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Hydrological non-stationarity in the northern Murray-Darling Basin

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Abstract: The northern Murray-Darling Basin catchments in Australia have experienced significant climatic events, including the Millennium Drought throughout the 2000s and the more recent Tinderbox Drought (2017-2019), which was the driest period on record for much of the region. These droughts were followed by periods of above-average rainfall, providing an opportunity to investigate the non-stationarity in runoff responses and hydrological recovery or non-recovery. This study characterises the occurrence and patterns of hydrological non-stationarity in the context of recent severe droughts and reviews potential causal mechanisms in 39 catchments across Gwydir, Namoi, Macquarie, and Border River valleys. We applied statistical analysis, namely Hidden Markov Modelling, to identify persistent changes in rainfall–runoff relationships. Results reveal 11 catchments exhibiting long-term shifts, among them 7 catchments clustered near the Gwydir–Namoi boundary. Specifically, affected catchments include the Upper Namoi (i.e., Macdonald River) and its adjacent tributaries of the Peel River (i.e., Cockburn River) and the upper Gwydir catchment (upstream of Yarrowyck). Moreover, many of the long-term shifts began in the early 1990s, predating the Millennium Drought, and have persisted despite recent wet years. Analysis of potential causes indicates that no single factor is the dominant driver in the Namoi–Gwydir region. Instead, the changes may result from the combined influence of climatic, ecohydrological, and subsurface processes. These findings have implications for hydrological modelling and water resource management, suggesting that current rainfall–runoff models may require refinement to address biases under non-stationary conditions.

Keywords: *Hydrological non-stationarity, Northern Murray-Darling Basin, rainfall-runoff relationship, Hidden Markov Model*

1. INTRODUCTION

Over recent decades, droughts have intensified and become more frequent in many regions, particularly in mid-latitude regions due to anthropogenic climate change (Devanand et al., 2024). In New South Wales and elsewhere, this has placed considerable stress on water resources, with observed streamflow reductions often disproportionate to declines in rainfall. Such changes reflect a shift in the rainfall–runoff relationship, termed hydrological non-stationarity, whereby equivalent rainfall now yields less streamflow than before. This was widely reported during the Millennium Drought in southeast Australia (Saft et al., 2015) and, in many areas, has persisted despite subsequent wet years (Peterson et al., 2021).

However, in contrast to the southern Murray Darling Basin (MDB), which is relatively well studied, the extent of hydrological non-stationarity in the northern MDB catchments remains unknown, particularly under recent drought conditions. The climatic conditions in northern MDB differ from the southern MDB, with summer-dominant rainfall and greater variability in both climate and streamflow. Thus, it is reasonable to expect that hydrological non-stationarity may also differ, suggesting the need for a region-specific study to inform water management strategies, particularly under climate change. This study is particularly focussed on the New South Wales (NSW) portion of the northern MDB, namely the Gwydir, Namoi, Macquarie, and NSW Border Rivers valleys.

The northern MDB has experienced major climatic extremes, including the Millennium Drought in the 2000s and the Tinderbox Drought (2017–2019), the driest period on record for much of the region. These events, followed by above-average rainfall years, present an opportunity to assess the degree of non-stationarity and potential non-recovery in runoff responses. Previous studies have provided some insights, such as Amirthanathan et al. (2023), who identified downward step changes in streamflow during 1990–2001 in selected northern MDB catchments, while Rassam et al. (2017) investigated non-stationarity in low flows during drought in the northern Namoi Basin. More recently, Peña-Arancibia et al. (2023) examined drivers impacting runoff in the northern MDB compared to the south, though their analysis was regional and thus did not focus specifically on characterising which catchments exhibited hydrological non-stationarity. Thus, despite these contributions, a detailed understanding remains limited.

Considering these gaps and aligning with existing methodologies applied in other regions of Australia, this study investigates the occurrence and patterns of hydrological non-stationarity and recovery through statistical analyses of streamflow and climate data. In addition, this study investigates the potential causal mechanisms and driving factors behind any observed non-stationarity. These findings contribute to a better understanding of catchment behaviour in the northern MDB and inform water resource management strategies under climate change.

