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Overlapping Scales of Place Based Indigenous Knowledge and Hydroclimate in Australia

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OVERLAPPING SCALES OF PLACE BASED INDIGENOUS KNOWLEDGE AND HYDROCLIMATE IN AUSTRALIA

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A DISSERTATION

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Dissertation Advisor: Dr Shaleen Jain

An Abstract of the Dissertation Presented
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Indigenous Peoples have been monitoring and adapting to uncertainty and change in their local regions for millennia, resulting in a holistic view of the interlinkages within the occupied complex socio-environmental systems. This research consists of investigating the overlapping scales of knowledge within Indigenous Australian seasonal calendars and colonial methods of hydroclimate assessment for improving adaptability to climate change impacts.

The analyses began with a sample of 25 Indigenous seasonal calendars providing a glimpse into interlinkages among biota, environment, and meteorology of the localised regions. Across the calendars, five themes of information and multiple categories within these themes became apparent and were explored for relevance to climate change and adaptability.

The next stage of research involved analysis and modelling of historical streamflow and observed historical streamflow for changes in trends and seasonality. Quantile regression and cluster analysis results indicate widespread decreases in streamflow across all seasons in the south half of the continent while streamflow in the northern region shows marked local coherence in increases and decreases. Trends within the lower and upper quantiles of flow distributions revealed unique sub-seasonal time windows in the extremes, underscoring that

systematic assessment of the entire spectrum of flow levels, and change therein, are necessary to understand vulnerability to human and environmental systems.

Climate change is increasing the risk of droughts and bushfires through increasing variability and long-term trends in the local and remote ocean-atmospheric phenomena as represented by two climatic indices: Southern Ocean Index and Indian Ocean Dipole. These two indices, sea surface temperature, and historical Standardized Precipitation Evapotranspiration Index were used to assess the nature of variability and spatial patterns in the bushfire season, as delineated from five Indigenous seasonal calendars. Results indicated increased water stress across the four eastern locations during the bushfire season while the western location is experiencing a change in rainfall seasonality.

Indigenous place-based knowledge has substantial awareness of the holistic interlinkages that make up the biota, environment, and climate of a region. Collaboration with knowledge holders on resource stewardship has the potential to improve adaptability of humans and ecological systems to the increasing challenges brought by climate change.

DEDICATION

To my mum for her love and support throughout my adventures, especially during the pandemic; to my grandmother without whom my graduate career would probably have gone very differently; and to my partner for his patience, humour, and for reminding me that it’s okay to take breaks.

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I am very grateful to my committee members, Dr. Firooza Pavri, Dr. Kirk Maasch, Cpt. Jim, Settele, and Dr. Darren Ranco, for their patience and understanding through the pandemic, and for their feedback and suggestions as my research progressed. I am particularly grateful to Dr. Darren Ranco for his perspectives and for the resources he shared regarding Native and Indigenous histories and presences. External to my committee, I am grateful to Dr. Emma Woodward for taking the time to understand my research aims and provide feedback and suggestions.

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CHAPTER 1

INTRODUCTION

Climate change is increasing uncertainty in hydrologic cycles resulting in increased vulnerability of marginalised populations, including Indigenous Peoples, to hazard exposure (Cardona et al., 2012; Kopp et al., 2017; Padron et al., 2020; United Nations, 2018). A measurement of one such change to hydrological cycles is streamflow (Milly, Kam, & Dunne, 2018), with associated climate change-driven alterations being inconsistent across the globe, with some regions of the world experiencing increases in annual streamflow while other areas have reduced annual streamflow (Gudmundsson, et al., 2018; Ye et al., 2013). Climate change is also anticipated to drive an increase in the occurrence and severity of extreme hydrological events, such as floods and droughts, which can have catastrophic impacts on water availability and quality for streamflow reliant communities (Kopp et al., 2017).

Beyond the necessity of water sources for sustenance and resources is the cultural value of water resources, including cultural cornerstones, sacred sites, fundamental for individual identity, group identity, and social relations, and representative of social norms (Jackson, 2008). Further to this, water represents a life force as living water to Australian Indigenous Peoples (Jackson, 2017) and has historically been managed and cultivated by Indigenous nations (Jackson, 2008; Maclean & Bubu, 2014; Prober et al, 2011; Woodward et al, 2012). Australian Indigenous Peoples have a great wealth of local ecosystem knowledges relevant to their local regions which has potential to contribute to climate change adaptation methods (Woodward et al, 2020). Research that has included Indigenous water values and the impact of changes in hydrological cycles is very limited, with prior studies focussing on a single region (Liedloff et al., 2013) or without involving quantitative hydrological data (Jackson, 2008). The research in this dissertation demonstrates the climate induced changes occurring across Australian streamflow locations and the relevance of Australian Indigenous seasonal knowledges for climate change adaptation methods. The studies in this dissertation have been designed to be as respectful of Indigenous Peoples as possible to avoid perpetuating harm towards Indigenous Peoples under the pretext of research. Indigenous Peoples were unfortunately not collaborated with for this research, so, where used, Indigenous knowledges have been summarised broadly to avoid re-representing or appropriating their intellectual property. The lack of Indigenous collaboration in this project means that it would be highly inappropriate to use outcomes from this research to make recommendations for actions to be taken at specific locations, so more generalised recommendations for education, practices, and policy are suggested instead (David-Chavez and Gavin, 2018; Woodward et al., 2020).

In Chapter 2 we conducted a thematic analysis on 25 publicly available Australian Indigenous seasonal calendars to identify the major themes and categories of information contained across the seasonal calendars. Indigenous seasonal calendars are highly tailored to specific regions and have historically provided Indigenous nations the prediction and management of weather events and seasonal changes (Woodward & McTaggart, 2019). These calendars provide a snapshot into the breadth and depth of Indigenous knowledges of the interlinkages among ecosystems and climate which can be used to better understand and anticipate the ripple effect of climate change on, for example, one aspect of phenology or ecosystem processes that has the potential to disrupt other phenologies and/or ecosystem processes. The aim is to highlight the relevance and necessity for respectful collaborative weaving of Indigenous knowledges with colonial knowledges for improving understanding and management of the impacts of climate change on ecosystems, resources, and humans.

Chapter 3 performed clustering, seasonal, and trend analysis on historical modelled streamflow data and observed rainfall data at daily resolution for 35 locations across Australia. The modelled streamflow data consisted of 39 years of daily streamflow records from 1979 to 2018 for each of the 35 available stations, provided by Alfieri et al. (2018). The observed rainfall data provided by the Australian Bureau of Meteorology (BOM) consisted of the 35 closest rainfall stations with complete daily data for the same time period to the modelled streamflow stations. Clustering was performed on the streamflow stations to identify similarities and differences across daily annual streamflow cycles and quantile regressions were performed to identify significant and near-significant increases and decreases in streamflow trends across stations within clusters. Seasonality was assessed through identification of the low and high rainfall and streamflow windows, with trend changes within these windows also assessed. The aims of the research in this chapter were to evaluate changes in streamflow and rainfall seasonality and trends.

Chapter 4 used the presence of bushfires within Indigenous seasonal calendars across the approximate months of the year to identify a bushfire season. This bushfire season was examined for drought trends through Standardized Precipitation Evapotranspiration Index (SPEI) at five locations across Australia. The SPEI trends were then compared with factors associated with influencing Australian climate through precipitation and temperature, namely the Southern Oscillation Index (SOI), and Indian Ocean Dipole (IOD). This chapter aimed to explore the interconnectedness between Indigenous place-based knowledge of bushfire risk and climatic influences of drought risk that contribute to bushfire occurrence.

CHAPTER 2

THEMES OF AUSTRALIAN INDIGENOUS SEASONAL CALENDARS TOWARDS CLIMATE ADAPTATION

Abstract

Indigenous Peoples have been monitoring and adapting to uncertainty and change in their local regions for millennia, resulting in a holistic view of the interlinkages within the occupied complex socio-environmental systems. A sample of Australian Indigenous knowledges of the interlinkages among biota, environment, and meteorology is portrayed in localised Indigenous seasonal calendars, 25 of which were used in a thematic analysis to determine the primary themes of information across the seasonal calendars. This produced five themes; biota, food, cultural and spiritual, hazards, and seasons. Further categories within each theme were also developed due to the abundance of information. The seasonal calendars show great attention to place-based particularities, thus offering greater diversity in ways to anticipate events and offer strands of knowledge across themes. The timing of categories within the hazards theme was mapped to the approximate months across the Gregorian year, demonstrating hazard timings consistent with Western knowledge. Indigenous knowledges have valuable insight into the interlinkages and stewardship of resources associated with the interlinkages of regions at high resolution. Weaving of Indigenous knowledges through equitable collaboration with Western knowledges is needed to better understand and adapt to local and global changing conditions at both low and high resolution scales.

Introduction

Indigenous knowledge and colonisation

Indigenous Australians and Indigenous Peoples around the world have developed sophisticated understandings of their proximal environment and climate through decades, if not centuries or longer, of experience and learning. Their long history within the complex systems of environment and climate (Johnson, 2006; Vigilante et al., 2009) has allowed them to amass a wealth of information and knowledge which some Indigenous communities have translated into seasonal calendars. These calendars are more flexible than and independent of the Gregorian calendar commonly used in Western cultures, operating more as holistic descriptors of occurring or expected environmental and climatic events and the associated activities rather than a prescriptive timekeeping method (O'Connor and Prober, 2010; Woodward and McTaggart, 2019).

Indigenous seasonal calendars are also representative of knowledge processes and relationships Indigenous Peoples' experience with their environment and resources within their proximal region (Jackson 2008; Rarai et al., 2022; Woodward and McTaggart, 2019). This relationship, as evinced in the seasonal calendars, was disrupted by the British invasion in 1788 that initiated the ongoing colonisation of Australia (Grewcock, 2018). Colonisation resulted in a massive deprivation of access to traditional lands and resources, family groups, and ability to transmit and apply knowledge for Indigenous Australians as colonisers perpetrated genocide towards Indigenous peoples (Grewcock, 2018) and installed colonial resource management methods (Jackson et al., 2015; Jackson, 2017). Colonial methods tend to prioritise outcomes which are determined by colonial values and/or measurements (such as volume of water, monetary value, etc.) which undervalues the complexity of Australian natural systems and results in difficulty accommodating uncertainty and emergent properties within complex systems (Johnson, 2006; Kopp et al., 2017).

Recent years have seen efforts across Australia to record Indigenous seasonal calendars to improve awareness of Australian Indigenous cultures and enhance knowledge accessibility and transmission cross-culturally and intergenerationally (Woodward et al., 2020). As a result, a selection of Indigenous Australian seasonal calendars (henceforth referred to as seasonal calendars) have become freely accessible through the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM) websites (BOM, 2016n; CSIRO, 2021). These calendars frequently contain a variety of observations and knowledge of the proximal region's complex system, including but not limited to, environmental, meteorological, and flora and fauna phenology knowledge (Liedloff et al., 2013; McKemey et al., 2020; Woodward, 2013; Woodward and McTaggart, 2019; Yang et al., 2019).

Indigenous knowledge processes and climate change

Indigenous knowledge is holistic, including weather, climate, environment, and biota information of a region that's been accumulated over generations, often through relationships experienced directly with the region (Nadasdy, 1999). Indigenous Peoples' holistic experience of a region results in expertise in observations in relative timing and condition of reoccurring phenomena. Western knowledge has allowed us to know that recent climate change has been increasing temperatures which has affected the severity and timing of climate and weather cycles and events through the increased redistribution of energy across the globe. Indigenous communities are disproportionately vulnerable to climate change (Shaffril et al., 2020) which functions as an intensification of colonialism (Jones, 2019). However, their holistic and detailed knowledge of localised cycles of climate and weather, and flora and fauna phenology, condition, population size, and distribution provide insight into these impacts of climate change to not only their communities but also the weather, environment, and biota of their local region (Green, Billy, and Tapim, 2010; Prober et al., 2011).

Examples of the impact of climate change on Australian flora and fauna include higher temperatures (Crous, 2019) and altered rainfall patterns resulting in large-scale canopy dieback of multiple tree species, and increased parasitic insect outbreaks causing defoliation and canopy dieback (Hoffman et al., 2018). Increased temperatures in alpine regions raising the snowline reduces viable habitat of snow-relient fauna and flora, and may result in a positive feedback loop with flammable vegetation, increasing fire frequency and severity. Increasing temperatures, longer and drier dry seasons, and increases in floods and cyclones in the wet tropics has caused vertebrate species to decline in population and distribution (Hoffman et al., 2018).

Observations of the impacts of climate change by Indigenous Peoples have been reported across the world, including Indigenous Taxkorgan's in western China observing changing climate and seasonal patterns and phenological indicators, taking steps to adapt their traditional agricultural activities to the new conditions (Yang et al., 2019). Torres Strait Islanders off the far northeast coast of Australia have witnessed some deviations to cycles which are not unexpected considering the variance within cycles, but other changes, such as the lack of turtle sightings during the season when turtles are common, are outside of the expected variation (Green et al., 2010). The Miriwoong people of northern Australia observed a lack of "knock-em-down" storms which annually flatten tall speargrass, and fruit from green and black plum trees have been ripening in poorer condition (quantity and quality) and months later than expected (Leonard et al., 2013). The Indigenous Peoples of northern Pentecost island of Vanuatu have observed changes to weather patterns and flora phenology, such as increased cyclone intensity, trees flowering and fruiting out of their expected temporal range, and plants growing outside of their normal spatial range (Rarai et al., 2022). The Tangkhul Naga people of northeastern India and northwestern Myanmar have observed a myriad changes in recent years, including seasonal changes, rapid loss of flora and fauna, monsoons or rains no longer predictable, increasing frequency of flash flooding, smaller water sources drying up, arable land shrinking, animals and insects behaving unusually, frogs and lizards becoming scarce, leeches, mosquitoes, and caterpillars becoming common where they were not previously prevalent, crop failure from insects, disease, and insufficient water, dominant high elevation plants dying out, disappearance of birds and bats that had commonly cohabited among humans, and migratory bird pattern changes (Varah and Varah, 2022). All of these examples provide clear evidence that Indigenous knowledge processes provide detailed information on biota, environment, weather, and climate at high resolution and are suited to tracking climate change at such scales. Indigenous knowledge assists communities with adaptation to climate change through sensitivity to the land and awareness of critical ecological signs. Support of Western knowledge through Indigenous knowledge is of itself original research and demonstrates the robustness of Indigenous knowledge (Berkes, 2009).

Knowledge processes and knowledge weaving

Indigenous knowledge has been undervalued since colonisation, with the knowledge process introduced by the colonisers prioritised and claimed to be the most legitimate method of understanding the world. However, there is more than one way of understanding the world just as there are multiple methods for observing phenomena. A knowledge process is a method of observing, discussing, making sense of new information, and storing information. It’s not just a method of passing on content from one person to another, and knowledge processes are not static, they change and develop with new information over time (Berkes, 2009; McGregor, 2004). Indigenous Australians' traditional knowledge processes are typically different to the colonial knowledge process, especially since the colonial knowledge process encourages uniformity while Indigenous knowledge processes can vary across Indigenous Peoples (Berkes, 2009).

Knowledge weaving is the bringing together of colonial and Indigenous knowledge methods in such a way that the integrity of neither knowledge process is lost. This means that the knowledge processes are not blended together but instead each retain their own epistemology and have to be woven together with consideration for the background of each knowledge process and the context from which the information is situated (Berkes, 2009).

Positionality statement

The authors of this research are non-Indigenous Australians and are some distance from the culture of Indigenous Australians. The intention of this article is to demonstrate the value of the depth and variety of Indigenous knowledge processes and their relevance to climate change. Our perspectives of the seasonal calendars are limited through our social and physical distances from Indigenous cultures and communities.

