From natural variability to flow homogenisation: how dams, water diversions, and climate change reduced seasonal flows in Australia's Murrumbidgee River

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Abstract

River regulation and climate change have profoundly altered seasonal flow dynamics globally, with cascading ecological impacts on freshwater ecosystems and biodiversity. Magnitude and timing are key components of the flow regime, connecting rivers with floodplains and driving feeding and breeding cues for aquatic organisms. We investigated the separate and combined effects of water resource development and projected climate change on seasonal flow regimes in the lower Murrumbidgee River (~1500 km), a major river system within Australia's Murray-Darling Basin. Using long-term hydrological data and rainfall-runoff modelling (1890-2022), we quantified changes in natural river discharge across key periods of river regulation and environmental flow management. Hydrological alterations, driven by dam constructions and water withdrawals, caused substantial homogenisation of seasonal flow patterns, reducing median river discharge by 24-68% between 1958-2022, compared to modelled natural flows. These declines persisted and intensified despite environmental water deliveries post-2006. Median climate projections (2047-2075) under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios indicated further reductions in flows during the wetter seasons of autumn, winter, and spring (4-22%), exacerbating the impacts of river regulation, while summer flows may experience slight increases or decreases. These flow reductions have driven extensive drying of the semi-arid Lowbidgee Floodplain, a nationally important 3250 km^2 wetland ecosystem, dependent on high interannual and seasonal flow variability for its "boom-and-bust" ecological processes. Flow homogenisation has disrupted natural flooding regimes, reducing floodplain connectivity, degrading riparian habitats, and facilitated the spread of invasive species at the expense of native biodiversity. Our research highlights the need for environmental flow management to better mimic natural flow regimes, prioritising large flow events to restore floodplain wetland health.

Keywords: flow seasonality; flow regime alteration; climate change; floodplain connectivity; wetland restoration; environmental flows; semi-arid ecosystems; Murray-Darling Basin.

Highlights

- We separated the impacts of damming and climate change on river flow regimes.
- River regulation homogenised seasonal flows in the Murrumbidgee River.
- Median river flows declined by 24-68% per season under river regulation.
- Historically wetter seasons will lose an additional 4-22% of flow under climate change.
- Environmental flows should supplement large flows to restore floodplain wetlands.

1 Introduction

The escalating degradation of the world's riverine ecosystems is a major environmental challenge, affecting global freshwater biodiversity, with catastrophic declines of 74-89% since 1970 (WWF, 2022). Many freshwater ecosystems services are also declining (Junk et al., 2013; Kingsford et al., 2016), driven by anthropogenic threats, including water resource development, land-use conversion, pollution, and invasive species, with climate change adding further pressure (Dudgeon, 2019; Junk et al., 2013; Reid et al., 2019; Xi et al., 2021).

The building of dams and the diversion of water upstream of major wetland ecosystems have driven much of this significant biodiversity loss (Kuiper et al., 2014; Poff et al., 2007; Poff and Zimmerman, 2010). Globally, freshwater withdrawals have more than doubled since 1960 (Wada and Bierkens, 2014), with future water demand projected to increase further due to rising incomes and population growth (Alcamo et al., 2007; Shen et al., 2008). There are currently about 50,000 large dams and reservoirs (Berga et al., 2006; Lehner et al., 2011a), collectively capable of storing one-sixth of global annual river discharge (Hanasaki et al., 2006). Hydroelectric power, contributing 16% of global energy production (World Bank, 2015), continues to expand, with at least 3700 major hydropower dams either planned or under construction, predominantly in emerging economies (Zarfl et al., 2019; Zarfl et al., 2015). These infrastructure developments have fundamentally altered or homogenised river flow regimes worldwide (Dynesius and Nilsson, 1994; Grill et al., 2015; Palmer et al., 2008; Poff et al., 2007; Vörösmarty et al., 2010). Flow regimes, including magnitude, duration, frequency, timing, and rate of change, fundamentally shape in-stream and floodplain ecosystem structure, functioning, and processes (Bunn and Arthington, 2002; Palmer and Ruhi, 2019; Pettit et al., 2017; Poff et al., 1997). Further, climate change affects river flows by altering runoff patterns (Haddeland et al., 2014; Schewe et al., 2014; Zheng et al., 2024) and the seasonality of flow

(Arnell and Gosling, 2013; Döll and Zhang, 2010; van Vliet et al., 2013), with both impacts varying significantly across regions.

River flow regimes typically follow distinct natural seasonal patterns, primarily driven by precipitation, evapotranspiration, and snowmelt patterns (Berghuijs et al., 2014; Dettinger and Diaz, 2000; Poff et al., 1997), creating distinct ecological niches. Many freshwater organisms rely on specific flow conditions for feeding, migration, and reproduction, including aquatic insects (Bogan and Lytle, 2007; Grgić et al., 2022), fish (Kennard et al., 2007; King et al., 2009; Pusey et al., 2004; Reynolds, 1983; Winemiller and Jepsen, 1998), amphibians (Littlefair et al., 2021; Ocock et al., 2014; Ocock et al., 2024), and waterbirds (Bino et al., 2014; Kingsford and Auld, 2005). Similarly, riparian vegetation communities are dependent on seasonal flow timing for water dispersal rates, seed germination, and plant growth (Greet et al., 2011). Consequently, many aquatic species are highly vulnerable to changes in river flow predictability or seasonality (Tonkin et al., 2017). Winter and spring flow peaks can play a crucial role in supporting native plants, particularly trees and shrubs, while limiting the spread of exotic species in the riparian zone (Greet et al., 2013; Stromberg et al., 2007). River regulation can alter flow magnitude and timing, reducing abundance and diversity of macroinvertebrates (Bunn and Arthington, 2002; Poff and Zimmerman, 2010), native fish (Bunn and Arthington, 2002; Freeman et al., 2001; Poff and Zimmerman, 2010), and waterbirds (Figarski and Kajtoch, 2015; Kingsford et al., 2004). However, some often invasive species benefit from regulated flow conditions (Poff and Zimmerman, 2010; Xia et al., 2016). Cultural values are also often dependent on the seasonality of river flows (Moggridge and Thompson, 2021; Tipa, 2009). Flow regimes can drive fundamental geomorphological and biogeochemical processes, including sediment transport processes, which influence habitat structure such as pools and riffle formations (Milhous, 1998; Pitlick and Wilcock, 2001), and nutrient transport downstream and across floodplains through high-flow events, enhancing ecosystem productivity (Palmer and Ruhi, 2019; Pettit et al., 2017). Flow variability also affects water quality, with low streamflow linked to increased water temperature and pollution concentrations (Palmer and Ruhi, 2019; van Vliet et al., 2013).

The consequences of disrupting seasonal flow timing are particularly acute for freshwater ecosystems in arid and semi-arid areas, already facing intense water stress (Huang et al., 2021; Micklin, 2007; Milly et al., 2005; Poff et al., 2007). Australia is the world's driest inhabited continent (Fujioka and Chappell, 2010), resulting in high competition for water resources, particularly in the Murray-Darling Basin, the country's largest river basin (1.1 million km^2) and its most important agricultural region, producing around 40% of the country's agricultural output (Leblanc et al., 2012). Extensive hydraulic infrastructure development has transformed the Murray-Darling Basin into Australia's most heavily regulated large river system (Döll et al., 2009; Kingsford, 2000; Pittock, 2016) with widespread degradation of wetlands (Arthington and Pusey, 2003; Kingsford, 2000; Leblanc et al., 2012) and flood-dependent biota (Gehrke et al., 1995; Grafton et al., 2022; Kingsford et al., 2017; Taylor et al., 1996). Despite the Australian Government's commitment of A$13 billion to water reforms under the Basin Plan since 2012, 74% of indicators have shown no improvement or have deteriorated, with particularly poor outcomes for Indigenous, social, and environmental indicators (Colloff et al., 2024). Climate change is projected to further decrease water availability in the Murray-Darling Basin in the future (CSIRO and BOM, 2022; Kreibich et al., 2024; Zheng et al., 2024). Although many Australian species, such as freshwater fish, are adapted to variable and unpredictable flow conditions, the projected rate and magnitude of climate change will likely outpace the adaptive capacities of many species (Morrongiello et al., 2011).

In this study, we investigated temporal changes in seasonal flows in the lower Murrumbidgee River, one of Australia's largest rivers, within the southern Murray-Darling Basin. We also focused on changes to the river's largest wetland ecosystem, the nationally important Lowbidgee Floodplain (DIWA, 2005; Environment Australia, 2001). We had three main objectives: 1.) developing a model to estimate 'natural' seasonal river flows, pre-dating major flow regulation (1890-1927), driven primarily by catchment runoff patterns; 2.) analysing the historic effects of water diversions and dam constructions on seasonal river flows over the period 1890-2022; and 3.) projecting climate change impacts on both natural and regulated seasonal river flows. Understanding changes to seasonal flows is crucial for effective river management, influencing water allocations to agriculture, industry, domestic usage, and environmental needs. Our research specifically aimed to inform environmental flow management for the large-scale restoration of the ecologically and culturally important Lowbidgee Floodplain.