2. MATERIALS AND METHODS

2.1. Study area

This study examines 39 catchments with at least 30 years of streamflow records, distributed across the four valleys mentioned above. These valleys encompass a range of climatic conditions, with mean annual rainfall of approximately 800–1000 mm, predominantly in summer-dominant seasonal patterns. Each valley contributes about 3–8% of the MDB's total water resources and plays a critical role in urban water supply, irrigated agriculture, stock and domestic use, and mining. Beyond their economic value, these valleys hold significant cultural importance for First Nations communities, allow for a wide range of recreational uses, and support diverse ecosystems, including forests, woodlands, wetlands, and grasslands.

2.2. Data selection and pre-processing

The statistical methods applied in this study require areal-average rainfall and streamflow for each catchment. For rainfall data, we adopted rainfall data used by the Department of Climate Change, Energy, the Environment, and Water (DCCEEW), where available. These data comprise weighted SILO patch-point rainfall information and were available for 31 out of 39 study catchments. Of those catchments missing this information, six were in the Namoi, one was in the Macquarie, and one was in the Border Rivers. For all such catchments, SILO gridded rainfall data were used instead of weighted patch-point data. Daily streamflow data were provided by the DCCEEW, and some data infilling was conducted as described below.

2.2.1. Data pre-processing

Since this study focuses on changes in the annual rainfall and streamflow relationship, the daily data needed to be aggregated to water years (July-June). The rainfall data from SILO, whether patch-point or gridded, contained no gaps and could be readily aggregated. In contrast, many catchments had missing streamflow records, necessitating infilling. Therefore, streamflow data records with daily data in a year with less than 5% missing data were infilled as discussed in the following paragraph. In some cases, larger gaps were considered on a case-by-case basis, if doing so extended the continuous record substantially.

This gap-filling was performed by establishing a linear relationship between daily streamflow in the target catchment and that of the nearest catchment with complete records. Although this approach is relatively simple, it was deemed sufficient because the infilled values were used only in aggregated water-year totals. As such, errors affecting short-term flow timing were inconsequential, and the key requirement was accurately reproducing the mean flow over the infilled period.

2.3. Method to identify shifts in rainfall-runoff behaviour using Hidden Markov Modelling

2.3.1. Hidden Markov Modelling

Hidden Markov modelling (HMM) is based on the premise that an unobserved (hidden) state governs the relationship between a system's inputs (in this case, rainfall) and outputs (in this case, streamflow). A tailored application of this approach was developed by Peterson et al. (2021) to detect changes in the rainfall–runoff relationship and used to examine Victorian catchments during and after the Millennium Drought. The method first tests for a parsimonious single-state solution and only progresses to a more complex multi-state configuration if warranted by the data. A single-state outcome indicates a stable, stationary rainfall–runoff relationship, whereas a multi-state outcome signals hydrological non-stationarity, with the relationship varying over time. A key advantage of this approach is its ability to pinpoint the timing of state transitions in multi-state cases, enabling the identification of how and when individual catchments respond to drought conditions, which can differ markedly in both timing and magnitude.

2.3.2. Identification of shifts in rainfall-runoff relationship

The aggregated rainfall and streamflow datasets were analysed using the open-source R package HydroState (Peterson et al., 2021), which fits Hidden Markov models with one, two, or three states. A single-state model reflects a stable or 'normal' hydrological regime, whereas a two-state model can capture an additional regime, so that the states are 'normal–dry' or 'normal–wet'. Three-state models represent more complex regime sequences (e.g., 'normal–wet–very wet' or 'dry–normal–wet'). All models for 39 catchments with multiple states allow for multiple transitions over time. Model selection for each catchment was based on minimising the Akaike Information Criterion (AIC), which balances explanatory power against model complexity, thereby favouring multi-state models only when justified by the data. In addition, the HMM method requires that one year be nominated as "normal", and this is always a subjective choice; in this case, almost all of the catchments turned out to be relatively stable (not changing state) during the 1970s and (to some extent) 1980s, meaning that the results are minimally sensitive to the choice of year provided it is in this period of time, and we chose 1976. Thus, a 'dry' or 'wet' year is defined as one in which the rainfall–runoff relationship has shifted downward or upward, respectively, relative to 1976.