Throughout colonial history, Indigenous Peoples have been exploited for their knowledge which has been stolen, abused, and/or used to benefit others than the associated Indigenous communities. In response to these violations, Indigenous communities and researchers have put forth standards of care for working with Indigenous knowledge (David-Chavez and Gavin, 2018; Woodward et al., 2020). Six indicators for responsible research practice are outlined by David-Chavez and Gavin (2018): emphasising community accessibility of findings related to the community, relevance of findings to community-defined interests, crediting of community members for contributions and efforts, ethical interaction with Indigenous communities that promote benefit and reduce harm, respect for Indigenous intellectual property rights, and research outcomes and outputs being actionable for the Indigenous community. Similarly, the best practice guidelines developed through an Australian Indigenous-led project included respectful and equitable relationship building, collaborating, partnerships, co-designing, and co-management with Indigenous knowledge holders, respect for knowledge customs and intellectual property, and making sure benefit for Indigenous communities is a fundamental aspect of all activities (Woodward et al., 2020).

This research has aimed to be respectful of Indigenous knowledge customs by only using publicly available Indigenous seasonal calendars which presumably have been willingly provided by Indigenous community members with acknowledgement of the Indigenous authors and contributors. Care has been taken to ensure that the knowledge contained within the individual Indigenous seasonal calendars is not being appropriated and re-represented or mis-represented by analysing themes and categories broadly across the 25 seasonal calendars. Due to the broad-scale approach of this research, recommendations for applications of this research are generalised and need to be tailored to each specific situation. The intention of the authors is to demonstrate the value of the Indigenous knowledge processes for complex systems while maintaining that it is a knowledge process which cannot be separated from Indigenous communities and knowledge holders. However, due to distance, time, and financial constraints, this research has failed to meet recommended best practice guidelines of collaboration and co-design with the Indigenous communities represented in the seasonal calendars.

Methods

Data

The 25 seasonal calendars were made available between 2009 and 2020 (table 2.1). It is apparent that some of the calendars were co-produced with researchers through trusting relationships which developed through collaboration between the Indigenous knowledge holders and researchers over extended time periods of time (Maung language contributors and BOM, 2016; McKemey and Banbai Rangers, 2020; Ngoorabul Nation and McKemey, n.d.; Woodward and McTaggart, 2019). In comparison, the Bureau of Meteorology website provides a toolkit for use by Indigenous nations to develop and share seasonal calendars (BOM, 2016b), but the documentation process beyond this toolkit is unclear.

Table 2.1. Seasonal calendars and related information.

Seasonal calendar	Approximate climate (BOM, 2016a)	Approximate availability year	Approximate colonial location	Reference
D'harawal	Subtropical	Not indicated	Sydney, NSW	BOM, 2016c
Gariwerd	Temperate	Not indicated	Grampians National Park, VIC	BOM, 2016d
Kaurna	Temperate/Grassland	Not indicated	Adelaide Plains, SA	BOM, 2016e
Masig	Equatorial	2018	Torres Strait Islands, QLD	BOM, 2016f
Maung	Tropical/Equatorial	2014	Goulburn Islands, NT	Maung language contributors and BOM, 2016
Ngoorabul	Temperate/Subtropical	2019	New England Tablelands, NSW	Ngoorabul Nation and McKemey, n.d.
Nyoongar	Grassland/Temperate	Not indicated	Southwest Western Australia, WA	BOM, 2016g
Walabunnba	Grassland/Desert	Not indicated	Approximately 300 kilometres north of Alice Springs, NT	BOM, 2016i
Wardaman	Tropical/Grassland	Not indicated	Approximately 150 kilometres southwest of Katherine, NT	BOM, 2016j
Yanyuwa	Tropical/Grassland	Not indicated	Gulf of Carpentaria shores, NT and QLD	BOM, 2016k
Yawuru	Grassland/Tropical	Not indicated	Broome, WA	BOM, 2016l
Yirrganydji	Tropical/Grassland	Not indicated		BOM, 2016m
Gooniyandi	Grassland	2011	Cairns - Port Douglas, QLD	Davis et al., 2011
Jawoyn	Tropical	2019	Pine Creek - Bulman - Mataranka - Katherine, NT	Jawoyn Association Aboriginal Corporation, 2019
Ngurrungurrudjba	Tropical	2016	Yellow Water, NT	Lawson and McKaige, 2016

Table 2.1. Continued.

Wagiman	Tropical	2012	Pine Creek, NT	Liddy et al., 2012
Banbai	Temperate/Subtropical	2020	Wattleridge Indigenous Protected Area, NSW	McKemey and Banbai Rangers, 2020
Miriwoong	Tropical/Grassland	2011	Kununurra, WA	Mirima Council, 2011
Kunwinjku	Tropical	2015	Oenpelli/Gunbalanya - West Arnhem Land, NT	Narndal et al., 2015
Walmajarri	Desert/Grassland	2011	Kimberley region - Fitzroy River, WA	Nuggett et al., 2011
Ngadju	Grassland	2010	Norseman - Ngadju Indigenous Protected Area, WA	O'Connor and Prober, 2010
Tiwi	Equatorial	2014	Bathurst Island - Melville Island, NT	Tipiloura et al., 2014a; Tipiloura et al., 2014b
Gulumoerrgin	Equatorial/Tropical	2012	Darwin - Cox Peninsula - Gunn Point - Adelaide River - Manton Dam, NT	Williams et al., 2012
Ngan'gi	Tropical	2009	Daly River region, NT	Woodward and McTaggart, 2019; Woodward et al., 2009
MalakMalak	Tropical	2010	Nauiyu - Daly River, NT	Woodward et al., 2010

Seasonal calendars (table 2.1) were available in two styles, the first being a seasonal wheel with the major seasons bordering the wheel and descriptions and images of seasonal predictors and activities within their respective portions of the wheel. An example of this format is shown in figure 2.1. The second style is webpage based with a section for each season and its details, with the sections organised in a chronological list (BOM, 2016b). A calendar may be presented in both formats and may have differing levels of information contained within each format.

Figure 2.1. An example of an Indigenous seasonal calendar, designed by McKemey and Banbai Rangers (2020), cropped.

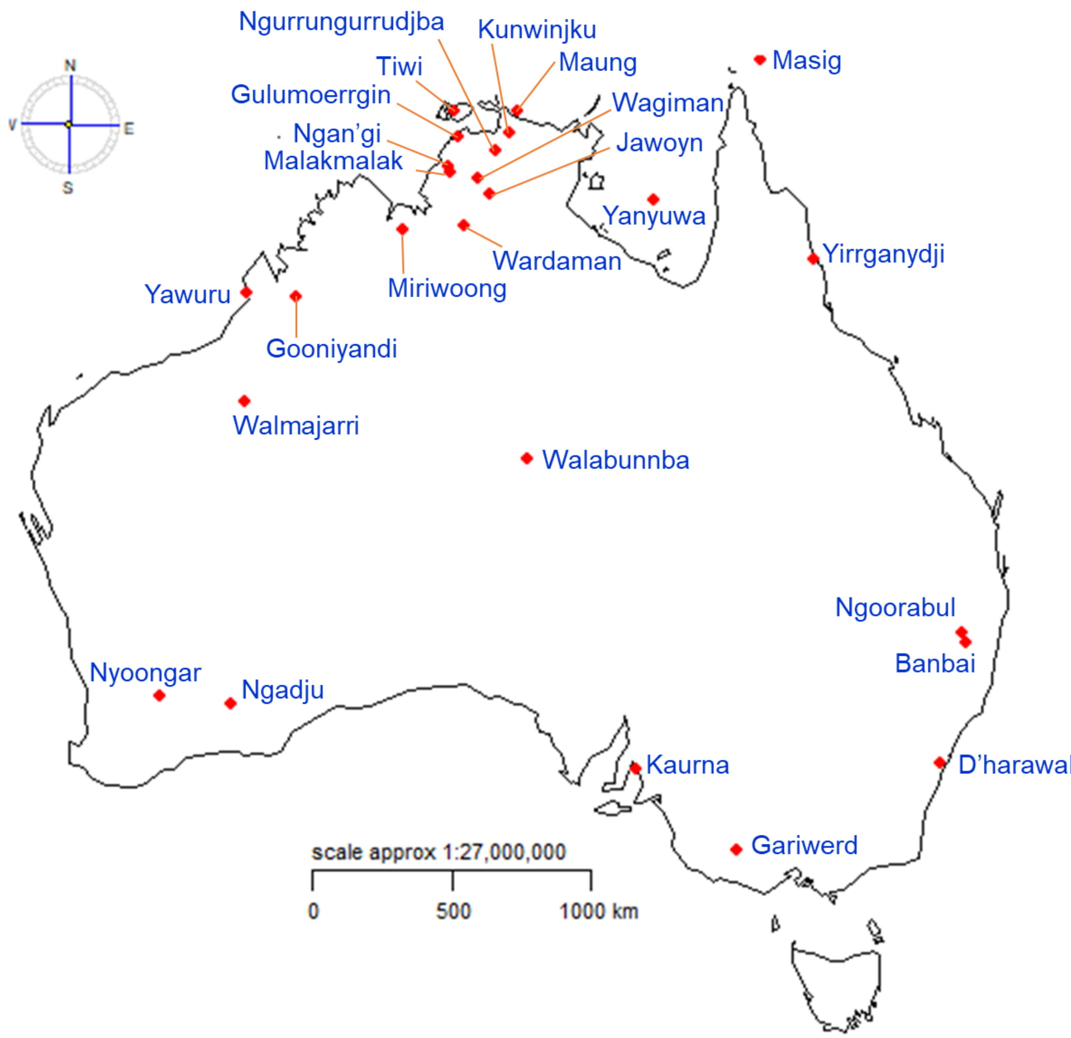
Many of the 25 seasonal calendars were developed to describe seasons, seasonal predictors, and seasonal activities through ecological, environmental, weather, and climate knowledge. The amount and type of information varies across the calendars; some contain great detail and others less, some focus more on the flora aspect while others appear to have prioritised fauna, while a couple of the seasonal calendars are tailored to cultural burning and managing bushfire risk. Much of the information provides insight into traditional resource management techniques of seasonal resources and managing uncertainty in timing and condition of such resources, but it bears highlighting that the information is a snapshot of Indigenous traditional knowledge at the time of calendar development. Indigenous and traditional knowledges are a process; they are a method of observing, discussing, and making sense of new information, rather than content, which is information passed on from one person to another without the knowledge process (Berkes, 2009; McGregor, 2004). To emphasise, the knowledge that contributed to and contained in these calendars is not static (Nadasdy, 1999).

Spatial distribution

The majority of the 25 seasonal calendars are concentrated in the northern half of Australia with only seven being located in the southern regions (figure 2.2). In 2016, the Indigenous and Torres Strait Islander population accounted for 3.3% of the total population of Australia, with the highest percent (1.1%) located in the southeastern state of New South Wales, followed by Queensland (0.9%). The state of Western Australia had the next most seasonal calendars (6), followed by New South Wales (3), Queensland (2), and Victoria (1) and South Australia (1). The approximate region of the calendars spanned equatorial, tropical, grassland, desert, subtropical, and desert climates (Table 2.1).

It may seem surprising that 12 of the 25 seasonal calendars are located in the Northern Territory (NT) where 0.3% of the Indigenous population reside; however, this is likely due to the NT having the highest ratio of Indigenous to non-Indigenous across the states and territories of Australia, with 30.3% of the NT population being Indigenous (AIHW, 2020). It is also important to remember that this research is only considering the 25 calendars publicly available through the BOM and CSIRO websites, and is not representative of all Indigenous nations or seasonal calendars present across Australia.

Figure 2.2. Map of the approximate centre of the 25 seasonal calendar regions.



Analysis method

Thematic analysis was performed on the 25 available Indigenous seasonal calendars through in-depth reading of each of the calendars and identifying overall commonalities and relevance to climate change and human wellbeing. A thematic analysis was chosen since it affords identification of commonalities and differences across the seasonal calendars without appropriating the information in the calendars and representing it anew; however, it also reduces the visibility of information interlinkages within each calendar. The themes were produced by an Australian who is of non-Indigenous descent, resulting in five themes being produced.

Due to the range and complexity of information contained within each theme, categories were then generated within each theme. The themes and categories were then further examined for frequency across calendars, and duration and frequency throughout the year where relevant.

Results

Thematic analysis

The five themes were: biota, food and nourishment, cultural and spiritual, hazards, and seasons, displayed in figure 2.3, along with each theme's categories.

Categories within themes

Detailed flora and fauna information was available across most of the calendars enabling a further categorisation within the biota theme. These categories consisted of plants flowering which relates to mentions of grasses, shrubs, and trees producing flowers; ripe fruits and vegetables which pertains to the indication of fruits, vegetables, and other plant matter being considered ripe; plant growth, which relates to new growth, regrowth after a fire event, and plants producing seed; and animal and insect activity which represents animal and insect prevalence, condition, behaviours, and breeding.

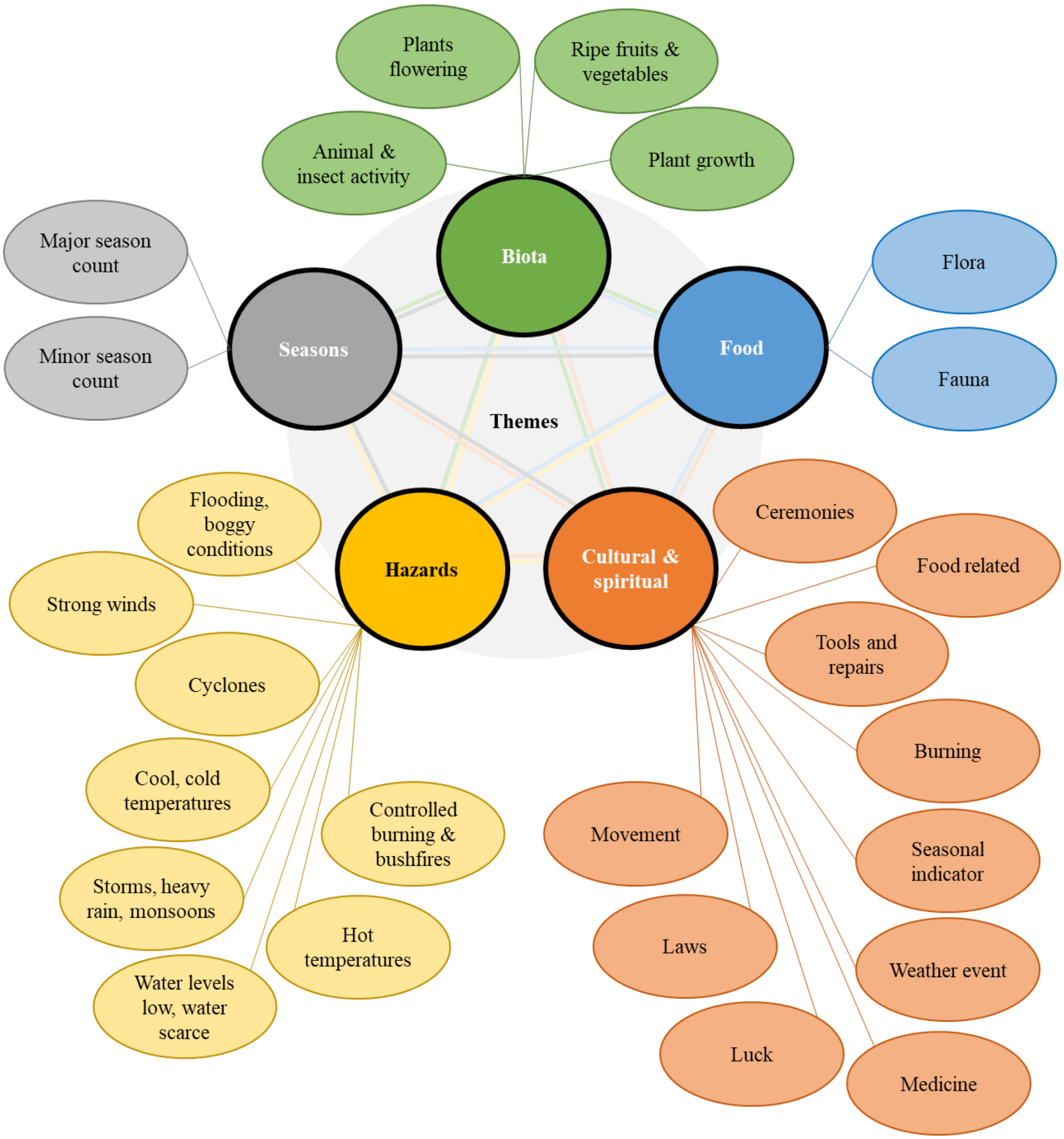
The food and nourishment theme related to flora and fauna used for food and nourishment. There was a lot of information that potentially qualified for both the biota and food and nourishment themes; however, the food categories had stricter inclusion criteria than the biota categories. Animals and insects that were directly stated as being hunted or eaten qualified for the fauna category of the food theme, while condition or prevalence changes of animals and insects were not included since these were presented as observations of fauna condition and prevalence related to seasons and not explicitly stated as a food source. Collaboration with the knowledge holders of the calendars would be required for improved delineation of whether fauna represented in a calendar is a seasonal condition or prevalence observation or is used as a food source.