2 Materials and methods

2.1 Study area

The Murrumbidgee River (~1485 km), within the southern Murray-Darling Basin (Figure 1), is among the three longest rivers on the Australian continent (Geoscience Australia, 2014). Originating in the Fiery Range of the Snowy Mountains at an elevation of 1600 m above mean sea level, it flows into the Murray River near Balranald (Wen et al., 2012). The Hay gauge (Figure 1) is upstream of the Lowbidgee Floodplain (3250 km^2), which includes Yanga National Park (670 km^2) and the Indigenous-owned Gayini (Nimmie-Caira) Wetlands (880 km^2). The floodplain has a dynamic 'boom-and-boost' environment (Arthington and Balcombe, 2011), characterised by natural cycles of drying and wetting from the Murrumbidgee River's frequent floods (Kreibich et al., 2024), supporting extensive stands of lignum (*Duma florulenta*) and nitre goosefoot (*Chenopodium nitrariaceum*) shrublands, river red gum forests and woodlands (*Eucalyptus camaldulensis*), and black box woodlands (*E. largiflorens*) (Kingsford and Thomas, 2004; Maher, 1990; Wen et al., 2012). This area is one of eastern Australia's largest breeding sites for waterbirds, including glossy ibis (*Plegadis falcinellus*), straw-necked ibis (*Threskiornis spinicollis*), royal spoonbills (*Platalea regia*), and Australian pelicans (*Pelecanus conspicillatus*) (Kingsford and Thomas, 2004; Maher, 1990). It also provides critical habitat for freshwater turtles (Ocock et al., 2018), the endangered Southern bell frog (*Litoria raniformis*) (Turner et al., 2024; Wassens, 2008), and threatened native fish such as Murray cod (*Maccullochella peelii*) (Turner et al., 2024). First Nations occupation on the Lowbidgee Floodplain reaches back about 50,000 years, evidenced by over 1200 cultural heritage sites, including scar trees, middens, earth mounds, and burial sites (Woods et al., 2022). After 180 years of dispossession due to European colonisation, the Gayini Wetlands were returned to their Indigenous traditional custodians, the Nari Nari people, in

2019 (Woods et al., 2022). This area is now the focus of a large-scale restoration effort aimed at protecting both its ecological and First Nations cultural values.

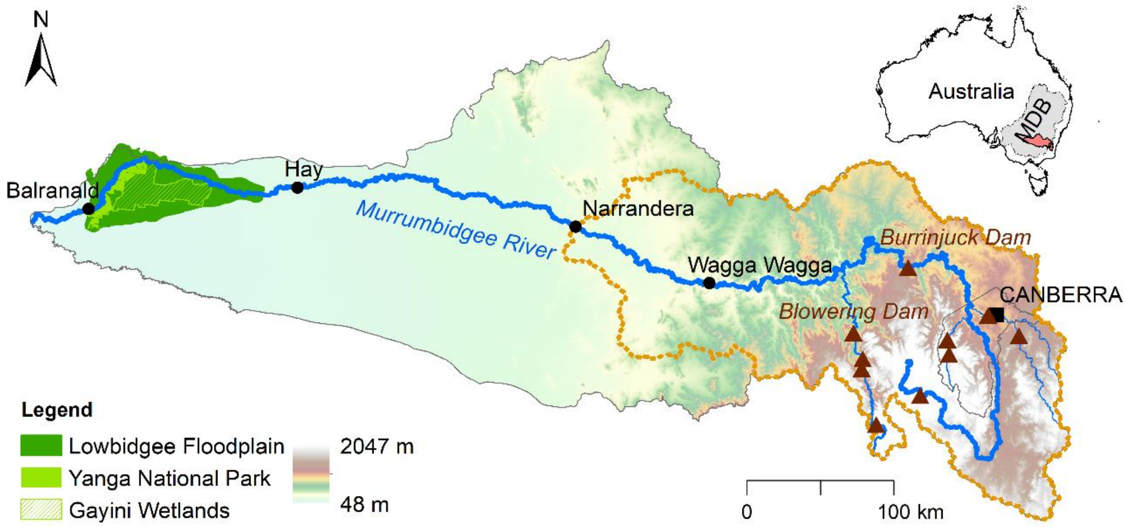

Figure 1. Murrumbidgee River (flows east to west) within its catchment (red inset), in Australia's Murray-Darling Basin (MDB, grey inset), with selected major dams (dark brown triangles), key locations of streamflow gauges used in analyses (Hay, Wagga Wagga), and the Lowbidgee Floodplain, including Yanga National Park and the Gayini Wetlands, with a delineated upper elevated catchment boundary used for gridded cell runoff data (orange dashed polygon).

The region's climate is semi-arid, characterised by low average annual rainfall of 322 mm, hot summers with mean temperatures of 31.6°C, and mild winters with mean temperatures of 18.1°C (BOM, 2024b; Kreibich et al., 2024). Before significant human interventions, river flows were highly seasonal, driven by winter and early spring rainfall and snowmelt from the Great Dividing Range (Kingsford and Thomas, 2004; MDBA, 2012). Most of the land use within the Murrumbidgee catchment (84.000 km^2) is for agricultural production, much of it relying heavily on the river for irrigation (CSIRO, 2008). Consequently, the Murrumbidgee River is one of the more heavily regulated major rivers in Australia, with 26 major dams and weirs controlling its flow (Kingsford, 2003). The cumulative dam storage on the river system surpassed 4307×10^6 m^3 in 2024, which included Burrinjuck Dam (1026×10^6 m^3) and

Blowering Dam (1628×10^6 m^3) (Kreibich et al., 2024). These dams regulate water supply for the Murrumbidgee and Coleambally Irrigation Areas (Kingsford, 2003; Wen et al., 2012), which are on the river's lower reaches but upstream of the Lowbidgee Floodplain.

2.2 Historical analysis (1890-2022)

2.2.1 Catchment runoff data

To assess changes in seasonal river flows, we used the daily runoff modelled by Zheng et al. (2024) across the upper Murrumbidgee River catchment. The modelling was carried out using the GR4J hydrological model, a daily lumped four-parameter rainfall-runoff model (Perrin et al., 2003). The model was calibrated and validated using streamflow observations from 780 largely unregulated and unimpaired catchments throughout Australia, including 130 catchments in the Murray-Darling Basin (Zheng et al., 2024). This provided the catchment's 'natural' runoff, unaffected by water resource development (Kreibich et al., 2024). The application of rainfall-runoff models calibrated against observed streamflow data is a mature science, and the use of different runoff datasets available for the region will provide similar interpretation and conclusion in the context of this study (Blöschl et al., 2013; Chiew, 2010).

We used daily precipitation (Jeffrey et al., 2001) and potential evapotranspiration (Chiew and McMahon, 1991; Morton, 1983) to model runoff at a 0.05° grid resolution for the upper catchment area upstream of Narrandera (Figure 1). This region generates the majority of runoff for the Murrumbidgee River (CSIRO, 2008), whereas downstream of Narrandera, the catchment transitions into flat terrain (Figure 1), introducing higher uncertainty in runoff dynamics.

Total daily runoff was calculated by summing across all grid cells in the upper catchment and then aggregated into seasonal totals based on the Australian water year (July–June): winter

(July–September), spring (October–December), summer (January–March), and autumn (April–June) (BOM, 2024a). The historical runoff dataset spans 1890-2022. We used R version 4.4.0 for all data analysis and modelling (R Core Team, 2024), unless stated otherwise.

2.2.2 Flow regulation periods

We identified four distinct periods representing water resource development in the Murrumbidgee River (Kingsford, 1995; Kreibich et al., 2024; Lehner et al., 2011b, a; Ren and Kingsford, 2014): (i) the natural flow period (1890-1927), characterised by a cumulative dam capacity of less than 5×10^6 m³; (ii) a low regulation period (1928-1957), when total dam storage increased to 1049×10^6 m³; (iii) a high regulation period (1958-2006), when total storage reached 4234×10^6 m³; and (iv) a subsequent high regulation period (2007-2022) with relatively constant total dam storage of 4307×10^6 m³ but including the delivery of environment water (NSW DCCEEW, 2024a). Environmental watering was intended to maintain and improve flow-dependent native vegetation, fish, frogs, waterbirds, river-floodplain connectivity, and Aboriginal cultural values (NSW DPIE, 2020b). To achieve these ecological and cultural objectives, specific environmental water requirements for each target were identified and classified based on river flow rate, timing, duration, frequency, and the maximum interval between events (NSW DPIE, 2020b, a).

2.2.3 River discharge data

Continuous long-term streamflow data for the Murrumbidgee River were obtained from the Hay gauge, located upstream of the Lowbidgee Floodplain and downstream of most major irrigation zones (Figure 1). Daily discharge records were aggregated into seasonal totals for the water years 1916-2022. To extend seasonal river discharge data back to 1890, we reconstructed historical discharge at Hay using observed records from the Wagga Wagga gauge (1868-present), which is upstream in the same river system (see Kreibich et al., 2024 for details).

We developed a generalised linear model (GLM) for each season to estimate historical discharge at Hay based on Wagga Wagga discharge during the natural flow period (1890-1927). The GLMs used a Gaussian error distribution with an identity link function, as this approach assumes a continuous, normally distributed response variable. To account for the estimated travel time of eight days between Wagga Wagga and Hay, we incorporated a time lag into the model (MDBA, 2012). Given the right-skewed distribution of river discharge, we applied a log transformation to improve normality and homoscedasticity.