2.4. Potential causes of observed shifts in rainfall-runoff relationship

Potential drivers of the observed non-stationarity were assessed under four categories: (1) meteorological conditions, (2) climate-driven vegetation changes, (3) climate-driven groundwater and subsurface water changes, and (4) increased water use. Drivers were selected for assessment following an initial prioritisation exercise, which was undertaken after initial results from Section 2.3 were known. This exercise deemed some topics as low priority for further analysis, such as the ENSO (El Niño–Southern Oscillation) and IPO (Interdecadal Pacific Oscillation) phases during the 1990s and 2000s, wildfire, irrigation, and expanded mining activity. In many cases, a key reason for their low priority was that their spatial influence did not correspond with the distribution of observed hydrological non-stationarity. This paper synthesises only the findings from the potential causes that were examined in detail; the complete results will be available in the full report (details listed in the acknowledgements section).

3. RESULTS

3.1. Observed long-term shifts in rainfall-runoff relationships

Figure 1a shows catchments with long-term hydrological shifts outlined in red, and stable catchments outlined in black. Of the 39 catchments assessed across the Gwydir, Namoi, Macquarie, and Border Rivers, 11 exhibited long-term hydrological changes. Figure 1b(i) presents an example of a catchment with a persistent shift, while Figure 1b(ii) illustrates a hydrologically stable catchment. In each subplot, the upper panel displays rainfall variation by water year, and the lower panel depicts changes in hydrological state over time. For example, catchment 419005 in the Namoi Basin shifted to a lower hydrological state in 1992 and has remained in that state since. Table 1 summarises the start and end years of hydrological non-stationarity for the 11 identified catchments, along with the magnitude of the observed changes.

Table 1 Summary of catchments with long-term hydrological non-stationarity observed.

Catchment ID	Basin	Hydrological non-stationarity		Magnitude[a]
		Start Year	End Year	
418014	Gwydir	1986	2023	-0.33
418015		2006	2018	-0.36
418027		2004	2023	-0.22
419005	Namoi	1992	2023	-0.34
419010		1991	2023	-0.31
419016		1992	2023	-0.52
419053		1985	2023	-0.40
416008	Border River	1999	2018	-0.30
416016		1993	2023	-0.31
421018	Macquarie	1999	2023	-0.38
421026		1992	2023	-0.46

[a]Hydrological shift magnitude was calculated considering the observed and expected streamflow data after the water year 1992 (inclusive). The water year 1992 was chosen subjectively, as many catchments shifted around this period. The magnitude was determined using the following equation:

$$Magnitude = \frac{\overline{(Q_{Observed} - Q_{Expected})}_{Wateryear}}{\bar{Q}_{Expected,wateryear}}$$

Please note that the negative value means the observed value is less than the expected value.

3.2. Synthesis of potential causes of observed hydrological non-stationarity

This section summarises only the potential causes of observed hydrological non-stationarity that were examined, while the complete results will be available in the project report titled '*Changes in Runoff Characteristics in the Northern Murray–Darling Basin*', published on the NSW Department of Climate Change, Energy, the Environment and Water website.

- **Rainfall seasonality** showed a post-1992 reduction in autumn rainfall, leading to lower rainfall-runoff ratios in autumn and winter. However, summer rainfall (which dominates in this region) did not decline significantly, and changes were not clearly different between shifted and non-shifted catchments in each season.
- **Evaporative demand and vapour pressure deficit** increased slightly, potentially intensifying water loss via evapotranspiration. Yet, the magnitude of these changes was small and similarly observed across both shifted and stable catchments.
- **Vegetation greenness** largely maintained, indicating vegetation may have prioritised precipitation for their survival during droughts. This could reduce streamflow, but again, the patterns were not distinctly aligned with catchment shift status.
- **Groundwater storage**, based on Gravity Recovery and Climate Experiment (GRACE) Terrestrial Water Storage (TWS) data, declined across both shifted and stable catchments during the Millennium Drought. However, some shifted catchments (particularly in Gwydir) showed prolonged post-Millennium Drought declines, suggesting potential localised subsurface depletion.
- **Runoff dam** (farm dam) development increased in some shifted catchments around the 1990s, but similar trends were observed in non-shifted catchments. The overall water storage impact (<5% of annual streamflow) was too small to account for the observed shifts in many cases.
- **Data errors**, particularly in rainfall inputs from SILO patch points and gridded data, were identified in a few cases but were not widespread enough to explain the broader non-stationarity patterns.