The cultural and spiritual theme was studied under 10 categories: ceremonies, food related cultural activities, making and using tools, and making repairs, cool burning, seasonal indicators, weather events, medicines, luck, laws, movement and migration. A seasonal being broadly mentioned as a time of ceremonies, as well as activities stated to be ceremonial in nature were included in the ceremonies category. The tools and making repairs category consisted of mentions of materials that had a purpose other than being eaten or used as seasoning, and materials and activities for making repairs to items and shelters. The cool burning category refers to mentions of cultural burns of landscape that often target grasses and shrubs, cover small areas, are slow moving and remain low to the ground, allowing flora and fauna to survive, and are controllable or self-extinguishing (Korff, 2022; Prober et al,. 2013). Unintended and uncontrolled bushfires are not included in this category but are included within the hazards theme. The seasonal indicators category was made for specific mentions of an event associated with or preceding a change of season(s), such as increased prevalence of a species of fauna, the flowering of a plant species, and changes in cloud presentation. The observation had to be directly stated as associated with predicting or causing a change of seasons to be included in this category. Observations associated with predicting weather events, but not seasonal changes, were included in the weather event category. For example, changes in animal behaviour or phenology could be associated with a cyclone in a few days or a drought in a year or two. Mentions of flora, fauna, and materials used for healing and medicinal purposes were included in the medicines category. The luck category consisted of flora and fauna activities associated with bringing a person good or bad luck. Disallowment of particular activities during certain seasons were included in the laws category. The movement and migration category related to mentions of nation members relocating from one place to another.

Hazards represent weather and other occurrences that could pose a risk to human health and wellbeing, including controlled burning (cool burns) and wildfires, hot temperatures, water levels being low or water scarcity, storms, heavy rain, and monsoons, cool and cold temperatures, cyclones, strong winds, and flooding and boggy conditions. Both cool burns and wildfires were included in this category since fire can pose a risk to health even when well-tended and lit in ideal conditions. Hot temperatures included mentions of temperatures becoming hot and sun-exposed ground becoming too hot to walk on barefoot. Reductions in water levels and actions taken to improve water access during dry periods were included in the water levels low and water scarcity category. Storms, heavy rain, and monsoons were all one category since different terminology was used to describe mentions of heavy rainfall events across calendars. Collaboration would be required with calendar knowledge holders to more accurately distinguish the severity of the mentioned rainfall events. The cool and cold temperatures category represent mentions of temperatures lowering. Only clear and specific mentions of cyclones were included in the cyclone category. If a calendar was located in a region that experiences cyclones and described features of cyclonic activity, it was not counted towards the cyclone category in the effort to retain the representative integrity of the information provided in the calendar. Strong winds consisted of mentions of winds that were mentioned as being strong in some manner; however, simple mentions of wind direction change without description of strength were not included in this category. Land and floodplains becoming flooded, inundated with water, too boggy to safely allow unaided human movement, or inaccessibility due to high waters were included in the flooding and boggy conditions category.

The seasons categories involved the number and approximate timing of major and minor seasons throughout the year. The approximate minimum and maximum duration of the seasons according to the calendars was also recorded.

Figure 2.3. The five themes and categories within each theme.



Seasons theme

Twenty-two of the 25 seasonal calendars had the approximate Gregorian months represented alongside the corresponding Indigenous seasons while three calendars lacked month approximations. The three calendars without approximate months (Gooniyandi, Ngan'gi, and

Walmajarri) were all in the North-Northwest region of Australia (Northern Territory and Western Australia). The number of major and minor seasons present in each calendar with the approximate minimum and maximum monthly duration of the seasons is shown in table 2.2. Four of the seasonal calendars noted minor seasons occurring within or across the major seasons. The Australian continent consists of diverse regions, with the seasonal calendars located across equatorial, tropical, grassland, desert, and temperate climates (BOM, 2016a). Many of the calendars within the same region and within the same climate category have differing season frequencies and season duration; for example, major seasons in the central north tropical climate region range from three (Maung) to 13 (Ngan'gi) and span three (eg. Gulumoerrgin) to seven months (eg. Masig) in duration. The high variance of seasons across seasonal calendars further demonstrates the high specialisation of Indigenous knowledge within their proximal region, and how culture and knowledge processes interact.

Table 2.2. Number of major and minor seasons represented in each calendar and the approximate minimum and maximum monthly duration of seasons.

	Major seasons			Minor seasons		
Seasonal calendar	Number	Approximate minimum month duration	Approximate maximum month duration	Number	Approximate minimum month duration	Approximate maximum month duration
Kunwinjku / Gunbalanya	6	2	3			
Gulumoerrgin / Larrakia	7	2	3			
Maung	3	3	3			
Tiwi	3	3	6	18	1	3
Jawoyn	5	1	3			
Ngan'gi	13	-	-			
Ngurrungurrudju / Yellow water	6	1	3			
Miriwoong	3	3	5			
Wardaman	4	2	5			
Yawuru	6	1	4			
Gooniyandi	3	-	-	4		
MalakMalak & Matngala	7	1	3			
Wagiman	2	6	6			
Walmajarri	3	-	-			
Walabunnba	2	6	6			
Masig	4	3	7			
Yirrganydji	2	6	7	5	3	5
Yanyuwa	5	2	3			
Ngoorabul	5	2	3			
Banbai	6	1	5			
D'harawal	6	2	3			
Kaurna	4	3	3			
Gariwerd	6	2	3			
Nyoongar	6	2	2			
Ngadju / Marlpa	2	5	7	4	2	5

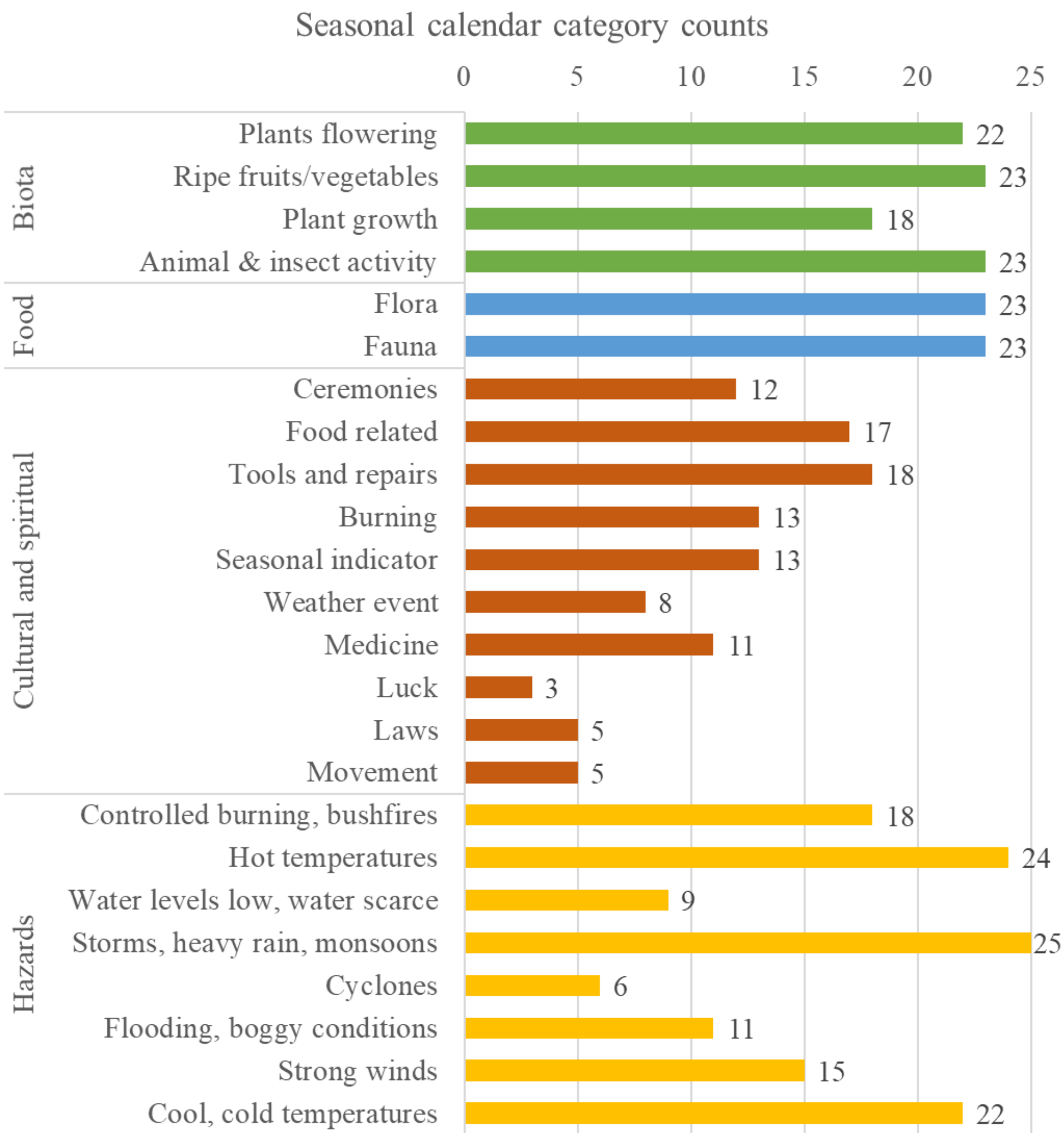
Category frequency across seasonal calendars

The number of seasonal calendars that qualified for each category, excluding the seasons theme, is shown in figure 2.4. A calendar needed to have at least one mention of information relevant to a category to be counted towards it, and a calendar could only be counted once towards a category. The biota theme was present in 18 to 23 calendars, with plant growth the least commonly present and ripe fruits and vegetables and animal and insect activity the most commonly present across the total 25 seasonal calendars. The food theme was present among all but two of the seasonal calendars, with both the flora present in 23 seasonal calendars and fauna present in 23 seasonal calendars.

The cultural and spiritual theme was more varied in category presence across the 25 seasonal calendars, with overall lower frequency compared to the other theme categories. There was three calendars present in the luck category, five calendars in each category of laws and movement, eight calendars in the weather event category, 11 calendars present in the medicine category, 12 calendars in the ceremonies category, 13 calendars in each the burning and seasonal indicators category, 17 calendars represented in the food related category, and as many as 18 calendars in the tools and repairs category.

The hazards theme had as few as six seasonal calendars in one category and complete representation across all calendars in another category. The cyclones category was least common across calendars (six), followed by water levels being low or scarce with representation in nine seasonal calendars, then flooding and boggy conditions with 11 calendars. Strong winds were present in 15 calendars, controlled burns and bushfires in 18 calendars, cool and cold temperatures in 22 calendars, hot temperature in all but one calendar, and storms, heavy rain, or monsoons were present across all of the seasonal calendars.

Figure 2.4. Count of seasonal calendars with category information out of the 25 seasonal calendars.



Hazards categories

The categories within the hazards theme were analysed according to their association with approximate months across the 22 seasonal calendars containing approximate month information to gauge synchroneity of hazard categories across calendars throughout the year (Ngan'gi, Gooniyandi, and Walmajarri lacked approximate month information and were excluded from this portion of the analysis). Mentions of each category were recorded within their associated months of the year in table 2.3, as well as the total mentions across categories for each month and the total annual mentions within a category. For the purposes of this analysis, multiple mentions of the same category in a month within a calendar were counted as a single mention.

It is worth noting that this is not representative of comprehensive hazard presence across approximate months since the seasonal calendars contained varying degrees of detail and were not designed to track hazard occurrence. For example, some hazards may be so interwoven in daily life and experiences that they were not considered worth mentioning during calendar development, hazards may be mentioned once and not mentioned at a later time due to the continuing nature of the hazard, or the hazards may not be perceived as hazards.

Frequencies

The months with the highest number of occurrences within each category are highlighted in table 2.3 according to the criteria in table 2.4. For each category, table 2.4 also contains the minimum and maximum frequency of occurrences across months, percent of high occurrences within the annual occurrences, and the number of months contained within the high period(s). The minimum monthly occurrence across categories ranged from zero to three, with hot temperatures, cyclones, flooding and boggy conditions, and cool or cold temperatures having months with zero frequency. Maximum monthly occurrence per category ranged from four to 19, with the categories of storms, rains, and monsoons and cool or cold temperatures having the highest maximum monthly occurrence.

The criteria for each category's high period was chosen through visual inspection of the frequencies in table 2.3, with the criteria often being close to the median (excluding zero) occurrences per month within each category. This method resulted in 56.0% to 93.9% (mean 77.9%) of annual occurrences being within the high period for each category.

The storms, rains, and monsoons category had the highest annual frequency with 121 mentions out of a possible total of 264 (22 calendars multiplied by 12 months). The next most commonly recorded categories across the year were hot temperatures (86), followed by cool or cold temperatures (76), strong winds (68), and controlled burning or bushfires (66). Flooding and water levels low or water scarce were then less than half as commonly recorded annually than controlled burning or bushfires (29 and 25 respectively). The cyclones category had the lowest annual occurrence (23), which is expected since the conditions for cyclone formation are not present year-round and the seasonal calendars in the southern regions of Australia are located at higher latitudes than are usual for cyclones to occur (BOM, 2022e).

Going by month, January (54), February (51), March (47), and December (46) had the most calendars across the hazards categories, with controlled burning and bushfires, hot temperatures, storms, rains, and monsoons, cyclones, and flooding and boggy conditions being the primary contributors. The lowest frequency of hazards across categories was in the months of April (26), May (35), July (36), and September (36).

Half of the hazard categories had at least one occurrence recorded across all of the months. This indicates that throughout the year, at least one hazard may be present or expected in at least one seasonal calendar region across Australia. These categories with year-round hazard occurrence were controlled burning and bushfires, water levels low or water scarce, storms, rains, and monsoons, and strong winds. The co-occurrence of controlled burning and bushfires, water levels low or water scarce, storms, rains, and monsoons categories appear to contradict each other; however, the seasonal calendars are located in a variety of locations around Australia, reflecting the diverse and complex climate, weather, and environmental systems present across the continent (BOM, 2016a; BOM, n.d.).

