos = significant positive trend; neg = significant negative trend; none = no significant trends; NA = not applicable
The value in brackets indicate the number of sites as a percentage of the total number of sites (30 sites). Shading indicates trends that are field significant (at 5% level), darker shading marks trends that are present at more than 25% of the sites.



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period

The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

Figure A1 Histograms of the mean differences in total SON rainfall in during the calibration and validation time periods from stochastic simulations at 30 pilot sites in Lachlan-Macquarie



(a) 1990 reference split sample test using a long calibration period, (b) 1990 split sample test using a short calibration period, (c) drought reference split sample test using a long calibration period, and (d) drought reference split sample test using a short calibration period
The dashed vertical lines mark the means of the respective histograms, the magnitude of the means are shown in the plot legends.

Figure A2 Histograms of the mean differences in total rainfall in DJF during the calibration and validation time periods from stochastic simulations (in mm) at 30 pilot sites in Lachlan-Macquarie