The GLMs were calibrated using observed discharge data from Hay (1916-1927) and Wagga Wagga (1890-1927 for spring, autumn, and winter; extended to 1935 for summer to avoid overestimation of high flows). Each model demonstrated a strong correlation between observed and predicted discharge at Hay, with the following seasonal model equations and performance statistics: (i) spring: R^2=0.96, $p<0.001$, $y=0.303+0.955x$; (ii) summer: R^2=0.75, $p<0.001$, $y=3.300+0.341x$; (iii) autumn: R^2=0.87, $p<0.001$, $y=0.730+0.874x$; and (iv) winter: R^2=0.99, $p<0.001$, $y=0.069+0.991x$. Model diagnostics confirmed that assumptions of linearity, independence of errors, normality, and homoscedasticity were met. Using these models, we hindcasted seasonal discharge at Hay for 1890-1915, acknowledging that the model slightly underestimated high discharge values in summer.

2.2.4 Modelling natural river discharge

To quantify the impacts of flow regulation, we developed seasonal ‘natural’ flow models, leveraging the strong linear relationship between seasonal runoff in the upper Murrumbidgee River catchment and downstream discharge at Hay during the natural flow period (1890-1927) (Figure 2). These models estimate unregulated discharge at Hay, representing conditions that would have occurred in the absence of river regulation.

We included an estimated 14-day lag in our analysis to account for flow moving from the upper elevated catchment to Hay (MDBA, 2012). We log-transformed the data to address positive skewness, and statistical tests confirmed the assumptions of linearity, independence of errors, normality of errors, and homoscedasticity. Model performance was evaluated using three metrices: Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), and Kling-Gupta Efficiency (KGE). The models showed strong predictive accuracy across all seasons: (i) spring: RMSE=0.22, NSE=0.89, KGE=0.92; (ii) summer: RMSE=0.38, NSE=0.70, KGE=0.77; (iii) autumn: RMSE=0.28, NSE=0.84, KGE=0.88; and (iv) winter: RMSE=0.19, NSE=0.92, KGE=0.94.

Using these models, we estimated natural river discharge at Hay for the full period 1890-2022, allowing us to compare observed (regulated) flows against modelled natural (unregulated) flows for each of the four flow periods described in Section 2.2.2. The effect of river regulation was then quantified as the percentage difference between observed and natural discharge for each season and flow period.

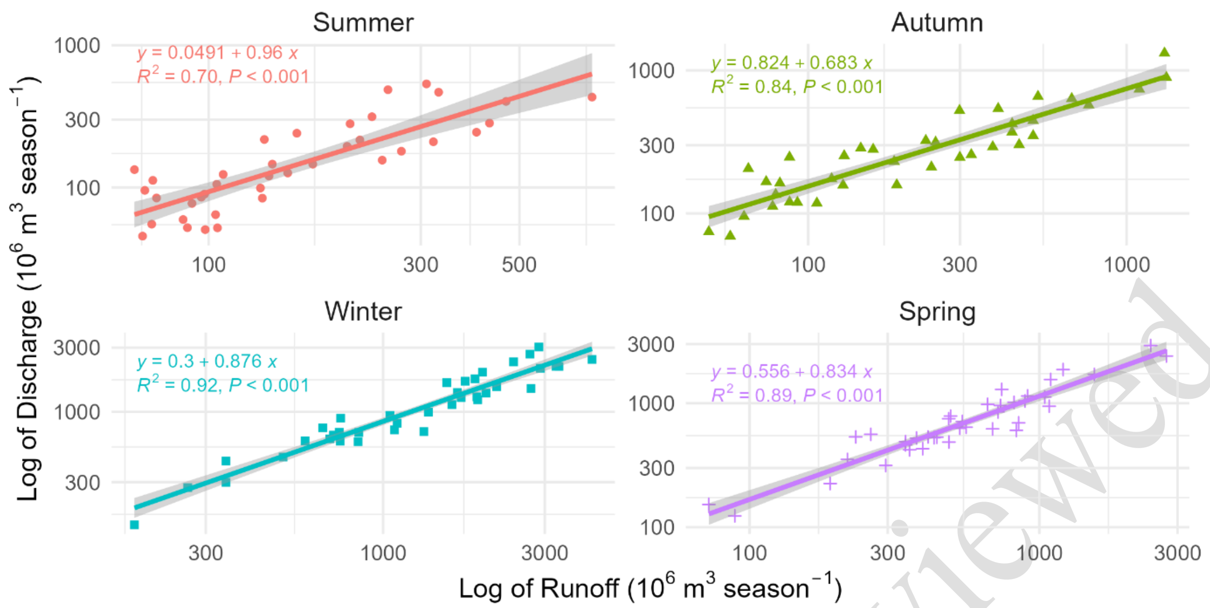

Figure 2. Linear relationships between log-transformed seasonal runoff in the upper Murrumbidgee catchment and log-transformed seasonal discharge in the lower Murrumbidgee River at Hay during the natural flow period (1890-1927).

2.3 Climate change analysis (2047-2075)

2.3.1 Projected catchment runoff

To assess the effects of climate change on seasonal runoff for the period 2047-2075, we used projected rainfall and potential evapotranspiration derived from 37 global climate models (GCMs) in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Zheng et al., 2024). Climate projections were applied to a baseline period (1977-2005) using an empirical scaling approach that adjusted historical climate data based on projected seasonal changes.

We focused on two CMIP6 Shared Socioeconomic Pathway (SSP) scenarios (IPCC, 2023; Riahi et al., 2017): (i) SSP2-4.5: an intermediate emissions scenario, where greenhouse gas (GHG) emissions stabilise around mid-century and (ii) SSP5-8.5: a high-emission scenario, where GHG emissions more than double by 2050, leading to intensified climate impacts.

Projected seasonal runoff was modelled using the GR4J hydrological model, consistent with historical runoff simulations (see Section 2.2.1). For each grid cell and emission scenario, we calculated the 10th (dry scenario), 50th (median), and 90th (wet scenario) percentiles of projected runoff based on the ensemble of 37 GCMs. The total seasonal runoff for the upper Murrumbidgee catchment (Figure 1) was then computed by aggregating across all grid cells.

The projected climate change impact on runoff from Zheng et al. (2024) used here were the most recent published hydrological projections for Australia. There have been many climate projection data sources developed for southeast Australia (Grose et al., 2023), and different methods have also been used for hydrological impact assessment. Nevertheless, the different methods showed the same hotter and drier future presented here (Chiew et al., 2022) with the same consistency from research and modelling studies over the past decades (Chiew et al., 2009; Whetton et al., 2016).

2.3.2 Modelling climate change effects on natural and regulated river discharge

To evaluate the impacts of climate change on seasonal river discharge in the lower Murrumbidgee River, we modelled projected flows under both natural (unregulated) and regulated conditions for the period 2047-2075. To estimate natural discharge, we applied the seasonal natural flow models (see Section 2.2.4) to the projected seasonal runoff under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios. This approach assumes that, in the absence of regulation, seasonal discharge at Hay would respond directly to changes in catchment runoff.

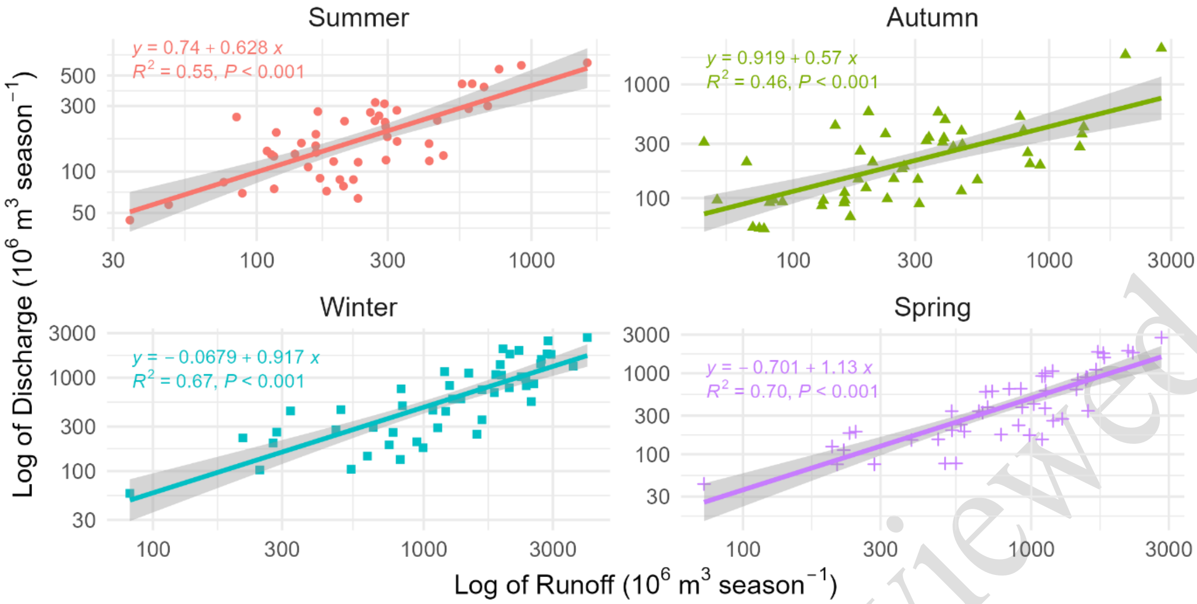

Figure 3: Linear relationships between log-transformed seasonal runoff in the upper Murrumbidgee catchment and log-transformed seasonal discharge in the lower Murrumbidgee River at Hay during the high regulation period, excluding environmental flow deliveries (1958-2006).