Across the cumulative seasonal calendars, no presence of the hot temperatures, cyclones, flooding and boggy conditions, and cool or cold temperatures categories were recorded across at least one month. For the hot temperatures, cyclones, and flooding and boggy conditions category these months included June through October, while cool or cold temperatures were absent across calendars in October through February. The months of no hazards for the high temperature categories are roughly during the high period of the low temperature category, approximately reflecting the warming and cooling seasonal cycles present in the southern hemisphere (BOM, 2018). The temperatures mentioned in the calendars are relative to the region of the seasonal calendars across Australia and are not representative of specific hot or cold temperatures. For example, a seasonal calendar located in the tropical climate of the northern coast of Australia and a seasonal calendar located in a southern region of Australia may both record cool or cold temperatures, but these would reflect differing ranges of cool temperatures (eg. 25°C compared to 12°C). Cyclones and flooding and boggy conditions had three of each of their four months with zero presence overlap. This period of zero occurrences is concurrent with the low period for storms, rains, and monsoons and has overlap with the high period for water levels being low and water scarcity, consistent with the annual climate cycle that provides conditions conducive to cyclone development, heavy or consistent rainfall, and tidal surges across much of Australia (BOM, 2022e, Collis, 2016).

Controlled burning and bushfires

Controlled burning and bushfires were reported throughout the year across seasonal calendars with the highest frequency in January and February (8) and high season being year-round, excluding the months of April (1) and July (3) which had the fewest calendars reporting controlled burning and bushfires. Controlled burns consist of fires deliberately lit to perform cultural practices, to provide healing to country (eg. reducing weeds), and to reduce hazards at a later time from an uncontrolled bushfire with high fuel load. Indigenous-lit cultural burns are intended as “cool burns”, typically occurring shortly after a season of heavy rain before temperatures become too hot, the land too dry, and when dew is present during the early morning to assist with extinguishing the fires (Korff, 2022; Prober et al,. 2013). In contrast, bushfires can occur at any time of year, often depending on fuel load, and meteorological factors such as humidity, wind, and temperature, but typically occur during a season of strong winds that occurs after a period of dryness and often result in more intense, more damaging, and less controllable fires (BOM, 2022a).

Hazard category timing and duration

Hot temperatures and storms, rains, and monsoons categories

High frequency for hot temperatures across calendars was September through March, with the highest frequency in October (16). None of the seasonal calendars indicated high temperatures in June or July. There was notable overlap between the categories of hot temperatures and storms, rains, and monsoons, with the highest monthly storms, rainfall, and monsoons frequency in December (19), and the high period starting the month prior in November and continuing through April (table 2.3). The high periods for hot temperatures and storms, rainfall, and monsoons align approximately with the western season conception of spring and summer which occurs September through February in the southern hemisphere, and also roughly aligns with the wet season of high temperatures and heavy rainfall experienced in the northern regions of Australia from October through April (BOM, 2018).

Water levels low, water scarcity category

Water levels dropping or water scarcity had overall low frequency but was reported across all months of the year with the high being in March and through August to October and the highest frequency occurring through August to September (4). Five months of the year had a frequency of one, all of which were during or within three months following the high period for storms, rains, and monsoons category.

Cyclones category

The high period for cyclones was slightly shorter than the storms, rains, and monsoons period, being December through March, with January and February having the highest frequency (5). June through September had zero mentions of cyclones in the seasonal calendars. Consistent with the requirements of cyclone formation, the cyclone high period falls within the high period for hot temperatures and storms, rainfall, and monsoons (BOM, 2022e).

Flooding and boggy conditions category

Flooding and boggy conditions had the same high period as the cyclone category (December through March), and had the same months of highest frequency (January and February) (7). July through October had a frequency of zero, with overlap with the lowest frequency period for storms, rain, and monsoons, and some overlap with the high period of the low water levels and water scarcity category.

Cool and cold temperatures and strong winds categories

The high period for cool and cold temperatures was in May through August with the highest frequency being in June (20), which, unsurprisingly, was the opposite of the high period for hot temperatures. Cool and cold temperatures had a frequency of zero for October through February, overlapping the high period for hot temperatures. The high period for cool and cold temperatures coincided largely with the high period for strong winds. Strong winds were reported throughout the year with the high period occurring in March and through May to November and the highest frequency occurring in August (9).

Table 2.3. Demonstrating synchroneity of categories across seasonal calendars using category counts across approximate months.

Hazard category	Approximate month												Annual total across calendars
	J	F	M	A	M	J	J	A	S	O	N	D	
Controlled burning, bushfires	**8**	**8**	7	1	5	7	3	4	6	6	6	5	66
Hot temperatures	10	9	8	1	1	0	0	5	13	**16**	14	9	86
Water levels low, water scarce	2	2	3	1	1	1	1	**4**	**4**	3	2	1	25
Storms, rain, monsoons	18	16	15	10	6	5	5	5	2	7	13	**19**	121
Cyclones	**5**	**5**	3	2	2	0	0	0	0	1	2	3	23
Flooding, boggy	**7**	**7**	5	2	2	1	0	0	0	0	1	4	29
Strong winds	4	4	5	3	5	5	8	**9**	8	6	6	5	68
Cool, cold temperatures	0	0	1	6	13	**20**	19	14	3	0	0	0	76
Monthly total across calendars	54	51	47	26	35	39	36	41	36	39	44	46	

Table 2.4. Descriptives and high period criteria for table 2.3.

Hazard category	Range of occurrences within months		High period monthly occurrences criteria	Percent of annual occurrences within high period	Months within high period
	Min	Max			
Controlled burning, bushfires	1	8	4+	93.9%	10
Hot temperatures	0	16	8+	91.9%	7
Water levels low, water scarce	1	4	3+	56.0%	4
Storms, rain, monsoons	2	19	9+	75.2%	6
Cyclones	0	5	3+	69.6%	4
Flooding, boggy	0	7	4+	79.3%	4
Strong winds	3	9	5+	83.8%	9
Cool, cold temperatures	0	20	12+	86.8%	4

Hazard preparation and impact

The inclusion of these hazards in the seasonal calendars and the overall synchroneity of occurrence reinforces that hazards are an expected experience to be navigated by Indigenous and non-Indigenous communities across Australia. All of the hazard categories are related to climate or weather driven events that can pose risk to human health and wellbeing. Presence in the calendars indicates that knowledge of weather, environment, and biota associated with the hazards enable Indigenous peoples to prepare and manage factors associated with the hazards to reduce vulnerability to such events or seasons.

For example, in a seasonal calendar located in the southeastern region of Australia, the flowering of Acacia implexa is a sign to reduce bushfire risk by only lighting fires on sand away from bushland, and to avoid occupation near creeks and rivers to reduce danger from flash flooding caused by violent storms and heavy rain (BOM, 2016c). In two of the northern seasonal calendars, cicadas singing loudly is a sign that heavy rains and storms are not far away (Jawoyn Association Aboriginal Corporation, 2019), while the dry season is heralded by descriptions of speargrass phenology, such as stalks dying and turning a reddish colour (Woodward et al., 2009). Each of these observations of interlinkages between weather, environmental, and biota phenology allows opportunity to adapt prior to the onset of the changing conditions. Another example comes from a southwestern calendar which mentions how a reduced number of fauna offspring is a predictor of water scarcity up to 18 months in the future (O'Connor and Prober, 2010). These demonstrate how long-term historical observations and relationships with country provide insight into the coming conditions of resources, environment, weather, and climate.

Climate change and hazards

Such insights into the high resolution interlinkages between biota, environment, and meteorological patterns enable a greater understanding of climate change, particularly as climate change is altering these patterns. Observation of the impacts of climate change at local scales will be vital for the safety and functioning of human lives and sustainable stewardship of resources. There is already evidence that changing precipitation patterns, water stress, droughts, and bushfires are detrimentally affecting the health and distribution of a variety of flora across Australia and increasing the risk of increased frequency and severity of bushfires (Hoffman et al., 2018). Findings by Di Virgilio et al. (2020) indicate that the ideal timing for prescribed and cultural burns to enable control of fires across southeastern Australia are changing beyond the expected temporal range. Indigenous knowledge processes can assist with adaptations to such transitions since Indigenous cultural burns are driven by the state of the landscape and relationships with country. For example, cultural burns are used when the land requires restoration, avoided when areas are rejuvenating, and are kept low and cool to protect tree canopy (Korff, 2022). Knowledge of temporal and spatial changes necessary for cultural burns and tracking these changes serve as an indicator to not only the health of country, but also to the impacts of climate change. Some calendars are even tailored to management of country through Indigenous fire methods, with orientation towards identifying ideal conditions for cool burns and when the risk for wildfires is highest (McKemey and Banbai Rangers, 2020; McKemey et al., 2022).

Resources Stewardship and Indigenous Seasonal Calendars

The availability of the seasonal calendars allows use as an intercultural tool for reducing the gap between Indigenous and Western knowledge processes. Indeed, many of the seasonal calendars include aspects of the equitable and adaptive resources stewardship principles posited by Lausier and Jain (2019). The principles of linkages across domains, where more than one aspect of the system is considered for an outcome, and adaptive risk management and co-produced solutions are frequently core features of the seasonal calendars through their holistic consideration of the biota, environment, weather, and climate. Where this principle isn't already applied among Indigenous knowledge processes, this predisposes them to being relatively prepared for incorporating linkages across domains into their stewardship practices. Inclusion of place, peoples, and values, as well as diverse knowledges, as stewardship principles are also predisposed to being applied if it isn't already utilised among Indigenous stewardship practices through the holistic nature of Indigenous knowledge practices and emphasis on relationships with others (Lausier and Jain, 2019). The resources stewardship principle of governance and institutions is where the greatest challenges lie due to the impacts of historical and ongoing colonisation, but also the greatest opportunities for encouraging decolonising steps in resource stewardship. In line with this, the availability of the seasonal calendars encourages collaboration between the dominant governing bodies and Indigenous knowledge holders and nations (Woodward et al., 2020).

Discussion

The 25 Indigenous seasonal calendars contain insight into comprehensive knowledge of biota, environment, weather, and climate at a local scale and within a holistic context. Thematic analysis of the information contained within these seasonal calendars resulted in five themes spanning descriptions of flora and fauna, food, culture, hazards and meteorological observations, and the timing of seasons. Categories within each theme were further defined due to the abundance and variety of information present within each theme. Delineating calendar information into themes and categories has obscured the holistic lens where originally no piece of information was in isolation from another within each calendar. However, the abundance of history and learning behind information in the categories remains apparent. The comprehensive accumulation of knowledge through extended historical and ongoing acute observations and learning of regions is demonstrated in at least the luck, laws, movement, and burning categories. Some visibility of the interlinkages within calendars is retained in at least the weather event and seasonal indicator categories of the cultural and spiritual theme.

The information within the seasonal calendars can be mobilised to enable better observation of the impacts of climate change at local scales and for the development of adaptive strategies. Weather events and the progression of seasons could be better understood, anticipated, and prepared for through the contextual understanding of precise environmental, meteorological, or phenological indicators which becomes increasingly vital as climate change increases the strength and severity of weather and climate events. Weaving of Indigenous knowledges and colonial knowledges together can yield new insights and opportunities for adaptive measures that either knowledge process could uncover functioning alone. Colonial knowledge can be augmented with Indigenous knowledge and Indigenous knowledge can be augmented with colonial knowledge for improved understanding and management at multiple scales (McKemey et al., 2020). For example, many of the features within the hazards categories can be quantified using hydroclimate data, such as temperature, rainfall, streamflow, and drought index. Such knowledge weaving through collaboration with Indigenous nations can further the decolonisation of dominant relations to land and resource management at daily, seasonal, and longer timescales.

Recommendations towards this include developing and nourishing equitable and respectful relationships between the Indigenous Peoples and the descendents and benefactors of colonialism. Through these relationships, trust can be built and weaving of knowledges towards equitable outcomes can be cultivated. Progress towards this can occur through those in positions of authority actively, respectfully, and ethically engaging Indigenous communities in decision-making processes. Accompanying this should be concurrent education and refreshers on the ethics of Indigenous knowledge and involvement to avoid ignorance based exploitation or other issues. Indigenous Peoples should identify and regularly assess their boundaries for sharing knowledge to maintain their rights. Meaningful, efficient, and effective methods for Indigenous Peoples asserting their rights when approached or involved with knowledge weaving should also be maintained at multiple levels to reduce the risk of harm towards Indigenous knowledge holders.

Conclusion

Indigenous People’s knowledge of their local region is rich in diversity and detail; including timing and phenology of biota, environment, weather, and climate information steeped in context that highlights the importance of considering holistic interlinkages and not just one aspect of an ecosystem or environment. Biota, food, hazard related information, and season timing and duration were most commonly reported across the calendars. Separating out one feature can be of value for enabling quantification; however, the holistic interlinkages of the feature need to be brought back into the context before mobilising the knowledge. Collaboration between Indigenous and colonial methods involving such actions will enable enhanced knowledge weaving and augment understanding of the variations within a local region. Those perpetuating and benefiting from colonialism need to be educated on the benefits of knowledge weaving and the ethics of Indigenous intellectual property to improve climate change adaptation methods and minimise the potential for exploitation and further harm towards Indigenous Peoples. This process through equitable collaboration with knowledge holders has great potential to enrich and enhance the monitoring of and adaptation responses to climate change while also improving equitable outcomes and sustainable resource stewardship.

CHAPTER 3

TRENDS IN THE SEASONAL CYCLE OF MODELED STREAMFLOW ACROSS AUSTRALIA, 1980-2018

Abstract

The seasonal cycle of streamflow over the Australian continent represents the diverse weather and climate variations and the distinctive influences from coupled ocean-atmospheric phenomena such as monsoons, frontal systems, and El Nino-Southern Oscillation, to name a few. Streamflow strongly modulates the health of ecosystems and is inextricably linked to the communities through consumptive use, cultural, and spiritual practices. Recent collaborative work in Indigenous communities have led to the availability of seasonal calendars, with detailed delineation of the seasonal environmental variability and societal relationship with water. As such, place-based knowledge of the co-evolution of river flow and the social and biophysical systems offer a unique nexus to understand the potential impacts of and adaptation to a changing climate. To this end, a comprehensive trend analysis of streamflow variability resolved at daily scales is pursued here. A serially complete dataset of daily streamflow for 35 rivers across Australia from the GloFAS-ERA5 operational global river discharge reanalysis is used to characterize the changes in the seasonal cycle of streamflow over the 1979-2018 period. Over the past four decades, Australian rivers have undergone spatially coherent changes in the seasonal cycle of streamflow. Quantile regression and cluster analysis results indicate that the rivers in the south half of the continent show widespread–across all seasons–decreases in streamflow. The streamflow in the northern tier of the continent shows marked local coherence in increases and decreases. Analyses of trends within upper and lower portions of the flow distributions reveal

unique sub-seasonal time windows in the extremes, thus underscoring that trends across the full distribution of streamflow are necessary to understand vulnerability to human and environmental systems. Finally, results from the high-resolution trend analysis are discussed within the context of their usability in identifying the potential impacts on local communities and ecosystems, especially in light of the recent delineation of indigenous seasonal calendars.

Introduction

Streamflows across the Australian continent are affected by coupled ocean-atmospheric climatic phenomena. The South Pacific Convergence Zone is associated with having a stronger effect on streamflows in the northern regions of Australia than the streamflows in more southerly regions (Shams et al., 2018) and the El Nino Southern Oscillation and the Interdecadal Pacific Ocean Oscillation both been indicated to have a strong relationship with Australian rainfall and resulting streamflow (Verdon et al., 2004). The interannual and longer-term variations in the strength of the monsoon strongly influences hydrologic variability in the northern portions of Australia (Higgins et al., 2022). Large scale climate patterns and climate change have been implicated in recent hydrologic changes in streamflow across regions of Australia (Zhang et al., 2014). Historical annual streamflows across south eastern Australia, namely in the states of New South Wales and Victoria, have been significantly decreasing, while there have been significant annual increases in Northern Australia (Zhang et al., 2016), and significant declines in both streamflow and rainfall in South Western Australia (Liu et al., 2019; Petrone et al., 2010).