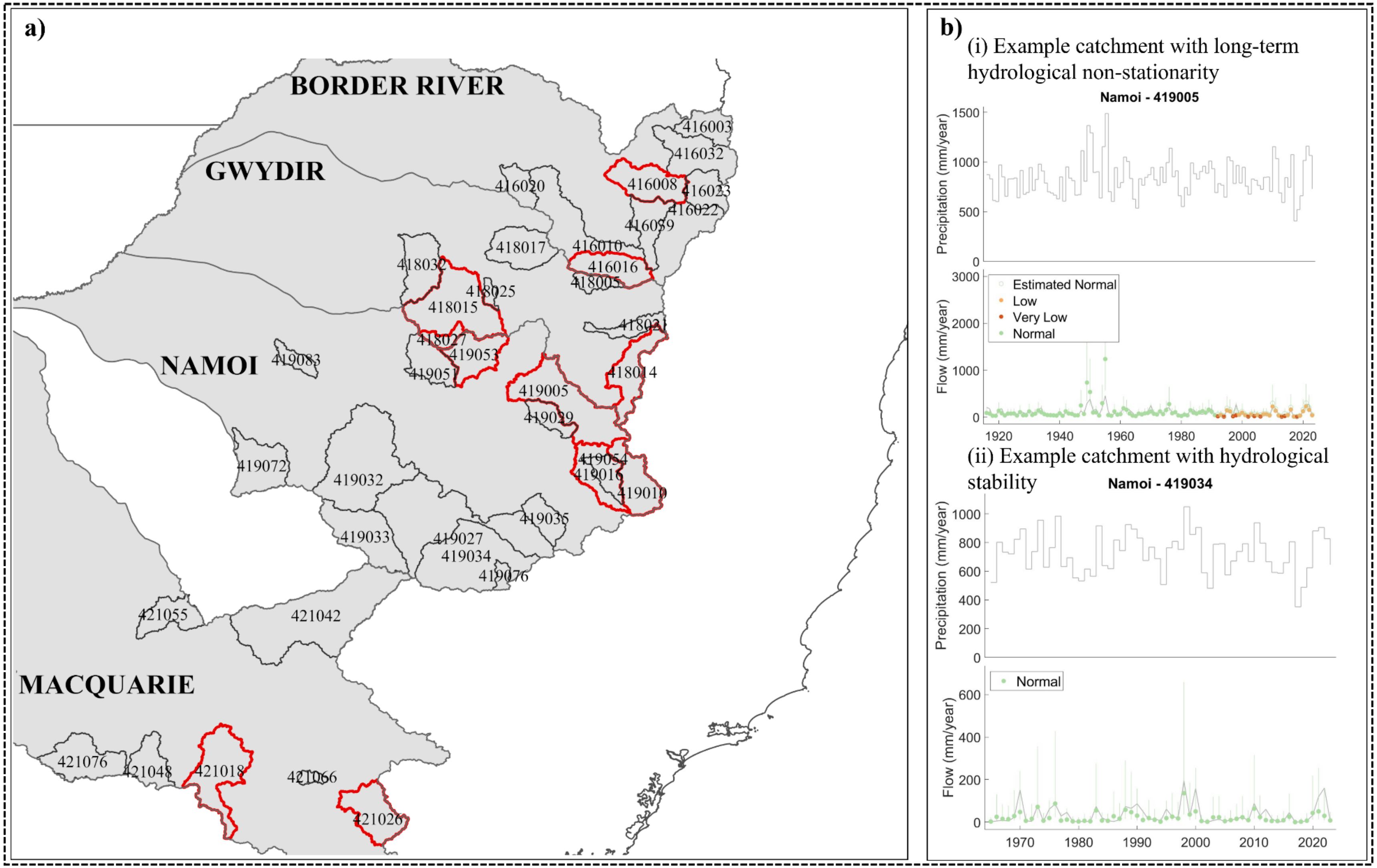

Figure 1 a) Identified long-term hydrologically shifted catchments (in red outlines) as indicated by the HMM analysis; b) Two examples of (i) long-term hydrologically shifted catchments, and (ii) hydrologically stable catchment.