To estimate regulated discharge, we developed seasonal flow regulation models (Figure 3), based on the relationship between seasonal runoff and observed regulated discharge (1958-2006) – a period of high regulation before the introduction of environmental flow management. These models assume that current regulation levels remain unchanged through 2075. All seasonal regression models were statistically significant ($p<0.001$), explaining reasonable variability and meeting assumptions of linearity, error independence, normality, and homoscedasticity: (i) spring: $R^2=0.70$, $y=-0.701+1.130x$; (ii) summer: $R^2=0.55$, $y=0.740+0.628x$; (iii) autumn: $R^2=0.46$, $y=0.919+0.570x$; and (iv) winter: $R^2=0.67$, $y=-0.068+0.917x$ (Figure 3). The seasonal models performed satisfactorily to well: (i) spring: RMSE=0.55, NSE=0.70, and KGE=0.77; (ii) summer: RMSE=0.42, NSE=0.55, and KGE=0.64; (iii) autumn: RMSE=0.59, NSE=0.46, and KGE=0.55; and (iv) winter: RMSE=0.54, NSE=0.67, and KGE=0.74.

Using these models, we projected seasonal discharge under both natural and regulated conditions for 2047-2075 by applying log-transformed seasonal runoff projections from the ensemble of 37 GCMs. To capture uncertainty in climate projections, we calculated the 10th (dry scenario), 50th (median), and 90th (wet scenario) percentiles for both natural and regulated flows under SSP2-4.5 and SSP5-8.5.

3 Results

3.1 Flow regulation effects on seasonal river discharge

During the natural flow period (1890-1927), the Murrumbidgee River at Hay exhibited strong seasonal variability, with nearly half of the total annual flow occurring in winter (mean: 47%), followed by spring (32%), autumn (14%), and summer (8%) (Table 1, Figure 4). This pattern reflects the dominant influence of winter-spring precipitation and snowmelt from the upper catchment. However, river regulation progressively homogenised seasonal flows. During the high regulation period (1958-2006), flow distribution became more evenly spread across the year, with winter flows declining to 40% of annual discharge, spring to 28%, autumn increasing slightly to 18%, and summer to 14%. This shift resulted from large-scale water storage in upstream dams and diversions for irrigation, which reduced peak winter and spring flows while increasing summer flows. In the most recent period of high regulation (2007-2022), which included environmental flow deliveries, seasonal patterns changed further. Spring flows became the dominant season (34%), followed by winter (28%), summer (22%), and autumn (16%), indicating an ongoing shift away from the historical winter-spring flow peak (Table 1). Despite environmental flow interventions, regulation-driven seasonal homogenisation persisted, with reduced inter-seasonal variability compared to natural flow conditions.

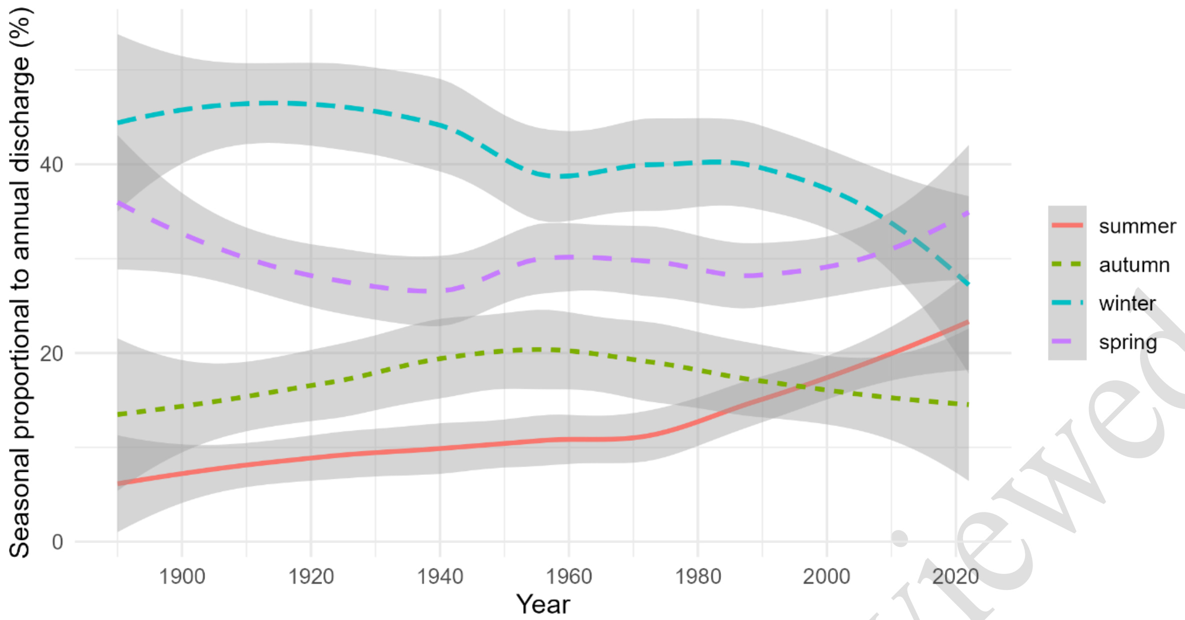

Figure 4. Modelled changes (±95% confidence intervals, shaded) in seasonal discharge in the lower Murrumbidgee River at Hay, 1890-2022, proportional to annual river discharge.

Table 1. Mean (median) seasonal river discharge as a percentage of annual river discharge (rounded), categorised by flow periods of increasing river regulation, until the more recent period with environmental flows.

Flow period	Seasonal discharge proportional to annual totals (%)[a]			
	Spring	Summer	Autumn	Winter
Natural flow (1890-1927)	32 (30)	8 (6)	14 (11)	47 (46)
Low regulation (1928-1957)	27 (27)	10 (7)	20 (15)	43 (40)
High regulation (1958-2006)	28 (25)	14 (13)	18 (14)	40 (42)
High regulation with environmental flows (2007-2022)	34 (35)	22 (22)	16 (14)	28 (27)

[a] Due to rounding and the use of median calculations, the percentages may not sum to 100%.

The absolute volume of seasonal discharge at Hay declined substantially over time, particularly in winter and spring (Figure 5, Figure 6, Table 2). Winter median discharge fell from 1064×10^6 m³ (natural) to 592×10^6 m³ (high regulation, 1958-2006), and further to 287×10^6 m³ (2007-2022). Relative to modelled natural conditions, which account for changes in rainfall and potential evapotranspiration, winter flows experienced a median reduction of 62% (2007-2022). Similarly, spring median discharge declined from 634×10^6 m^3 (natural) to 369×10^6 m^3 (high regulation), and further to 255×10^6 m^3 (with environmental flows), a median reduction of 55% relative to modelled natural flows. Autumn median discharge decreased from 255×10^6 m^3 (natural) to 200×10^6 m^3 (high regulation), and further to 112×10^6 m^3 (with environmental flows), representing a 68% reduction. Summer median discharge initially showed an absolute increase, from 130×10^6 m^3 (natural) to 161×10^6 m^3 (high regulation) but then decreased slightly to 140×10^6 m^3 in the most recent period, marking a 32% reduction.

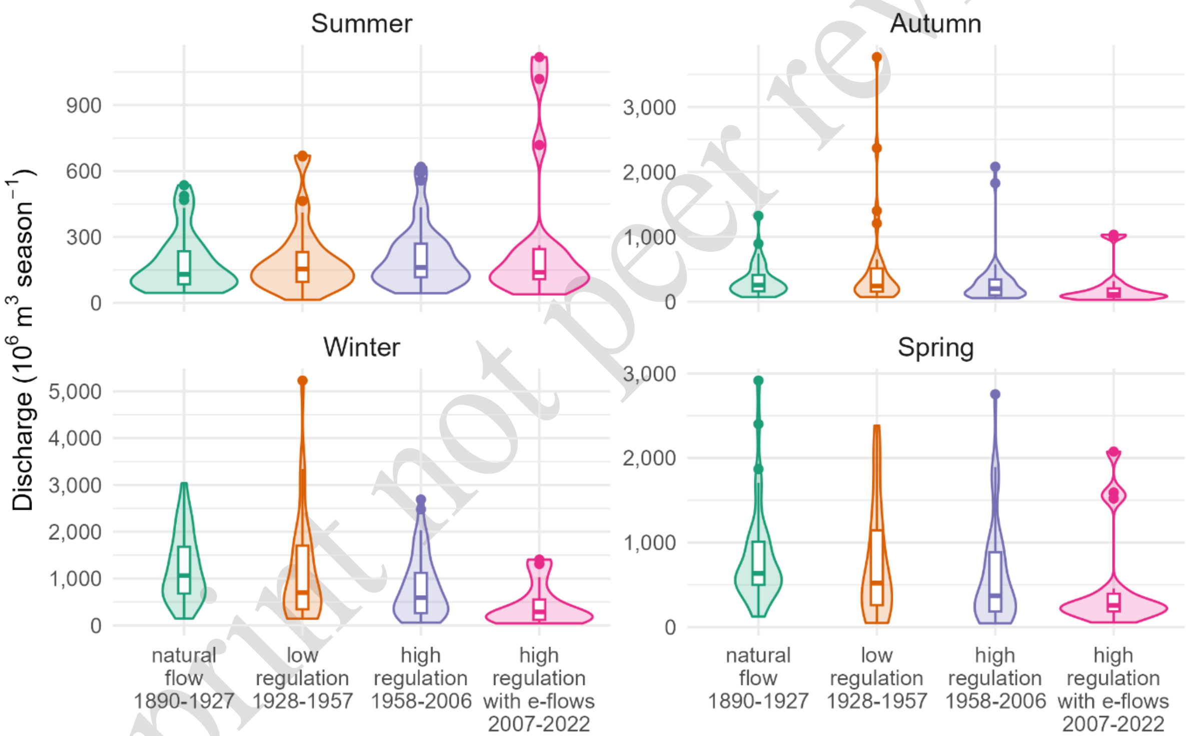

Figure 5. Violin plots (median, range) of seasonal river discharge in the Murrumbidgee River at Hay, upstream of the Lowbidgee Floodplain (see Figure 1), comparing the four flow periods (natural flow: 1890-1927, low regulation: 1928-1957, high regulation: 1958-2006, and high regulation with environmental flow deliveries (e-flows): 2007-2022).