Communities rely on certainty in streamflows for consumptive use, cultural, and spiritual practices, with streamflow changes also impacting ecosystem health and sustainability. Indigenous seasonal calendars from across Australia highlight these interlinkages between communities, ecosystems, and streamflows, with relationships with country encompassing both land and water resources (Prober et al., 2011; Woodward and McTaggart, 2019). Changes to streamflow cycles beyond the expected variation limits may detrimentally impact ecosystems and human cultural experiences.

To that end, the seasonal cycle of streamflow affords a timeframe within which episodic to annual variability and trends in streamflow can be analysed to ascertain the diverse array of impacts on human and environmental systems linked to riverine flow. In this study, we seek to quantify trends in modeled daily streamflow across Australia by carefully considering the entire distribution of streamflow based on quantile regression and clustering. Trends across streamflow quantiles and resolved at daily scales are especially important for a side-by-side assessment of the potential impacts on human and environmental systems delineated in the seasonal calendars.

Methods

Data and Study Region

A serially complete dataset of daily streamflow for 35 rivers across Australia from the GloFAS-ERA5 operational global river discharge reanalysis is used to characterize the changes in the seasonal cycle of streamflow over the 1979-2018 period (Alfieri et al., 2020). Prior to analysis, leap day values (February 29) were averaged with the previous day's values (February 28) to generate a new average value which replaced the February 28 value in leap years while February 29 was removed for data consistency across years. The majority of the 35 streamflow stations were located in the northern and eastern regions of Australia (figure 3.1), with most of the stations in Queensland (QLD) (11), followed by New South Wales (NSW) (10), Northern Territory (NT) (6), Western Australia (WA) (6), and Victoria (VIC) (2). The majority of the rivers relating to the streamflows were regulated to some degree (water permits, water licences, water sharing plans, dams, mining, etc.).

Daily observed rainfall data from the Bureau of Meteorology (B.O.M.) from 1980-2018 was also subject to analysis for comparison with the modelled streamflow results. Rainfall stations were selected based on their proximity to modelled streamflow station coordinates and completeness of daily records for the time period (table 3.1). Using this matching criteria, two sets of duplicates resulted from the close proximity of streamflow stations; both of the Borroloola Crossing and M.I.M. Pump streamflow stations matched with the McArthur River Mine Airport rainfall station, and both the Glenore Weir and Walkers Bend streamflow stations matched with the McAllister Station for rainfall observations. The resulting observed rainfall dataset consisted of 35 stations, equivalent to the modelled streamflow dataset, including the two repeated rainfall stations. Rainfall leap days received the same treatment as was performed in the streamflow dataset prior to analysis.

Figure 3.1. Streamflow station and rainfall station locations.

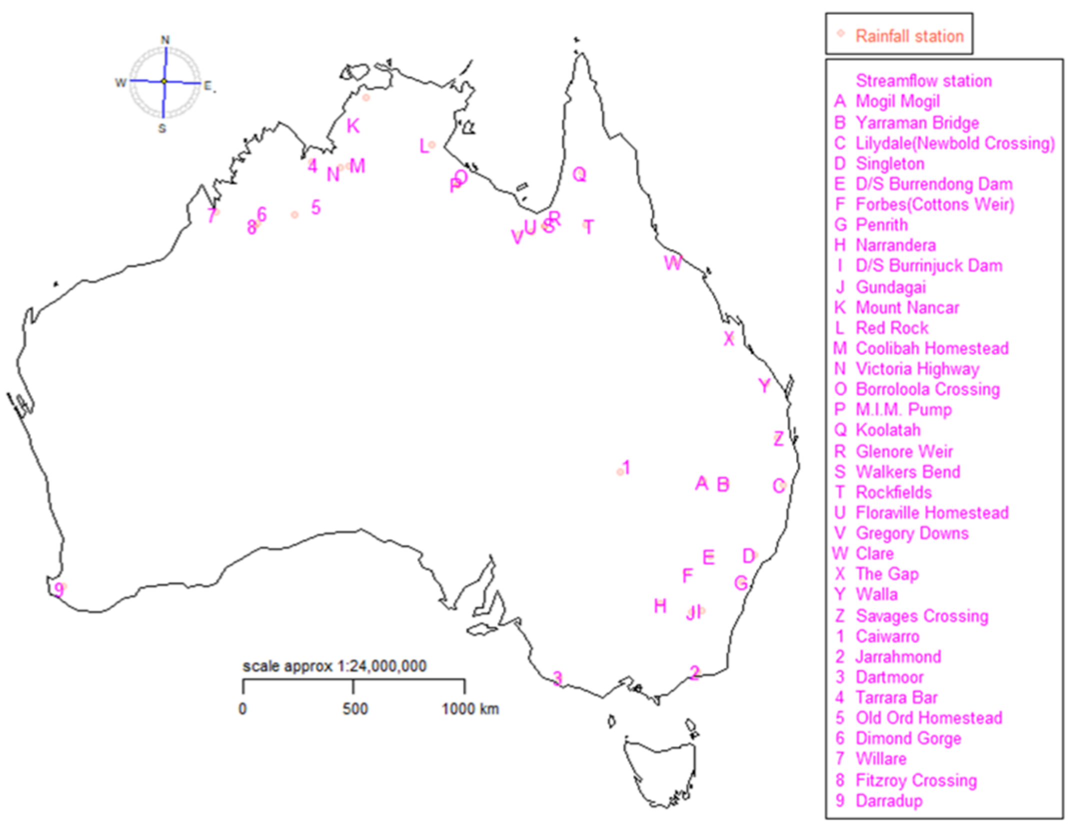


Table 3.1. Streamflow station and rainfall station IDs, locations, distances, and years of data.

Streamflow					Rainfall					Distance between stations (km)
Station	Latitude	Longitude	GRDC ID	Drainage basin area (km^2)	BOM station	Latitude	Longitude	BOM station number	Years of data	
Borroloola Crossing	-16.08	136.32	G1360	15700	McArthur River Mine Airport	-16.44	136.08	014704	1987-2018	48.0
Caiwarro	-28.69	144.79	G1456	21446	Hungerford (Paroo River)	-29.00	144.41	044181	1980-2018	43.2
Clare	-19.77	147.24	G1397	129900	Clare	-19.79	147.23	033122	1980-2014	1.6
Coolibah Homestead	-15.55	130.96	G1347	44900	Timber Creek	-15.66	130.48	014850	1981-2014	1.3
D/S Burrendong Dam	-32.63	149.08	G1485	13980	Lake Burrendong	-32.67	149.10	062003	1980-2018	3.1
D/S Burrinjuck Dam	-35.00	148.57	G1507	13100	Burrinjuck Dam	-35.00	148.60	073007	1980-2018	0.8
Darradup	-34.07	115.62	G1498	11593	Nannup	-33.98	115.77	009585	1980-2018	18.8
Dartmoor	-37.93	141.28	G1511	11914	Drik Drik	-37.97	141.31	090036	1980-2018	6.4
Dimond Gorge	-17.67	126.03	G1377	17152	Fossil Downs	-18.14	125.78	003027	1980-2018	58.0
Fitzroy Crossing	-18.21	125.58	G1385	46133	Gogo station	-18.29	125.59	003014	1980-2018	8.7
Floraville Homestead	-18.26	139.88	G1386	23660	Augustus Downs Station	-18.54	139.87	029001	1980-2018	19.4

Table 3.1 continued.

Forbes (Cottons Weir)	-33.41	147.99	G1492	19000	Forbes (Muddy Water)	-33.33	147.85	065039	1980-2018	15.2
Glenore Weir	-17.86	141.13	G1380	39360	McAllister Station	-18.24	140.53	029148	1987-2018	77.8
Gregory Downs	-18.64	139.25	G1390	12690	Gregory Downs Outstation	-18.64	139.25	029100	1980-2018	0.9
Gundagai	-35.08	148.11	G1508	21100	Gundagai (Nangus Rd)	-35.06	148.10	073141	1995-2018	0.7
Jarrahmond	-37.66	148.36	G1510	13421	Bete Bolong (Russells Estate)	-37.71	148.40	084093	1980-2018	1.9
Koolatah	-15.95	142.38	G1358	45872	Koolatah Station	-15.89	142.44	029029	1980-2015	5.7
Lilydale (Newbold Crossing)	-29.51	152.68	G1464	16690	Copmanhurst (Fernglen)	-29.53	152.80	058073	1980-2017	12.7
M.I.M. Pump	-16.45	136.09	G1365	10400	McArthur River Mine Airport	-16.44	136.08	014704	1980-2018	1.6
Mogil Mogil	-29.35	148.69	G1462	64800	Mogil Mogil (Benimora)	-29.35	148.69	052019	1980-2018	1.9
Mount Nancar	-13.83	130.73	G1325	47100	Beatrice Hill NT	-12.65	131.32	014086	1980-2017	13.1
Narrandera	-34.76	146.55	G1504	34200	Narrandera Airport AWS	-34.71	146.51	074148	1980-2018	6.0

Table 3.1 continued.

Old Ord Homestead	-17.37	128.85	G1371	19513	Springvale	-17.78	127.69	002050	1980-2018	60.5
Penrith	-33.75	150.68	G1495	11000	Orchard Hills Treatment Works	-33.80	150.71	067084	1980-2018	6.0
Red Rock	-14.70	134.42	G1333	47400	Ngukurr Airport	-14.72	134.75	014299	2012-2018	23.1
Rockfields	-18.20	142.88	G1384	10987	Inorunie Station	-18.21	142.66	029054	1980-2014	11.2
Savages Crossing	-27.44	152.67	G1448	10170	Lowood Don St	-27.46	152.57	040120	1980-2018	9.5
Singleton	-32.56	151.17	G1484	16400	Elderslie	-32.59	151.33	061092	1980-2018	15.4
Tarrara Bar	-15.56	128.69	G1349	51028	Carlton Hill	-15.49	128.53	002005	1980-2018	69.9
The Gap	-23.09	150.11	G1421	135757	The Gap TM	-23.09	150.11	033285	2000-2018	0.1
Victoria Highway	-15.93	129.73	G1356	10204	Auvergne	-15.68	130.01	014814	1980-2018	25.3
Walkers Bend	-18.17	140.86	G1383	106300	McAllister Station	-18.24	140.53	029148	1987-2018	34.7
Walla	-25.13	151.98	G1435	32455	Walla TM	-25.14	151.98	039313	2000-2018	11.8
Willare	-17.75	123.50	G1379	91902	Yeeda	-17.62	123.65	003026	1980-2018	26.7
Yarraman Bridge	-29.43	149.85	G1463	12960	Moree Aero	-29.49	149.85	053115	1995-2018	7.7

Statistical Methodology and Data Preparation

The primary analysis methods used in this study were clustering, quantile regressions, and Poisson regressions. Cluster analysis enabled identification of data with similar features into groups while quantile regression revealed the direction and significances of trends in low, median, and high flows. Poisson regressions were used to determine changes in rainfall during low and high rainfall seasons.

Cluster Analysis

The data used in this study come from diverse environment and climate regions, so it was of interest to identify if the streamflow stations could be grouped by common characteristics. Euclidean clustering was chosen since it would classify the streamflow stations with the most similar annual streamflow patterns together. Data from each streamflow station was delineated into three quantiles to further analyse the difference in streamflows across the probability distribution. Low streamflow was represented by quantile 0.2, median streamflow by quantile 0.5, and high streamflow by quantile 0.8.

Rolling pentad averages were a common starting point throughout the analyses due to the smoothing of outliers provided by using rolling averages. The average daily streamflow and rainfall values by station and by median cluster were used to compare patterns between the two datasets and median clusters. Proportions of station streamflow throughout the year were examined using the percent of station median streamflow rolling pentad averages.

Data preparation began with getting the rolling pentad average of daily streamflow values across the 39 years. A basic quantile function was then applied at tau = 0.2, 0.5, and 0.8, resulting in 365 values for each station. Plots of the stations at this stage revealed a wide range in streamflow magnitudes between stations which had the potential to skew clustering outcomes.

The large difference in magnitudes between stations was standardized by rank ordering each station's values from 1 to 365, dividing by n+1 (366), and then normalizing the distribution of values using qnorm() in R.

These values were then clustered using the kmeans function from the "stats" R package with the parameter of nstart = 55 to stabilise cluster membership. The number of clusters for each quantile was selected using silhouette plots, with 2 clusters being optimal for all three quantile levels. When $k > 2$, the overall average silhouette coefficient for the clusters decreases rapidly ($k = 2$, $S = 0.31$; $k = 4$, $S = 0.16$); the additional individual clusters have very low or negative silhouette coefficients, indicating that $k > 2$ is less effective at grouping clusters.
The average daily streamflow and rainfall values by station and by median cluster were used to compare patterns between the two datasets and median clusters. The daily average across years was used to get 365 values for each location from the streamflow data and rainfall data. The locations were then grouped by median streamflow cluster membership and the daily values averaged again for one overall cluster average for visual comparison.

The five-day rolling mean for each day across the 39 years was used to get daily median values resulting in 365 daily median values for each streamflow location. These daily medians were then summed to provide the total annual median streamflow from which the daily percent of annual median streamflow was found.

Quantile Regression

Analysis of the streamflow data consisted of quantile regressions to get the significance of daily streamflow changes, the direction of these changes, and analysis of seasonal variation through the median daily percent of annual streamflow. Quantile regressions provide flexibility through the ability to change thresholds in the upper and lower while being more robust to the variability present in streamflow. The benefit of this method over linear regression is that changes in direction and magnitude in the quantile extremities can be revealed where they would otherwise be obscured through linear regression methods (Koenker, 2005). In the application of quantile regression, a no-cross provision was employed to prevent invalid results from overlapping quantile regression lines (Bondell et al., 2010).

Analysis of the streamflow data used quantile regressions to assess daily streamflow change significance and the direction of these changes. The following steps were applied to each of the 35 stations. The modelled daily streamflow values were averaged over 5 days to provide rolling means across the 39 years of data. For each day, the five-day rolling average values across the 39 years were then sampled with replacement 1,000 times to generate a comparison distribution for tau levels of 0.2, 0.5 (median), and 0.8, resulting in 365 sample distributions per year. The actual five-day rolling average regressions values for each day were then located on the sample probability distribution. The slope and significance values were retained for subsequent analyses. The tail ranges of $\boldsymbol{\tau} = 0.2$ and $\boldsymbol{\tau} = 0.8$ were chosen to allow examination of changes in the more extreme values over the 39 years.

Significance values from the quantile regressions were used to identify daily increases and decreases in streamflow that were significant and near-significant at each tau = 0.20, 0.50, 0.80. Increases in streamflow are represented by significance values above the 0.90 thresholds while decreases in streamflow are represented by significance values below the 0.10 threshold. For example, a span of days with $p < 0.05$ at $\boldsymbol{\tau} = 0.2$ is indicative of significant decreases in streamflow when streamflow is already low and could be interpreted as representing an increase in hydrological uncertainty.

Low and High streamflow seasons

Annual seasonal variation in streamflow across each station was assessed using the daily percent of annual streamflow. The five-day rolling mean for each day across the 39 years was used to get daily median values resulting in 365 daily median values for each streamflow location. These daily medians were then summed to provide the total annual median streamflow from which the daily percent of annual median streamflow was found.

High streamflow volume trends

The 75 day rolling sum of the daily annual streamflow was calculated for each streamflow station and the first and last years of data removed due to subsequent 37 days of missing data. Next, the daily median across years for each streamflow station was found, resulting in 365 days of data per station. The stations were then separated into their 0.5 cluster groupings and the maximum median day for each station found. These overall cluster maximum medians were then identified as the peak rainfall day and 37 days added on either side to get the full 75 day high rainfall season window for each cluster.