4. DISCUSSION

The HMM analysis identified 11 of the 39 assessed catchments across the Gwydir, Namoi, Macquarie, and Border Rivers as exhibiting long-term hydrological non-stationarity. The most prominent cluster occurred along the Namoi–Gwydir basin boundary, particularly in the Upper Namoi (Macdonald River), adjacent Peel River tributaries (such as the Cockburn River), and the upper Gwydir catchment upstream of Yarrowyck. While these catchments displayed persistent reductions in streamflow generation, only a few, such as 418015 and 418027 (Gwydir), 416008 (Border Rivers), and 421018 (Macquarie), appeared to show significant reductions that were initiated by the Millennium Drought or the subsequent Tinderbox Drought.

This contrasts with patterns in the southern MDB, where the Millennium Drought had a widespread effect, with more than half of Victorian catchments shifting to a new rainfall–runoff relationship. Recent analysis by Wang et al. (2025) suggests that most southern MDB catchments did not recover after the drought ended. Later events, including the Tinderbox Drought, had limited additional impact, likely because many catchments were already in a shifted state and had not returned to pre-drought conditions. In the northern MDB catchments examined here, however, the transition to a lower hydrological state generally occurred earlier during the 1992–1994 water years, coinciding with droughts in southern Queensland and New South Wales, particularly the severe 1994 event. These shifts have persisted since, with no recovery even after the recent sequence of wet years following the Tinderbox Drought.

Some other catchments in Macquarie and Border River basins exhibited persistent non-stationarity but were more spatially isolated. For example, in the upper Border Rivers, several catchments showed low-state persistence for at least five years, with catchment 416008 remaining in a reduced state from 1999 to 2018 before returning to normal conditions during recent wetter years. In the Macquarie, catchments 421026 and 421018 experienced extended low states beginning in 1992 and 1999, respectively, with neither recovering by the end of the 2022 water year. These findings are broadly consistent with Raut et al. (2019), who reported significant post-1992 hydrological shifts in Border Rivers catchments 416008 and 416016 by comparing observed streamflow with SACRAMENTO model simulations calibrated to pre-1992 conditions.

In terms of the possible causes of observed hydrological non-stationarity, government and scientific reports suggest that land-use and land-cover changes, such as shifts in agricultural practices, increased runoff dam constructions, and greater unregulated water extractions, may have contributed to these long-term changes. Despite the broad range of investigations undertaken here, no single factor could be identified as the dominant driver in the Namoi–Gwydir region. However, given the piecewise analysis that only considered one driver at a time, it is possible that a combination of climatic, ecohydrological, and subsurface processes acted together to produce the observed effects. If so, different drivers may have exhibited varying degrees of influence across catchments.

5. CONCLUSION AND RECOMMENDATIONS

This study investigated hydrological non-stationarity in 39 catchments of the northern Murray–Darling Basin (MDB) and examined potential causal mechanisms. 11 catchments across the Gwydir, Namoi, Macquarie, and Border Rivers showed persistent streamflow declines since the early 1990s. Of these, 7 catchments near the Namoi–Gwydir basin boundary formed a distinct cluster of long-term hydrological changes. Unlike patterns in the southern MDB, these shifts, particularly in the Namoi, were not linked to the Millennium or Tinderbox droughts but were instead initiated with earlier dry years (1992–1994) and persisted throughout subsequent droughts. The remaining 4 affected catchments, in the Border Rivers and Macquarie, were more spatially isolated. The investigation of possible causes of observed hydrological non-stationarity found no single factor that accounted for the changes, rather, they may have resulted from the combined influence of climatic, ecohydrological, and subsurface processes. The findings highlight the need for continued, multi-disciplinary monitoring to better understand and manage hydrological variability in the northern MDB.

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