Flood volumes generally decreased with increasing flow regulation over time, with the exception of summer, which slightly increased (Figure 6). During the high regulation period with environmental flow deliveries (2007-2022), there were a few noticeable outliers across all seasons: water years 2011, 2017, and 2022 in spring; 2012 in summer; 2022 in autumn; and 2017 and 2022 in winter.

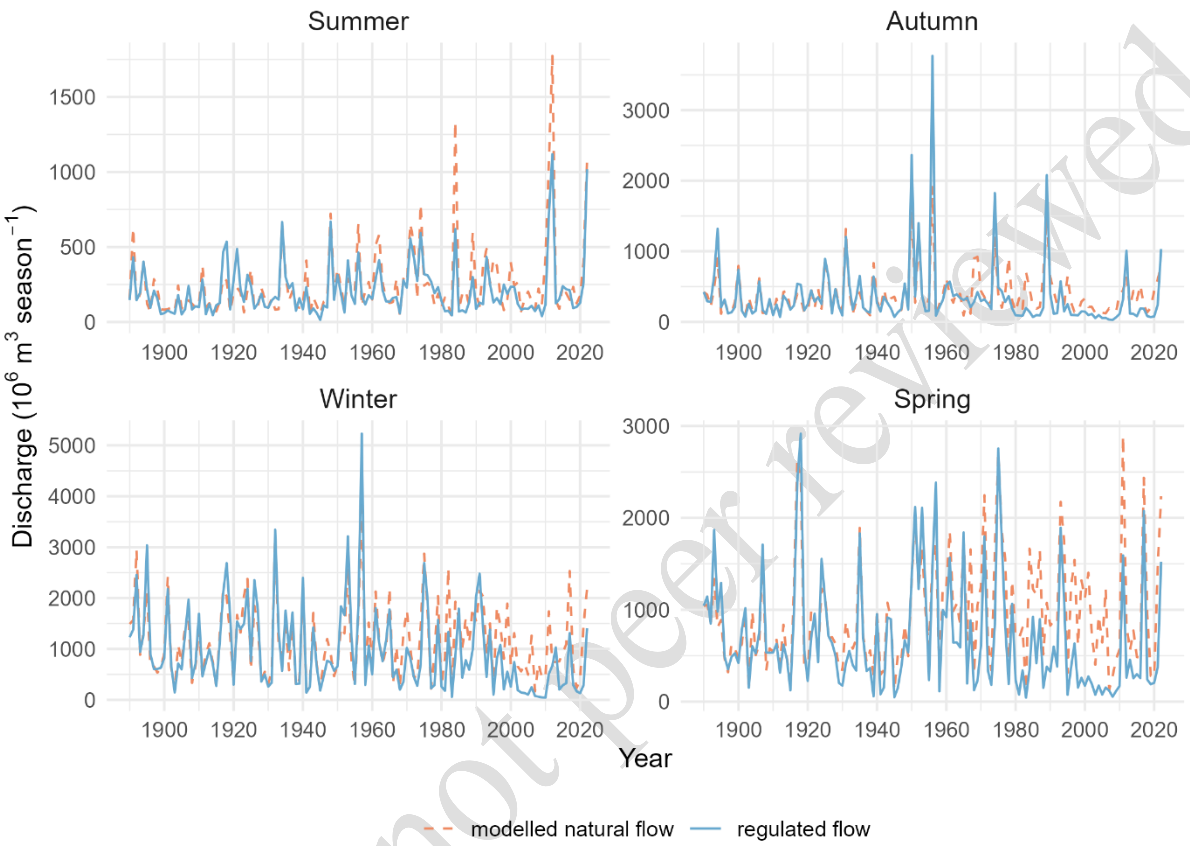

Figure 6. Seasonal comparison of actual river discharge (blue continuous line), including hindcasted data before 1916, measured on the Murrumbidgee River at Hay (Figure 1), and modelled natural river discharge (orange dashed line), 1890-2022. To accommodate significant seasonal flow variability, y-axis scales vary between panels.

Table 2. Mean seasonal volumes of runoff and river discharge (± standard error; median; range) on the Murrumbidgee River at Hay (Figure 1), comparing the natural flow period (1890-1927) with the low regulation (1928-1957), high regulation (1958-2006), and high regulation with environmental flow deliveries (2007-2022) periods, as well as the average percentage change (median) of actual river discharge, relative to each flow period's modelled natural river discharge.

Season	Runoff (10^6 m^3 $season^{-1}$)				Modelled natural discharge (10^6 m^3 $season^{-1}$)			
	natural flow	low regulation	high regulation	high regulation with e-flows	natural flow	low regulation	high regulation	high regulation with e-flows
Spring	699 ± 90 (537; 72-2743)	719 ± 96 (525; 70-2012)	1002 ± 85 (930; 73-2828)	861 ± 231 (427; 73-3052)	817 ± 86 (680; 128-2646)	838 ± 94 (667; 125-2044)	1114 ± 81 (1074; 129-2715)	943 ± 214 (561; 128-2892)
Summer	189 ± 23 (135; 68-728)	247 ± 38 (170; 55-842)	311 ± 39 (234; 35-1597)	475 ± 145 (230; 91-2146)	171 ± 19 (125; 65-628)	220 ± 33 (156; 52-722)	274 ± 33 (211; 34-1336)	408 ± 120 (207; 86-1773)
Autumn	328 ± 54 (212; 49-1334)	639 ± 179 (286; 47-3977)	448 ± 75 (266; 45-2746)	389 ± 76 (337; 83-1100)	318 ± 35 (258; 95-907)	465 ± 85 (317; 92-1912)	387 ± 42 (302; 90-1485)	367 ± 51 (353; 136-795)
Winter	1540 ± 158 (1451; 185-4134)	1378 ± 240 (903; 190-5484)	1523 ± 136 (1372; 82-4018)	1176 ± 243 (862; 156-3478)	1213 ± 111 (1177; 193-2946)	1080 ± 165 (776; 198-3774)	1201 ± 96 (1120; 95-2873)	948 ± 173 (746; 166-2532)

Season	Actual discharge (10^6 m^3 $season^{-1}$)				Change (%)			
	natural flow	low regulation	high regulation	high regulation with e-flows	natural flow[a]	low regulation	high regulation	high regulation with e-flows
Spring	840 ± 96 (634; 123-2917)	758 ± 122 (519; 48-2384)	609 ± 85 (369; 43-2755)	511 ± 156 (255; 53-2076)	2.8 (-6.8)	-9.5 (-22.2)	-45.3 (-65.6)	-45.8 (-54.5)
Summer	181 ± 22 (130; 45-535)	200 ± 30 (154; 14-670)	207 ± 20 (161; 44-619)	295 ± 85 (140; 39-1118)	5.8 (4.0)	-9.1 (-1.3)	-24.5 (-23.7)	-27.7 (-32.4)
Autumn	331 ± 42 (255; 69-1321)	526 ± 142 (241; 70-3769)	300 ± 53 (200; 54-2079)	234 ± 79 (112; 27-1032)	4.1 (-1.2)	13.1 (-24.0)	-22.5 (-33.8)	-36.2 (-68.3)
Winter	1232 ± 119 (1064; 145-3038)	1178 ± 210 (699; 142-5230)	810 ± 95 (592; 58-2689)	429 ± 112 (287; 44-1405)	1.6 (-9.6)	9.1 (-9.9)	-32.6 (-47.1)	-54.7 (-61.5)