The original streamflow values were then subset to the 75 day high streamflow window for each station within the clusters. Next, these original streamflow volume values within the 75 day high window were summed for each cluster, resulting in one volume value per year for each station. Quantile regressions using tau = 0.5 were then performed on 75 day high streamflow volume value against the number of years of data. Slope and significance from the regressions were used to identify significant increases and decreases in streamflow for each station within their clusters' 75 day high volume period of streamflow.

Low and high rain seasons

The same procedure for identifying the 75 day high streamflow window was repeated on the rainfall data to find the 75 day high rainfall season. To find the 75 day low rainfall season, the process was repeated again but used the minimum median day for each station instead of the maximum median day.

Poisson regression trends

Rainfall trends across stations were analysed using Poisson regressions to identify increases and decreases of rain during the 75 day low and high rainfall windows over the years of available data. Poisson regression on the counts of no rain days and substantial rain days compared with the number of years of rainfall data will indicate whether the number of no rain days or substantial rainfall days are significantly increasing or decreasing during the identified 75 day low and high rainfall windows at each location.

Within each cluster, each station's original rainfall values within the identified 75 day high rainfall season were then dichotomised according to whether they met the threshold for substantial rainfall, that is, 2.54mm or greater in a day. The number of days with rain during a high season were used against the number of years of available rainfall data in Poisson regression for each station. The analysis was then repeated for the low season, except the number of days without substantial rainfall were counted instead and used with the number of available years rainfall data for each station. The slopes and significances from the Poisson regressions of both the low and high rain seasons were then used to identify if the day of lowest or peak rainfall had experienced significant increases or decreases over recent years.

Results

Seasonal Cycle of Streamflow

Cluster Analysis

Across the quantiles there was similarity in cluster sizes and membership, with the largest cluster in quantile 0.2 accounting for 74% of stations, 69% of stations in quantile 0.5, and 71% of stations in quantile 0.8 (figure 3.2.a.). The cluster groupings were overall split between northern and southern regions of Australia for all three quantile levels, with a map of the median cluster result in figure 3.3.a.

Figure 3.2. Number of streamflow stations in each cluster across quantiles and parallel coordinates plot.

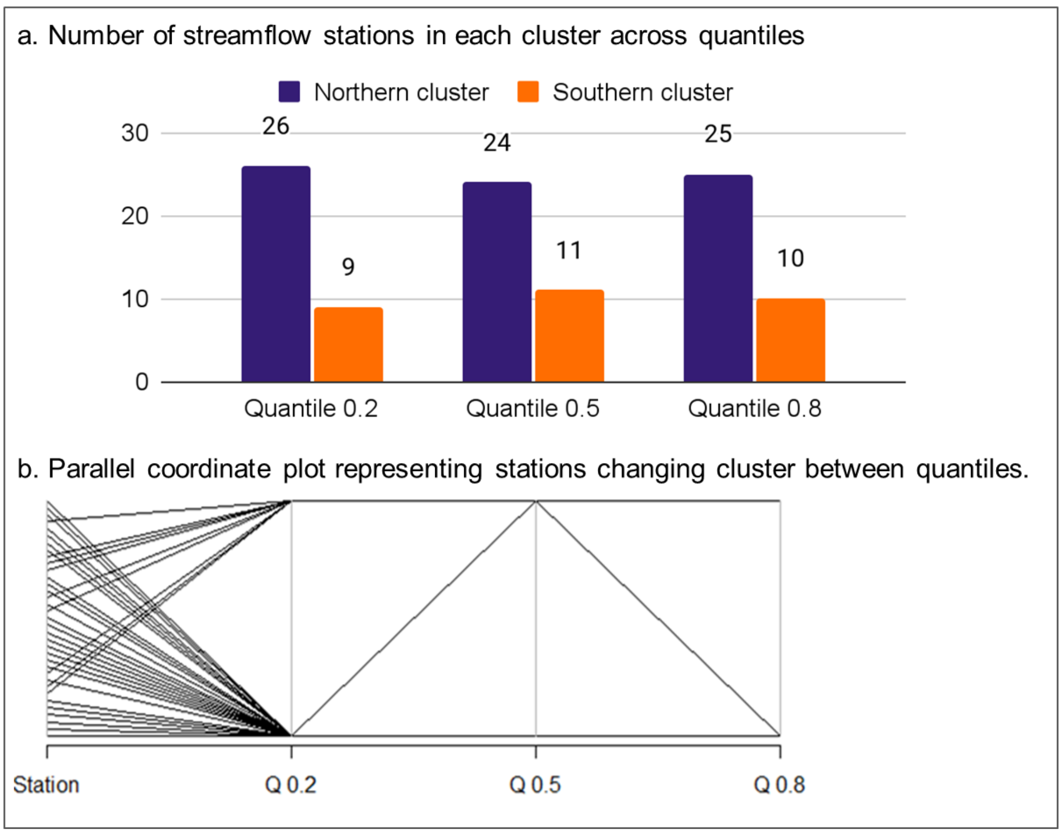
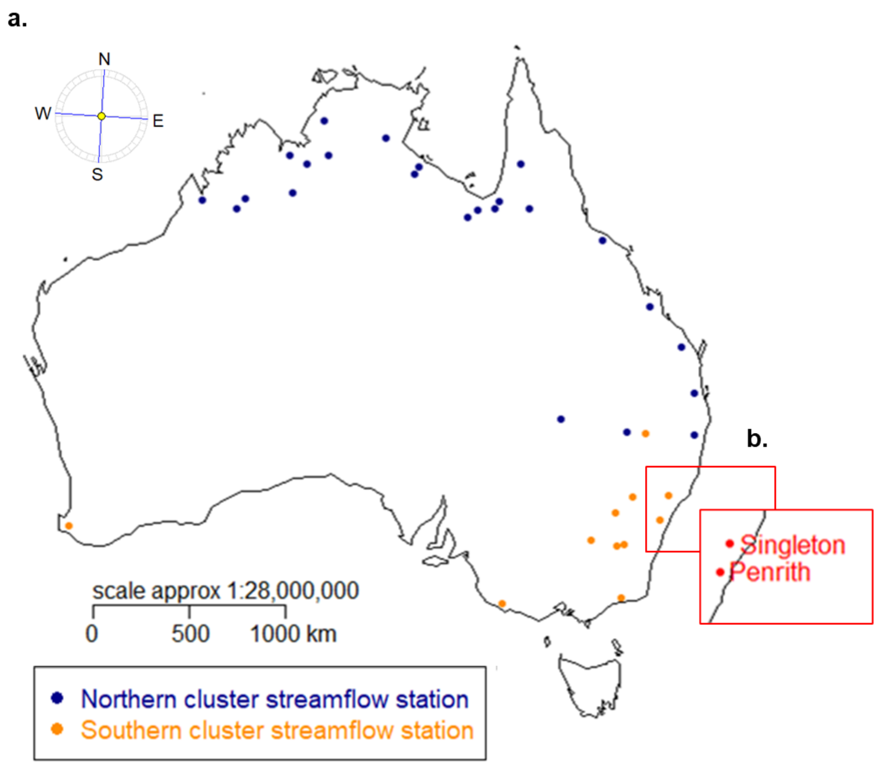


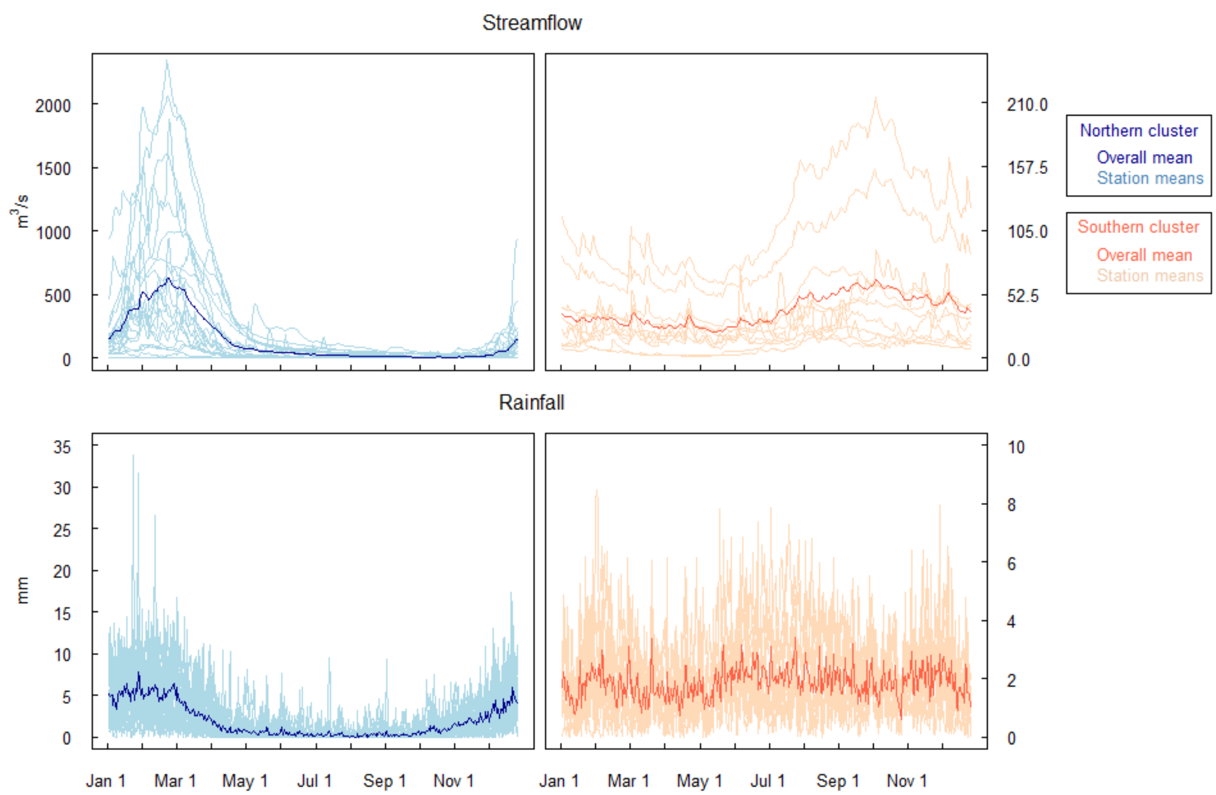
Figure 3.3. Map of clustered streamflow stations at quantile 0.5 and highlighted stations that changed cluster membership across quantiles.



The parallel coordinates plot (figure 3.2.b.) demonstrates the changes to group membership across the quantile clusters with size and membership staying fairly stable in the largest two clusters across quantiles. Two stations changed cluster membership. Station 24 (Penrith, NSW) was in cluster one for quantile 0.2, changed to cluster two for quantile 0.5, and then returned to cluster one for quantile 0.8. Station 28 (Singleton, NSW) was also in cluster one for quantile 0.2 and changed to cluster two for quantile 0.5, but then remained in cluster two for quantile 0.8. These two stations are located close to each other on the southeastern coast near the border between the two clusters (figure 3.3.b.), possibly indicating that the distinction between the two clusters is less clear in this region, or that proximity to the coast in this region results in different streamflow behaviour compared to nearby inland stations.

The daily annual means for streamflow and rainfall are visualised in figure 3.4, with stations split into the median northern and southern clusters. Streamflow peaks in the first part of the year for the northern cluster and is followed by declining streamflow through the rest of the year until the start of an increase in the last couple of months. Rainfall follows a similar pattern in the northern cluster, except with a less extreme high and a more steady increase in the last third of the year. The southern cluster displays a noticeably different trend with an increase in streamflow present in the latter half of the year and no clear overall peak in rainfall. The y-axis of each plot is tailored to enable visualisation of the streamflow and rainfall patterns at the relevant scales.

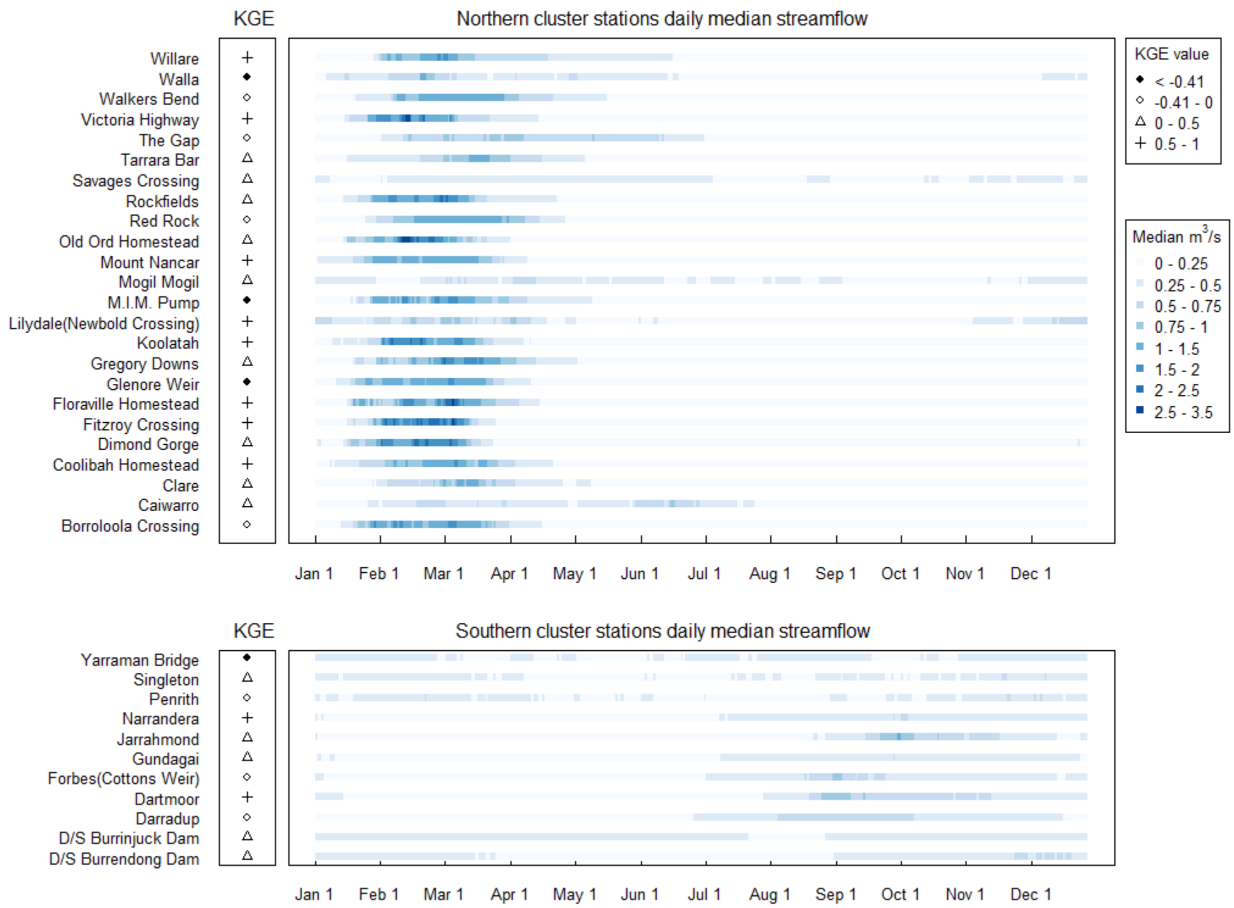
Figure 3.4. Streamflow and rainfall overall and station means.



The median annual streamflow was concentrated early in the year between January and May across streamflow locations in the northern cluster. Stations in the southern cluster displayed the opposite trend, with median streamflow commonly rising in the latter half of the year, though to a reduced extreme compared with the northern cluster stations (figure 3.5).

The accuracy of the modelled data was evaluated using Kling-Gupta Efficiency (KGE) validation values which ranged from -1.97 to 0.84. These KGE values were included in the dataset provided by Alfieri et al. (2020). For the purposes of this analysis, KGE values greater than -0.41 are considered as improving upon mean streamflow (Ayzel et al., 2021; Nickles & Beighley 2021; Knoben, Freer, & Woods, 2019). The KGE values were split into four ranges with less than -0.41 being very low, -0.41 to zero being low, zero to 0.5 being moderate, and good was greater than 0.5. These are represented in the left side column figure 3.5 with the corresponding streamflow station on the right. Ten locations had KGE values greater than 0.5, 14 locations had moderate KGE values, and seven locations had low KGE values. The remaining four locations had very low KGE values (KGE < -0.41).

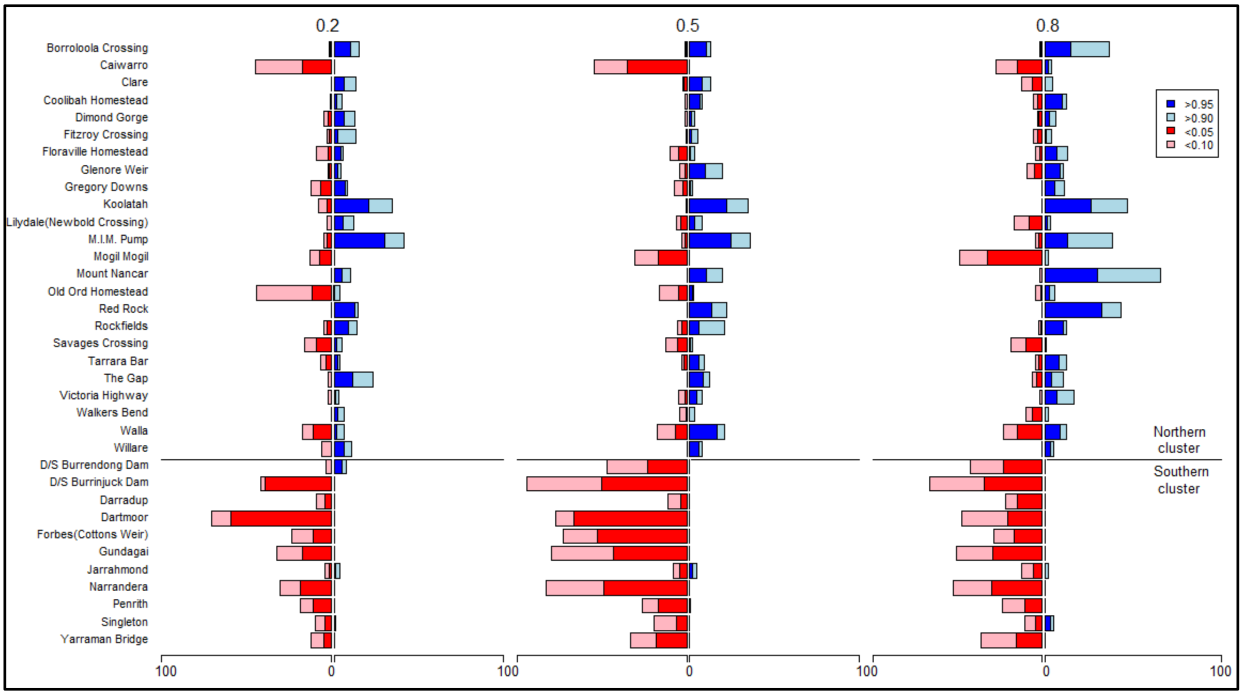
Figure 3.5. Daily median streamflow values by cluster.



Quantile regressions

The percent of days out of the year with significant positive (P > 0.95) or near-significant positive (P > 0.90 & ≤ 0.95) streamflow daily trends and significant negative (P > 0.05) or near-significant negative (P < 0.10 & ≥ 0.05) streamflow daily trends for each station and quantile are presented in figure 3.6. Significant and near-significant negative trend days are represented in red on the left within each quantile, while positive trends are represented on the right in blue. The stations have also been separated into the median cluster grouping, with the 24 northern cluster stations above and separated from the 11 southern cluster stations below by a line. The northern cluster stations display a mix of significant and near-significant positive and negative trends, with positive trends being overall more frequent. In contrast, the southern cluster stations had overwhelmingly significant and near-significant negative trends in daily streamflow with very few stations presenting positive significant or near-significant trends.

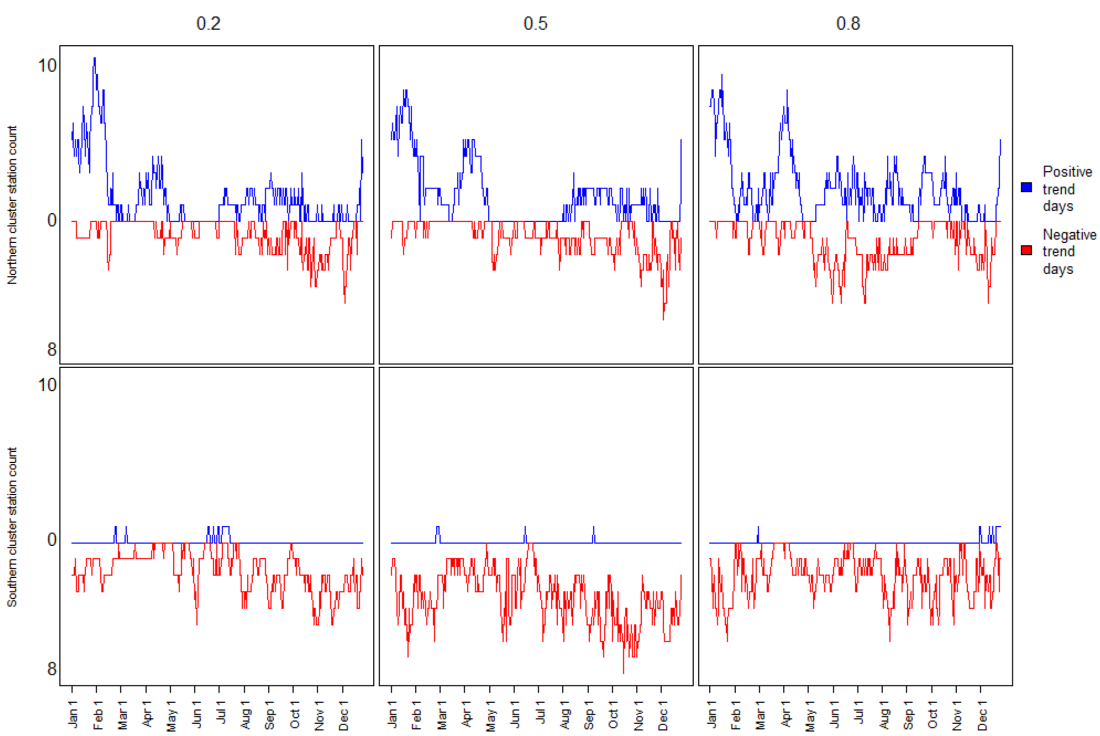
Figure 3.6. Percent of days per year that had significant or near-significant trends for each streamflow station.



The number of stations with significant positive and negative streamflow trend days within each cluster and quantile are represented across the year in figure 3.7. In the northern cluster, significant positive streamflow trends were present throughout the year but most frequent in the early portion of the year across all quantiles with a daily maximum ranging from 8 to 10 stations. Meanwhile, significant negative trends in streamflow were also present throughout the year in the northern cluster, with the greatest frequency in the latter part of the year for quantiles 0.2 and 0.5, and the increased frequency in the middle of the year and end of the year for quantile 0.8. The highest daily frequency of stations with a significant negative trend in the northern cluster was lower than the significant positive trend, with daily stations ranging from five to six.

The southern cluster displayed very different significant daily trend patterns, with most days experiencing zero stations with a significant positive trend. Quantile 0.2 had some days early and in the middle of the year with one station per day having a significant positive streamflow trend; quantile 0.5 had a similar pattern but with greater sparseness, and quantile 0.8 had mostly days at the end of the year with one station per day experiencing a significant positive streamflow trend. The significant negative streamflow trends were far more prevalent than the significant positive trends throughout the year in the southern cluster, both in daily frequency and station frequency. Across the three quantiles, there was lower frequency of stations through approximately March and April, with up to five to eight stations per day recording significant negative streamflow trends throughout the rest of the year, primarily in January through February, and May through November.

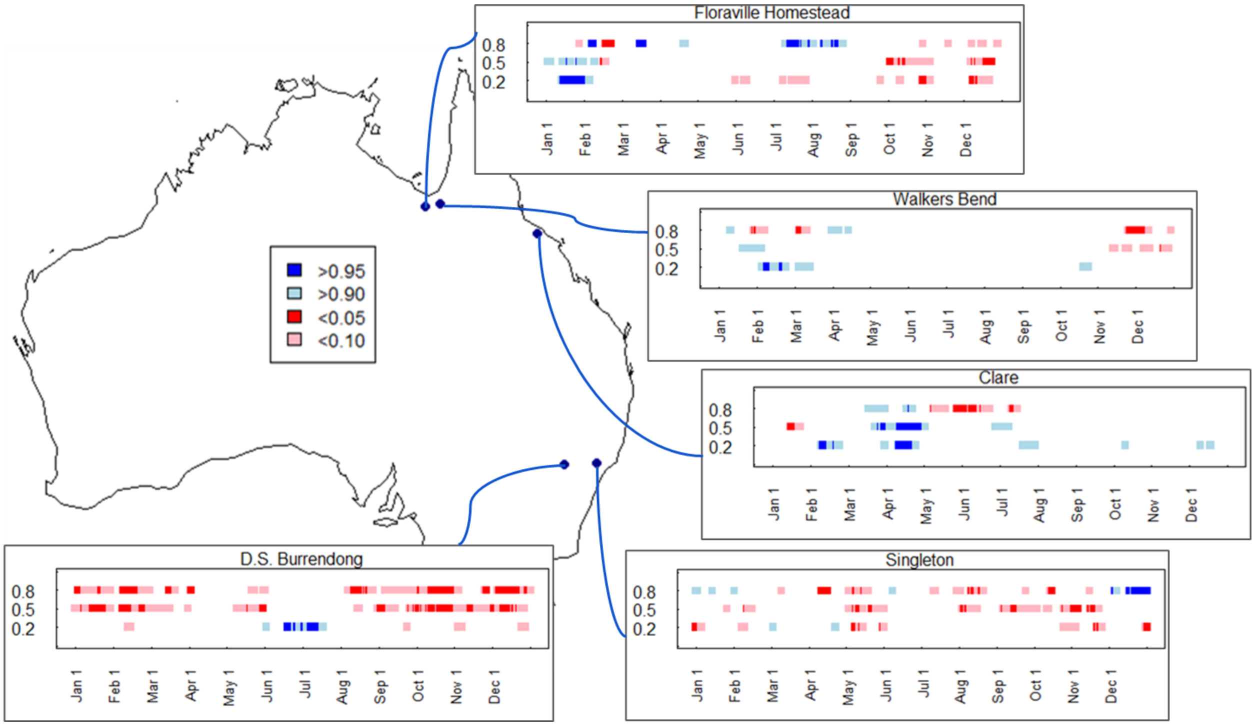
Figure 3.7. Cumulative daily significant positive trend counts and significant negative trend counts by quantile and cluster.



Five stations are shown in figure 3.8 to visualise how significant and near-significant trends can present differently across quantiles within the same station. Floraville Homestead displays overall increasing trends in January and early February followed quickly with decreasing trends and then later in March with increasing trends again. The period in the middle of the year has some indication of decreasing trends at low flow mixed with and followed by increasing trends, while the latter third of the year is dominated by decreasing trends. Walkers Bend has a mix of increasing and decreasing trends through the first quarter of the year, no trend changes present through the middle of the year, and mainly decreasing trends in the latter portion of the year. Clare has decreasing trends in January, followed by increasing trends from February to May, followed quickly by mostly decreasing trends in the middle of the year. Singleton displays almost exclusively decreasing trends throughout the year until December where increasing trends are present. D.S. Burrendong has decreasing trends throughout the year except for the presence of increases in June and July.

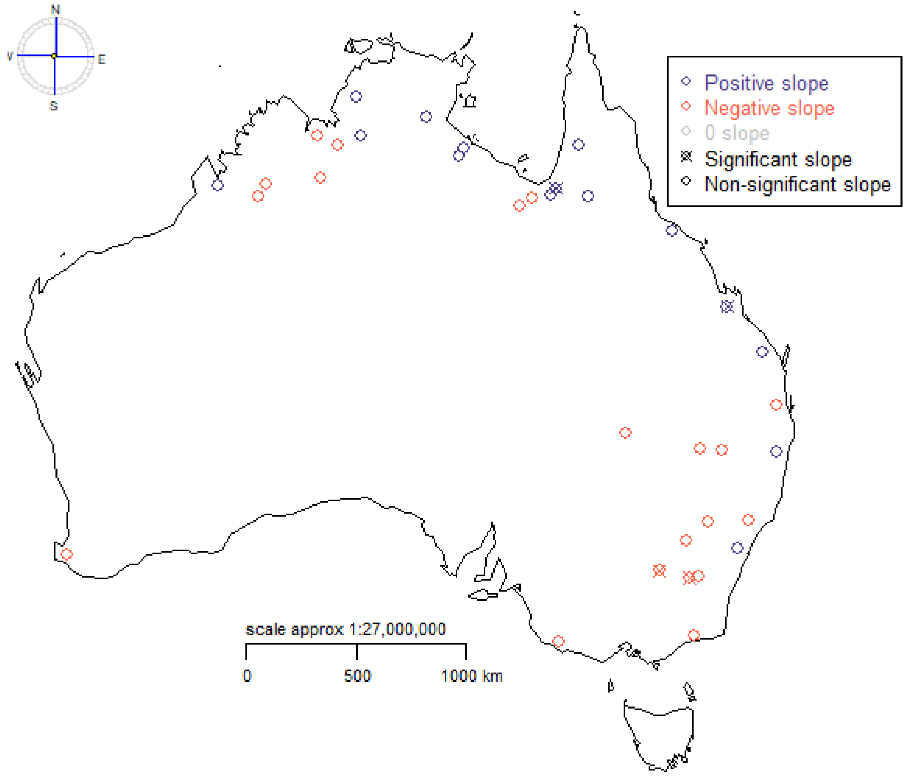
These trend changes across quantiles throughout the year demonstrate the changing behaviour of streamflow across the year. For example, increases in high streamflow trends indicate increased risk of floods while decreasing trends in low flow could restrict the water supply available for human activities and impact biota processes. It bears mentioning that D.S. Burrendong is a dam with the streamflow heavily regulated, so the decreasing trends are likely related to conserving water in the dam while increases at low flow may be related to releasing stored water during drier periods in the middle of the year.

Figure 3.8. Example stations that have low and high flow slope and significance inconsistencies with the median flow slope and significance.



The high streamflow volume trends from the quantile regression of the high flow volume against the number of years are presented in figure 3.9. Two of the streamflow stations had significant positive slopes indicating significant increases in streamflow volume during the 75 day high volume window, while another two stations had significant negative slopes, indicating significant decreases in streamflow volume during the 75 day high volume window. The stations with significant increases were located in the northern cluster while the stations experiencing significant decreases were in the southern cluster.