[a] Indicates model accuracy

3.2 Climate change effects on seasonal river discharge

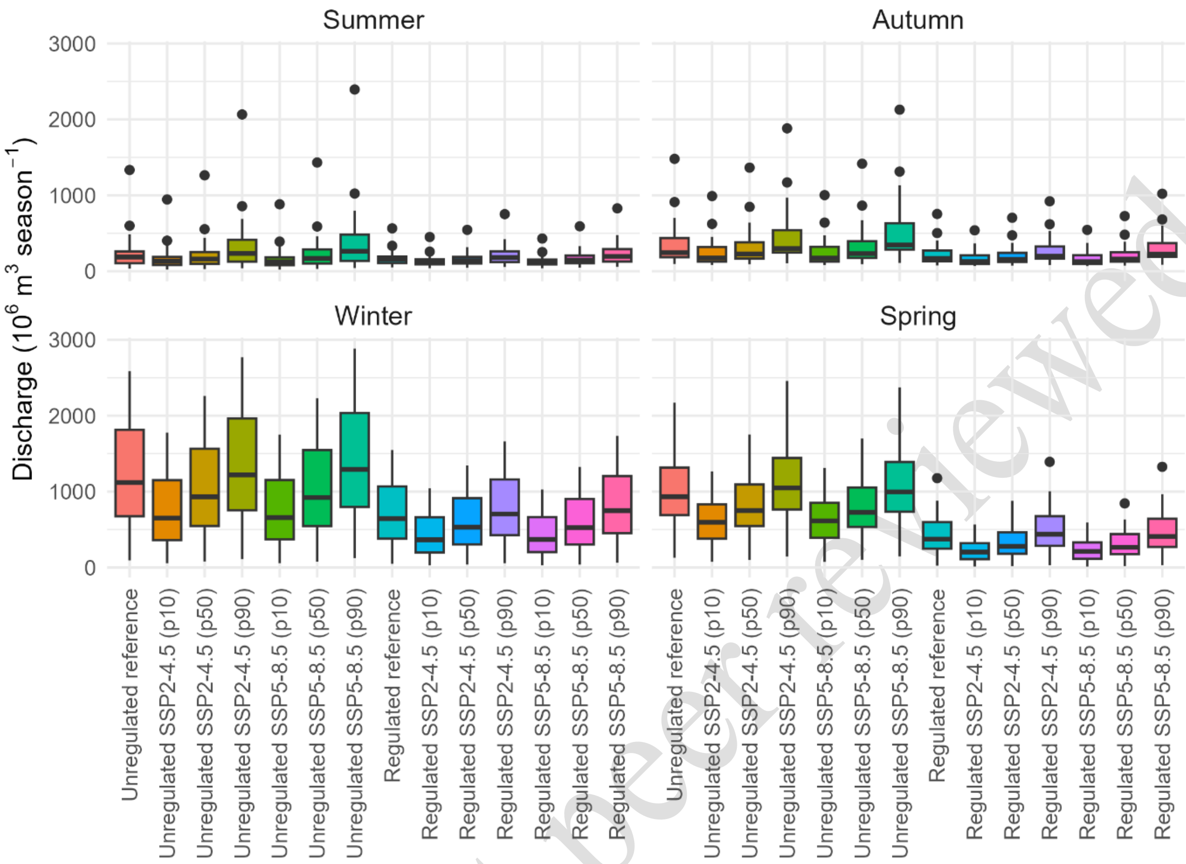

Figure 7. Boxplots of seasonal river discharge in the Murrumbidgee River at Hay (Figure 1), comparing unregulated (natural) and regulated flows under CMIP6 SSP2-4.5 and SSP5-8.5 climate change scenarios, 2047-2075, relative to the 1977-2005 reference scenario, with climate projections calculated for the 10th percentile (dry scenario; p10), 50th percentile (median; p50), and 90th percentile (wet scenario; p90).

Projected river discharge varied substantially under different climate change scenarios (CMIP6 SSP2-4.5 and SSP5-8.5), while river regulation generally reduced seasonal flows (Figure 7, Table 4). Under the median SSP2-4.5 scenario, natural discharge was projected to decline across all seasons, with the most significant reductions occurring in winter (16-21%), followed by autumn (6-8%). River regulation further amplified these reductions, particularly in spring (63-77%) and winter (50-58%), whereas summer projections ranged from a 40% decrease to a 6% increase. Under the dry SSP2-4.5 scenario (10th percentile), projected declines were more severe, particularly in winter (36-47%) and spring (34-40%), with regulation intensifying these reductions, leading to spring flows decreasing by 76-83%. Conversely, under the wet SSP2-4.5 scenario (90th percentile), natural flows were projected to increase, particularly in summer (12-52%) and autumn (20-32%). Despite this, regulation substantially reduced flow volumes, particularly in spring (43-67%) and winter (35-38%), while summer flows ranged from an 18% decrease to a 20% increase.

Under the median SSP5-8.5 scenario, projected natural discharge declined across all seasons, except summer, where projections ranged from a 10% decrease to a slight 7% increase. River regulation further intensified these reductions, particularly in spring (65-77%) and winter (52-58%). In the extreme dry SSP5-8.5 scenario, projected natural flow reductions were most pronounced in winter (36-46%) and spring (32-39%), with regulation further exacerbating these declines, leading to spring flows decreasing by up to 83% and winter flows by 63-72%. In contrast, under the wet SSP5-8.5 scenario, natural flows were projected to increase, particularly in summer (20-74%) and autumn (34-52%). However, flow regulation diminished these gains, leading to reductions in spring (46-69%) and winter (33-34%), while summer flows remained highly variable, ranging from a 10% decrease to a 24% increase.

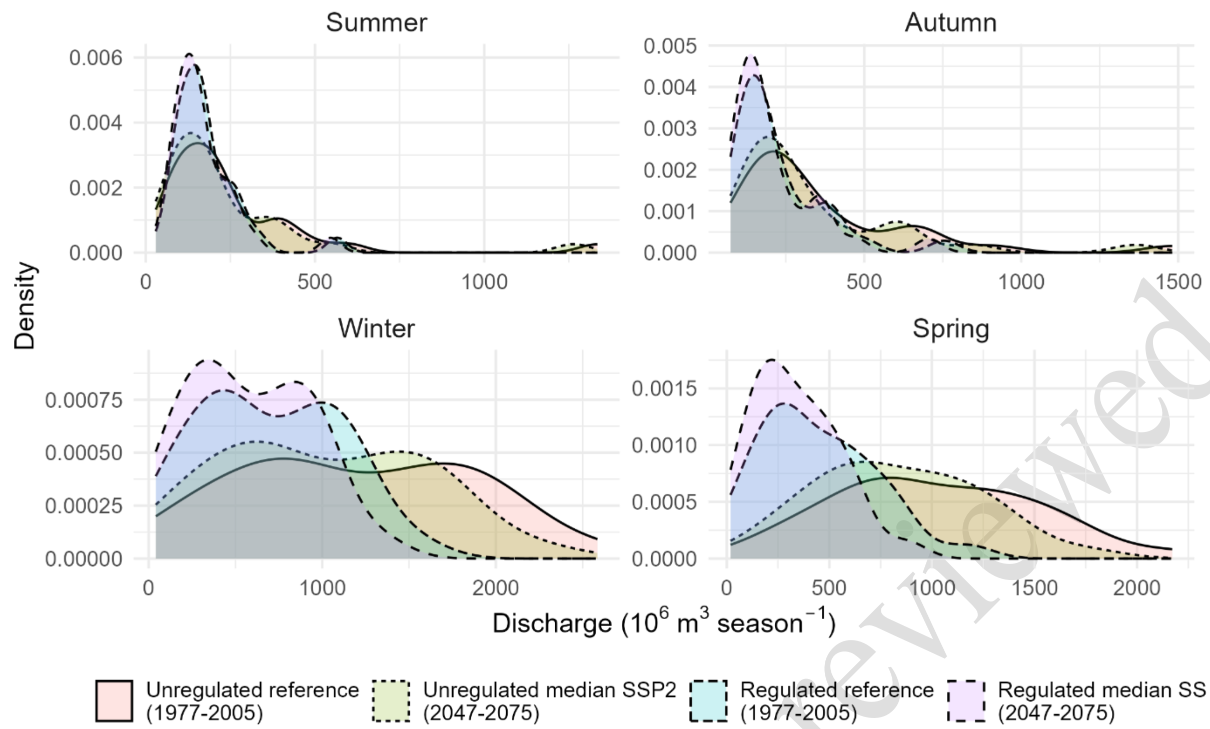

Figure 8. Density plots of seasonal river discharge, comparing the 1977-2005 reference and selected 2047-2075 climate change scenarios (median CMIP6 SSP2-4.5), under both unregulated (natural) and regulated flow conditions on the Murrumbidgee River at Hay (Figure 1). To accommodate significant seasonal flow variability, y-axis scales vary between panels.

The magnitude and frequency of large seasonal flow events were projected to decline due to climate change, with flow regulation further exacerbating these reductions (Figure 8). Historically, spring natural flows often exceeded 1500×10^6 m^3 per season, but under the moderate SSP2-4.5 scenario, volumes declined, regulation intensifying this trend, reducing most spring flows to around 250×10^6 m^3 with few exceeding 1000×10^6 m^3. In summer, natural river flows typically remained below 250×10^6 m^3, with occasional peaks over 500×10^6 m^3 and rare extreme events exceeding 1250×10^6 m^3. Climate change was projected to slightly reduce these flows, while regulation significantly constrained discharge, preventing extreme events from surpassing 650×10^6 m^3.

Autumn flows historically remained below 500×10^6 m^3, with moderate flows ranging between 500 and 1000×10^6 m^3 and occasional extreme cases reaching 1500×10^6 m^3. Climate change was projected to cause slight declines, while river regulation had a more pronounced impact, reducing average flows by half and constraining most discharge to below 250×10^6 m^3, with the largest events limited to 800×10^6 m^3. Winter flows were historically more uniformly distributed, with some exceeding 2000×10^6 m^3. However, climate change was projected to substantially reduce these flows, with regulation further intensifying the decline, causing most flows to remain below 1000×10^6 m^3 and only a few exceeding 1500×10^6 m^3, effectively halving natural winter flows.

Under future climate scenarios (SSP2-4.5 and SSP5-8.5), natural river discharge was projected to remain seasonally distributed, with 38-40% occurring in winter, followed by spring (33-36%), autumn (16-17%), and summer (9-11%) (Table 3). However, river regulation continued to shift the seasonal balance, leading to a less distinct seasonal pattern, with 41-42% of discharge occurring in winter, 23-28% in spring, 18-20% in autumn, and 13-16% in summer. This trend reinforces the long-term homogenisation of seasonal flows, where peak winter and spring flows are suppressed, and water redistribution shifts toward summer and autumn, primarily for irrigation demand.

Table 3. Seasonal river discharge as a percentage of annual river discharge in the Murrumbidgee River at Hay (Figure 1), comparing the 1977-2005 reference period with 2047-2075 climate scenarios (SSP2-4.5 and SSP5-8.5) under both natural and regulated flow conditions, with climate projections for the 10th, 50th, and 90th percentile.

Period	**Climate scenario**	**Flow condition**	**Percentile**	**Seasonal discharge proportional to annual totals (%)**			
				spring	summer	autumn	winter
Reference (1977-2005)		natural		36	9	15	40
		regulated		28	12	17	43
Projected (2047-2075)	SSP2-4.5	natural	50	35	9	16	40
			10	35	10	16	38
			90	35	10	16	39
		regulated	50	25	14	19	42
			10	23	16	20	41
			90	28	13	18	41
	SSP5-8.5	natural	50	34	10	16	39
			10	36	10	16	38
			90	33	11	17	39
		regulated	50	25	14	19	42
			10	24	16	20	41
			90	26	13	19	42

Table 4. Seasonal river discharge in the Murrumbidgee River at Hay, comparing the 1977-2005 reference scenarios with the 2047-2075 climate scenarios (SSP2-4.5 and SSP5-8.5), under natural and regulated flow conditions, showing the 10th, 50th, and 90th percentiles. Percentage changes are relative to the 1977-2005 natural flow reference scenario.

				Discharge (10^6 m^3 season^{-1})												**Change (%)**											
				Spring			**Summer**			**Autumn**			**Winter**			**Spring**			**Summer**			**Autumn**			**Winter**		
Period	**Climate scenario**	**Flow condition**	**Percentile**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**	**50**	**10**	**90**
Reference (1977-2005)		**Natural**		932	391	1646	187	82	430	246	130	672	1119	277	2030												
		Regulated		374	115	809	157	91	269	168	99	390	644	149	1201	-60	-71	-51	-16	11	-37	-32	-24	-42	-42	-46	-41
Projected (2047-2075)	**SSP2-4.5**	**Natural**	**50**	750	330	1336	161	76	403	228	122	621	931	219	1715	-20	-16	-19	-14	-7	-6	-7	-6	-8	-17	-21	-16
			10	596	258	981	132	68	297	176	103	448	651	147	1308	-36	-34	-40	-29	-17	-31	-29	-21	-33	-42	-47	-36
			90	1049	426	1843	235	92	652	299	156	888	1220	315	2219	13	9	12	26	12	52	22	20	32	9	14	9
		Regulated	**50**	278	91	609	142	87	258	158	94	365	531	117	1007	-70	-77	-63	-24	6	-40	-36	-28	-46	-53	-58	-50
			10	204	66	401	125	81	211	128	82	278	365	77	758	-78	-83	-76	-33	-1	-51	-48	-37	-59	-67	-72	-63
			90	439	129	942	182	98	354	199	116	492	705	171	1318	-53	-67	-43	-3	20	-18	-19	-11	-27	-37	-38	-35
	SSP5-8.5	**Natural**	**50**	727	326	1289	169	76	460	233	125	639	922	218	1679	-22	-17	-22	-10	-7	7	-5	-4	-5	-18	-21	-17
			10	614	266	1011	126	68	277	175	103	456	658	149	1297	-34	-32	-39	-33	-17	-36	-29	-21	-32	-41	-46	-36
			90	996	408	1772	264	98	750	346	174	1023	1293	338	2254	7	4	8	41	20	74	41	34	52	16	22	11
		Regulated	**50**	267	90	580	146	87	282	161	96	374	526	116	985	-71	-77	-65	-22	6	-34	-35	-26	-44	-53	-58	-52
			10	212	68	417	121	80	202	127	81	282	369	78	752	-77	-83	-75	-35	-2	-53	-48	-38	-58	-67	-72	-63
			90	409	122	894	196	102	388	224	127	554	749	184	1340	-56	-69	-46	5	24	-10	-9	-2	-18	-33	-34	-34

4 Discussion

Globally, flow regimes have been disrupted by large dams and water diversions, particularly upstream of large wetland systems (Grill et al., 2019; Kingsford et al., 2016; Nilsson et al., 2005). Our understanding of these impacts has been primarily focused on reductions in the magnitude of flow and flood events (Döll et al., 2009; FitzHugh and Vogel, 2011; Kreibich et al., 2024). To date, few studies have focused on changes to timing of river flows, despite its importance for many ecosystems and their processes. This is also true in Australia's Murray-Darling Basin, one of the most regulated river basins on the continent (Döll et al., 2009; Kingsford, 2000).

Results from this study highlight that natural flows in the lower Murrumbidgee River, one of the largest tributaries of the Murray-Darling Basin (Figure 1), varied strongly with the season, with lower flow volumes in summer/autumn and higher flow volumes in spring/winter (Figure 4, Table 1). River regulation has homogenised flow patterns across seasons and substantially reduced river flows throughout the year. Median flows decreased by approximately a quarter in summer to two-thirds in spring during the high regulation period (1958-2006), compared to natural flows, further intensifying in the subsequent period (2007-2022) (Figure 6, Table 2). Based on projected climate change for 2047-2075, further declines of up to a fifth were predicted for spring, autumn, and winter, with minor reductions or slight increases in summer (Figure 7, Table 4). These changes to the timing of natural flows and flooding regimes pose significant threats to the ecological integrity of the river's largest wetland system, the Lowbidgee Floodplain (Figure 1). Importantly, we were able to use simulated runoff, largely unaffected by river regulation, enabling the analysis and modelling of natural river discharge in the lower reaches of the Murrumbidgee River since 1890.

4.1 Flow regulation effects on seasonal flow regimes

The building of dams in the upper reaches of the Murrumbidgee River catchment (Figure 1) allowed the capture of flows during winter and spring, particularly from snowmelt. This regulation significantly altered the natural flow regime, shifting flows toward summer to align with irrigation water demands. Much of this water is diverted to major irrigation zones, including the Murrumbidgee, Coleambally, and Hay Irrigation Areas, upstream of the Lowbidgee Floodplain. This also resulted in an altered timing of flows and flooding coinciding with a considerable reduction in magnitude (Kreibich et al., 2024). Winter and spring, historically characterised by high flows from precipitation and snowmelt, were particularly affected by regulation, with respective reductions of 62% and 55%, 2007-2022 (Table 2).

Seasonal flow redistribution and declines in the Murrumbidgee River at Hay, 1970-1998, were also identified using the Integrated Quantity-Quality Model (IQQM) (Frazier et al., 2005). Monthly flow reductions were observed at Hay from 1921-2007, but timing remained consistent with natural patterns (Wen, 2009). Our estimates, however, identified higher reductions in winter and spring compared to these analyses over different time periods. This probably reflects the differences in methodologies, including the use of IQQM, which can underestimate large flows and overestimate small flows (Ren and Kingsford, 2014), whereas the finer temporal resolution of monthly analyses (Wen, 2009) may obscure clear seasonal patterns. As a result of river regulation, seasonal flow redistribution and reduced flows were also observed in the Murray River, a more southerly river with a similar catchment (Maheshwari et al., 1995).

4.2 Climate change effects on seasonal flow regimes

While water resource development was the primary driver of seasonal flow homogenisation, declining cool-season rainfall (April-October) in southeastern Australia further reduced river discharge during wetter seasons, a trend projected to intensify (CSIRO and BOM, 2022). This is exacerbated by projected decreases in median annual flows between 2047-2075, compared to 1977-2005, based on CMIP5 RCP4.5 and RCP8.5 climate scenarios (Kreibich et al., 2024). Our estimated declines of up to 22% in river flows in spring, autumn, and winter (Figure 7, Table 4) will exacerbate the effects of river regulation in terms of drying up the river. Projections varied from declines of nearly half and up to a three-quarter increase for respective dry and wet scenarios (Figure 7, Table 4). Notably, differences between the SSP2-4.5 and SSP5-8.5 scenarios were small in the median projections but became more pronounced at the 10th and 90th percentiles (Figure 7, Table 3, Table 4). Climate change did not increase homogenisation of seasonal flows resulting from river regulation (Table 3).

Under an extreme dry future climate scenario, our findings indicated substantial flow reductions of 33-78% across all seasons (Table 4). However, these results contrast with governmental analyses, which projected reductions in average rainfall of 17-18% during winter and spring, with increases of up to 30% in late summer by 2079 under similar conditions (NSW DCCEEW, 2024b). Additionally, the southeast of the continent is expected to have reductions in both high-flow and low-flow days, varying in severity under a respective dry or wet scenario by 2075 (Zheng et al., 2024).

The changing climate has consequences. Shifts in snowmelt patterns with climate moved peak discharges earlier in the Snowy Mountains, the upper catchment of the Murrumbidgee (Reinfelds et al., 2014). Furthermore, climate change is likely to drive higher irrigation water use on existing irrigated lands (Haddeland et al., 2014), exacerbating the impacts of river regulation and potentially reducing flows to dependent environments.

4.3 Modelling challenges

Accurately modelling the low summer river flows is challenging, with substantial uncertainties in the modelled summer discharge. This may be attributed to the pronounced effects of hot and dry summer conditions in the lower Murrumbidgee River region, significantly influencing downstream river flows. Additionally, water withdrawals, such as for irrigated agriculture, are likely to have occurred during the 'natural flow' period (pre-1928), albeit at relatively low levels (Monash, 1904; WaterNSW, 2018). Therefore, our modelled changes may represent conservative estimates of actual impacts. Further, these early irrigation withdrawals would have disproportionately affected summer flows, as the naturally low discharge during this season makes the system sensitive to additional reductions, further complicating modelling.

Although we incorporated catchment rainfall and potential evapotranspiration, our natural flow model likely did not fully capture the complex interplay between runoff in the upper catchment and streamflow in the Murrumbidgee River's lower reaches, particularly the long-term impacts on water storage and groundwater baseflow, under these exceptionally severe and prolonged drought conditions (Peterson et al., 2021). The rainfall-runoff modelling dataset used here do not represent snow hydrology, which although important for the upper catchment, will have little influence in the streamflow at the Lower Murrumbidgee River at Hay.

Our study period also included the 1997-2009 Millennium Drought, Australia's most severe hydrological drought in the past 800 years (Higgins et al., 2023; Leblanc et al., 2012). As the rainfall-runoff model calibration included datasets over this drought period, the hydrology over this and future long dry periods has been partly taken into account. However, there are limitations in extrapolating hydrological models to predict the future under higher temperature and atmospheric CO_2, and potentially longer dry periods, not seen in the historical data. Some processes like the explicit modelling of farm dams intercepting runoff can be modelled

(Robertson et al., 2023) but the understanding and modelling of other hydrological non-stationarities are challenging (Blöschl et al., 2019a; Fowler et al., 2022). By not accounting for hydrological non-stationarity in a changing climate, the future runoff reductions presented here are likely to have been underestimated (Chiew et al., 2014; Saft et al., 2016).

4.4 Environmental and ecological effects

Our findings align with a recent assessment that suggested environmental water requirements in the lower Murrumbidgee River were not met between 1979-2022, with conditions worsening over the last decade (Sheldon et al., 2024). The altered seasonal flow patterns had profound ecological consequences for freshwater ecosystems on the lower Murrumbidgee River, including native species that rely on the distinct drying-wetting cycles of these natural boom-and-bust environments (Arthington and Balcombe, 2011). Reduced flow and flooding have already created considerable challenges for ecosystems dependent on the Murrumbidgee River (Kreibich et al., 2024). In all, the major wetland system of the Lowbidgee Floodplain has been severely degraded or destroyed, and waterbird abundance declined by 90% between 1983-2001, mainly as a result of river regulation and floodplain development (Kingsford and Thomas, 2004).

Many organisms depend on cues linked to flow, temperature, and light for aspects of their life histories (Perkin and Wilson, 2021). Shifts from naturally high flow variability with winter-spring peaks toward a more homogenised regime with relatively low flows year-round, as observed in the lower Murrumbidgee River, may prevent native organisms from recognising flow and flooding cues critical for migration and reproduction. This applies to invertebrates (Suren and Jowett, 2006), fish (Krabbenhoft et al., 2014; Thorstad et al., 2008), amphibians (Ocock et al., 2024), waterbirds (Roshier et al., 2002), and riparian vegetation (Stromberg et al., 2005), all of which rely on seasonal flow cues. In turn, flow homogenisation favours the spread of invasive species over native ones (Poff et al., 2007). Moreover, the decline in high-flow and flooding events reduces hydrological connectivity in the Murrumbidgee River system (Kreibich et al., 2024), which is essential for many aquatic organisms to move across the floodplain (Page et al., 2005; Palmer and Ruhi, 2019).

When flows decrease, thermal buffering capacity also diminishes (van Vliet et al., 2013), leading to higher water temperatures (Glazaczow et al., 2016). Climate change is likely to exacerbate this warming effect, with river water temperatures in the Murray-Darling Basin projected to increase by about 1.3°C by 2100 (van Vliet et al., 2013). Such shifts alter habitat conditions and change temperature cues for aquatic organisms (Anderson et al., 2019; Glazaczow et al., 2016; Perkin and Wilson, 2021). Further, lower flows may alter light conditions in rivers and floodplains by reducing water depth and turbulence due to fewer and smaller flood events.

Environmental flows can play a crucial role in restoring natural flow regimes, including flow variability and river-floodplain connectivity, and must be carefully managed to reflect the distinct regional-scale flow patterns (Greet et al., 2011; Horne et al., 2017; Kennard et al., 2010). Since 2007, environmental flows have been delivered to the lower Murrumbidgee River (NSW DCCEEW, 2024a). Our seasonal flow analysis identified only a weak signal of change during spring when comparing the high regulation period (1958-2006) to the period of high regulation that included environmental flow deliveries (2007-2022). While river discharge appeared constant or slightly increased in spring, flows in other seasons continued to decline (Figure 6, Table 2). Unusually large summer flow events ($>1000\times10^6$ m^3 $season^{-1}$) in 2012 and 2022 were linked to exceptionally high rainfall events rather than environmental flow releases (Figure 5).

To support large-scale restoration of the wetland ecosystems on the Lowbidgee Floodplain, particularly the Indigenous-owned Gayini Wetlands (Woods et al., 2022), environmental water should primarily be released in winter and spring to more closely mimic the Lower Murrumbidgee River's natural flow regime. By timing releases to coincide with larger flow and flood events, environmental water can supplement these flows, enabling widespread inundation and recharging of the floodplain wetlands at ecologically critical times. However, achieving this remains challenging due to limitations in current water policies, focused on the delivery of water for irrigation, and operational constraints and liability concerns faced by water managers. Beyond environmental flow management, other restoration strategies, such as riparian vegetation management, are also dependent on understanding and responding to seasonal flow patterns (Greet et al., 2011; Palmer and Ruhi, 2019).

Our analysis further indicates that although climate change will reduce flows, it is not expected to shift timing significantly relative to the effect of flow regulation (Figure 7, Figure 8, Table 4). Even so, less flow and flooding will result in less water availability for biota at key times of the year. Therefore, it may be important to protect environmental water specifically for ecological purposes in dams to counteract the effects of a changing climate (Prosser et al., 2021). Overall, achieving ecological objectives in the face of flow regulation and climatic challenges will require coordinated, adaptive management approaches that balance ecological needs with operational, policy, and societal constraints.

4.5 Global outlook

The challenges faced by the Murrumbidgee River catchment are not unique. Globally, 48-65% of river discharge is already substantially affected by flow regulation (Dynesius and Nilsson, 1994; Grill et al., 2019; Nilsson et al., 2005; Vörösmarty et al., 2010). This figure is projected to rise dramatically to 93% by 2030 due to large-scale dam construction, particularly in ecologically critical regions such as the Amazon Basin (Grill et al., 2015; Zarfl et al., 2019; Zarfl et al., 2015). Regulation often impacts flow seasonality, reducing native biodiversity (Poff et al., 2007).

Climate change adds a further layer of complexity, as it alters water availability by increasing potential evapotranspiration through rising temperatures and regionally variable precipitation patterns (Greve et al., 2014; Huang et al., 2017; IPCC, 2023). In Europe, increased autumn-winter rainfall has heightened flood risk in the northwest, while decreasing precipitation has lowered flooding in the south, and declining snow cover and snowmelt has similarly decreased floods in the east – highlighting the regionally diverse impacts of climate change (Blöschl et al., 2019b). A global analysis of major river basins found that Australia's Darling Basin and Europe's Rhine Basin stand out, as climate change is projected to substantially affect the magnitude of streamflow seasonality in these systems (Eisner et al., 2017).

These findings highlight the complex interplay between river regulation and climate change in shaping seasonal flow regimes. Consequently, efforts to assess these impacts and devise effective restoration strategies must be tailored to regional contexts (Kennard et al., 2010). Meanwhile, global interdependence requires coordinated international action to mitigate climate change (UNFCCC, 2016). Balancing global cooperation with regionally specific adaptive management will be key to sustaining the health and resilience of river and floodplain ecosystems in the face of mounting pressures from anthropogenic activities.

5 Conclusions

Water resource development has profoundly altered seasonal flow regimes in one of Australia's major river systems, the Murrumbidgee River, with projected climate change adding further pressures. Flow regulation has substantially homogenised seasonal flows and reduced river discharge by up to 68%, disrupting natural inundation dynamics critical for sustaining the natural boom-and-bust ecology of the semi-arid Lowbidgee Floodplain, the river's largest wetland ecosystem. Many aquatic species depend on timing of flows for critical stages of their life histories. Climate change is projected to further reduce these flows and floods. Conservation management should increase environmental water releases and shift them toward winter-spring peaks to align their timing with natural flow patterns, thereby increasing floodplain inundation events, restoring hydrological connectivity, and supporting flood-dependent native biodiversity.

Our findings reflect a global challenge: balancing human with ecological water needs. Globally, most large river systems are now regulated by dams, and climate change introduces additional complexities, including increased evapotranspiration and changes in rainfall patterns which will be amplified in the streamflow. Lessons from the Murrumbidgee River are widely applicable, demonstrating the urgent need for adaptive, region-specific strategies to restore natural flow variability and protect freshwater biodiversity. Ultimately, solutions must integrate local actions with global cooperation to address the growing pressures on freshwater ecosystems worldwide.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI's ChatGPT 4o/o1 and Anthropic's Claude 3.5 Sonnet to assist with minor R coding tasks and to enhance the manuscript's writing. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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