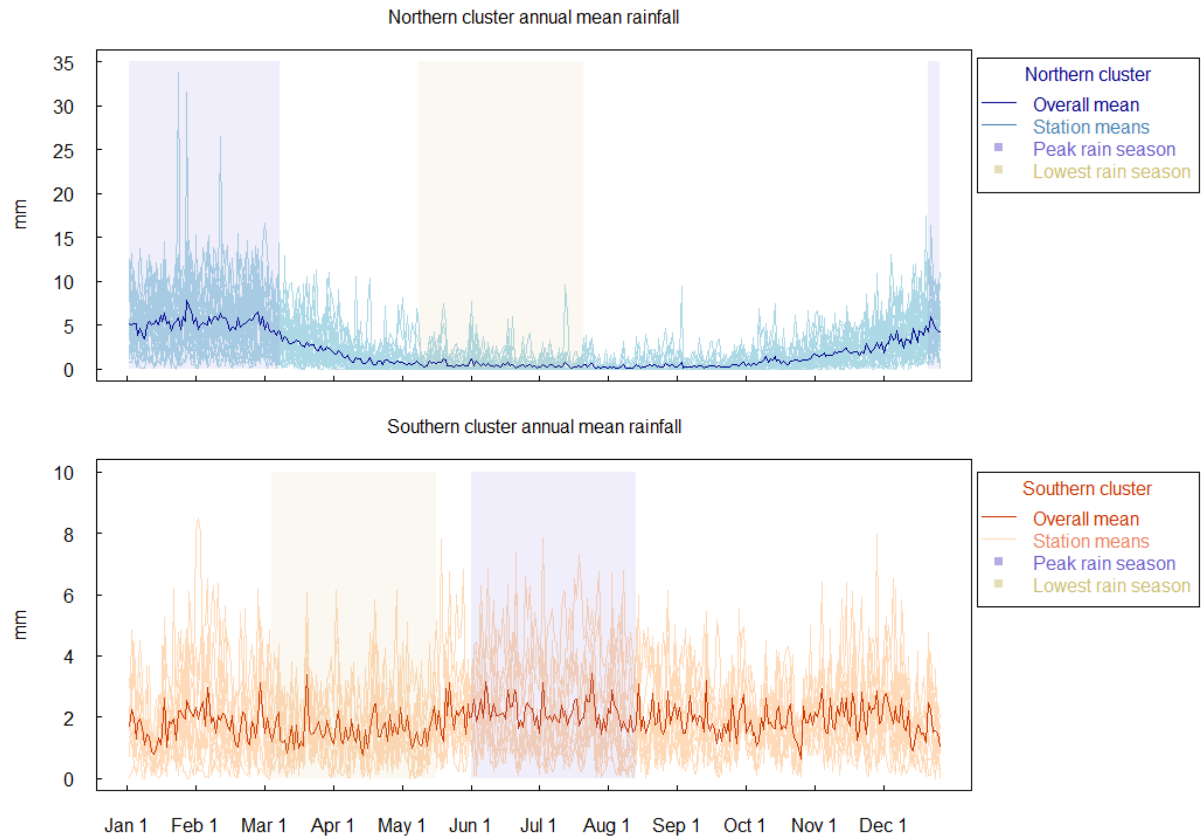
Figure 3.9. High streamflow season volume trends.



Low and high rainfall seasons

The 75 day high rainfall season in the northern cluster ran through 26 December to 10 March, while the southern cluster's 75 days high rainfall season was 4 June through 17 August (figure 3.10). The northern 75 day low rainfall season shortly after the northern high season, being through 11 May to 24 July. In contrast, the low season for the southern cluster, 6 March through 19 May, was found to be directly preceding the high season.

Figure 3.10. Rainfall high season and low season for each cluster.



Poisson regressions

Poisson regression results of substantial rain within the high rain season were grouped by streamflow cluster (table 3.2). Out of the 24 stations in the median northern cluster, seven had significant positive slopes. The rainfall stations with significant positive Poisson regression values were more spread out across the northern and eastern coast, indicating that days of substantial rainfall during the high season have been increasing for some areas. The change in the number of substantial rainy days across the remainder of the northern cluster's stations were non-significant, and there were a number of stations with no change in rainfall trend detected (table 3.2). The trend for the number of rainy days over years decreased for all stations in the southern cluster except for one station (Penrith), and only one station's negative trend was significant (Drik Drik). Low rain season trends across the median southern cluster were more mixed with both positive and negative slopes present, but no significance was detected.

Table 3.2. Rainfall station Poisson regression trends.

Northern cluster					
Streamflow station	Rainfall station	75 day high rain season (dd/mm)	Slope & $P < 0.05$	75 day low rain season (dd/mm)	Slope & $P < 0.05$
Borroloola Crossing	McArthur River Mine Airport	13/1 - 28/3	+***	19/8 - 1/11	-
Caiwarro	Hungerford (Paroo River)	9/1 - 24/3	+	12/6 - 25/8	+
Clare	Clare	28/12 - 12/3	+	17/7 - 29/9	+
Coolibah Homestead	Timber Creek	27/12 - 11/3	+	19/5 - 1/8	-
Dimond Gorge	Fossil Downs	27/12 - 11/3	+	20/5 - 2/8	-
Fitzroy Crossing	Gogo station	20/12 - 4/3	-**	15/4 - 28/6	-
Floraville Homestead	Augustus Downs Station	22/12 - 6/3	-	14/4 - 27/6	+
Glenore Weir	McAllister Station	25/12 - 9/3	-	3/4 - 16/6	+
Gregory Downs	Gregory Downs Outstation	1/1 - 16/3	+	23/3 - 5/6	-
Koolatah	Koolatah Station	12/1 - 27/3	-	23/4 - 6/7	+
Lilydale(Newbold Crossing)	Copmanhurst (Fernglen)	25/12 - 9/3	-	2/7 - 14/9	+
M.I.M. Pump	McArthur River Mine Airport	14/1 - 29/3	+	11/6 - 24/8	+
Mogil Mogil	Mogil Mogil (Benimora)	16/11 - 29/1	-	29/7 - 11/10	+
Mount Nancar	Beatrice Hill NT	3/1 - 18/3	-***	2/5 - 15/7	+
Old Ord Homestead	Springvale	23/12 - 7/3	-	31/3 - 13/6	-

Table 3.2 Continued.

Red Rock	Ngukurr Airport	19/12 - 3/3	+**	18/7 - 30/9	+
Rockfields	Inorunie Station	28/12 - 12/3	-	1/4 - 14/6	-
Savages Crossing	Lowood Don St	8/12 - 20/2	+***	17/6 - 30/8	-
Tarrara Bar	Carlton Hill	30/12 - 14/3	+	18/4 - 1/7	-
The Gap	The Gap TM	24/12 - 8/3	+***	12/6 - 25/8	-
Victoria Highway	Auvergne	22/12 - 6/3	-*	22/4 - 5/7	-
Walkers Bend	McAllister Station	25/12 - 9/3	-	3/4 - 16/6	+
Walla	Walla TM	1/12 - 13/2	+	25/5 - 7/8	-
Willare	Yeeda	15/12 - 27/2	+	17/4 - 30/6	-

Southern cluster

Streamflow station	Rainfall station	75 day high rain season (dd/mm)	Slope & P < 0.05	75 day low rain season (dd/mm)	Slope & P < 0.05
D/S Burrendong Dam	Lake Burrendong	4/11 - 17/1	-	6/3 - 19/5	+
D/S Burrinjuck Dam	Burrinjuck Dam	18/4 - 31/8	-	8/2 - 23/4	+
Darradup	Nannup	25/3 - 7/8	-	14/12 - 26/2	+
Dartmoor	Drik Drik	4/4 - 178	-*	19/12 - 3/3	-
Forbes(Cottons Weir)	Forbes (Muddy Water)	18/3 - 31/7	-	25/3 - 7/6	-
Gundagai	Gundagai (Nangus Rd)	25/5 - 7/10	-	12/3 - 25/5	-

Table 3.2. Continued.

Jarrahmond	Bete Bolong (Russells Estate)	2/8 - 15/12	-	12/3 - 27/3	-
Narrandera	Narrandera Airport AWS	5/5 - 17/9	-	10/2 - 25/4	+
Penrith	Orchard Hills Treatment Works	23/1 - 7/4	+	23/6 - 5/9	+
Singleton	Elderslie	26/10 - 10/3	-	14/6 - 27/8	+
Yarraman Bridge	Moree Aero	5/10 - 17/2	-	17/7 - 29/9	+

Discussion

Spatial patterns of streamflow variability were delineated robustly by examining coherent scales of variability across three representative quantiles of streamflow resolved to daily time scales. The identified groups of streamflows belonging to the two clusters show similar variability and thus represent regional scales appropriate for analyses of human-environmental system linkages, future changes induced by climate change, and scales over which may be drivers of hydrologic variability, for example, monsoonal weather may evolve and affect regional resources.

The northern and southern regions exhibit markedly different streamflow and rainfall behavior. The northern group demonstrated strong seasonality with high rainfall and streamflow November through May followed by much reduced rainfall and streamflow in the later months. The streamflow trends were mixed increases and decreases but increases were more frequent early in the year across the low, median, and high flows. In comparison, the southern region experienced a slight increase in rainfall and streamflow in the middle to later portion of the year; however, streamflow trends were almost exclusively negative with greatest frequency in the early and later months of the year.

Northern cluster seasonal variation implications

Communities develop in tandem with their environment, particularly around their water sources which are so vital for health and life. Excesses or shortages in water can be devastating to human health, life, and infrastructure. The northern streamflow stations demonstrate a strong seasonality with a dramatic spike in streamflow volume followed by much decreased volume; however, communities in these northern regions are not devastated by the considerable changes in streamflow volume and associated meteorological events. Rather, their lives are adapted to these seasons. This is particularly evident among Indigenous Peoples within the northern region and across Australia whose relationships with country have produced detailed knowledge of local seasonal activity which some Indigenous nations have made available in seasonal calendars (Green, Billy, & Tapim, 2010; Prober et al., 2011; Woodward & McTaggart, 2019). Many of these Indigenous seasonal calendars have observations for the timing, duration, and severity of hydroclimatic events. Recent climate variability and change is driving an increase in variations from what has historically been consistent seasonal cycles within an expected range of variation; however, the seasonal calendars, through respectful and equitable collaboration with Indigenous knowledge holders, can assist in identifying and anticipating variation in hydroclimate events at local scales. These fine scale observations of estimated hydroclimate deviations can be further quantified through the analysis methods used in this study.

Southern cluster water deficits implications

The much reduced scale of seasonality in the southern cluster has meant that communities in these regions have had less experience with regular water excesses and shortages, resulting in a historically reduced need for communities to develop adaptation strategies to such extremes. This prior lack of need to manage water deficits could result in greater vulnerability to increased occurrences of such events which is of particular concern since the significant negative streamflow trends across the southern cluster indicate reduced water availability throughout the year. Adaptation strategies used in the northern cluster locales may be applicable to locations in the southern cluster for improving resiliency to the increasing water uncertainty coinciding with climate change.

Alternatively, knowledge of how to live and manage resources sustainably are likely already present among the Indigenous Peoples in the region of the southern cluster through their greater holistic knowledge of their local region (Woodward, 2013; Woodward and McTaggart, 2019; Yang et al., 2019). Knowledge available within Indigenous seasonal calendars is indicative of rich and detailed knowledge of signs of dryer periods and management methods to reduce the severity of these periods (McKemey et al., 2020). There is great opportunity for collaboration efforts prioritising respect and equitable outcomes through relationship building between Indigenous Peoples and colonial benefactors. Such collaboration could result in real changes to resource management, policies, and attitudes towards relationships with country which could enhance adaptation methods for climate driven declining water trends in the southern cluster.

Conclusion

Streamflow and rainfall trends are changing across Australia in accordance with the hydro-meteorological response to climate change. Clustering and quantile regression methods delineated locations into groups of streamflow seasonality and demonstrated how seasonal trends are changing at each location and within clusters, while Poisson regressions identified changes in substantial rainfall during low and high rainfall seasons. The increases and decreases in rainfall and streamflow trends are representative of advancing hydrological uncertainty in the region. These uncertainties can culminate in floods and droughts with devastating immediate and long term effects on communities and regions. The analyses presented in this study sought to present quantitative estimates of long-term changes in streamflow along the timeframe of the seasonal calendar. Indigenous knowledge of the expected range in variations in local seasonal hydroclimate events can enable them to estimate unusual variations in hydroclimate at fine scales which can be further quantified using the methods in this study. Collaboration with community members from regions that have historically extensive experiences of similar seasonality presentations to the current and future seasonality trends of other regions may be able to offer insight into resiliency methods.

CHAPTER 4

AUSTRALIAN BUSHFIRE SEASON FROM INDIGENOUS SEASONAL CALENDARS AND ASSOCIATED DROUGHT TRENDS

Abstract

Climate change is driving changes in rainfall and temperature across Australia which is increasing drought and bushfire risk, each of which have detrimental impacts on water quality. The Southern Ocean Index and Indian Ocean Dipole influence drought and bushfire conditions through changes in rainfall occurrence and temperature. Climate, environment, and biota patterns have been recorded by Indigenous Peoples across Australia in seasonal calendars. The approximate timing of bushfires has been included in five seasonal calendars, and this was used to determine a bushfire season (October to March) which was used for examination of Standardized Precipitation Evapotranspiration Index, Southern Oscillation Index, and Indian Ocean Dipole historical data from 1950 to 2021. Analysis of data included Principal Component Analysis of the SPEI data and correlations between the PCA results and SOI and IOD data which found moderate positive associations between the four eastern locations and SOI. SPEI trends indicate decreasing trends in water excesses and increasing trends in water deficits across the four eastern regions and increasing trends in water excesses and decreasing trends in water deficits in the western location. These results indicate increased water stress is being experienced across the eastern locations during the bushfire season while the western location is experiencing a change in rainfall seasonality.

Introduction

Water security across Australia is being impacted by climate change, with increased severity of droughts and heavy rainfall events (Steffen et al., 2018). A warmer atmosphere holds more water vapour enabling the development of increasing heavy rainfall and flooding events. However, the intensification of the subtropical ridge acts to limit the movement of tropical water vapour laden air towards the more southern regions of Australia. Declining rainfall trends are leading to drier conditions, particularly during the cool seasons in Southeast and Southwest Australia (Keywood et al., 2016; O'Donnell et al., 2021). These drying trends facilitate and exacerbate drought conditions with reduced streamflow from the associated reduced rainfall (Steffen et al., 2018). Droughts are anticipated to become more severe through increases in drought intensity and duration, particularly in the southern and eastern regions of Australia (Kirono et al., 2020). The hotter conditions cause declines in plant and soil moisture, resulting in drier conditions (Steffen et al., 2018).

Extended and amplified hot and dry conditions contribute to bushfire risk (Climate Council of Australia, 2019), and in turn bushfires pose risks to water quality, especially when drought and bushfires are increasingly followed by heavy rainfall (King et al., 2020; Steffen et al., 2018). The loss of vegetation from bushfires reduces soil permeability (Ruthrof et al., 2019), rainfall runoff, and soil erosion, all of which increases the risk of flash flood events and facilitates the mass movement of ash into water bodies (Kumar et al., 2020; Steffen et al., 2018). Sudden and large influxes of nutrient rich ash into water sources increases the risk of contamination of pathogens and algae which can drastically reduce water quality and pose health hazards (Steffen et al., 2018).

Drought and bushfire risk across Australia is associated with climate events related to sea surface temperature (SST) which is driven by global ocean-atmospheric circulation patterns. Two indexes related to SST that function as approximate indicators of global and regional climate variations are the Southern Oscillation Index (SOI) and Indian Ocean Dipole index (IOD). These indexes perform as a measure of impact of climate cycles on precipitation and temperature across large regions of Australia. El Niño (a period of SOI with negative values) and positive IOD events reduce rainfall and increase temperatures, contributing to drought and bushfire conditions across Australia, particularly in the southeast (Cai, Cowan, & Raupach, 2009; Wang & Cai, 2020). Standardized Precipitation Evapotranspiration Index (SPEI) is a recognised method for monitoring drought conditions across a large scales, using temperature, precipitation, and potential evapotranspiration to evaluate moisture content and therefore drought conditions in a region (Vicente-Serrano et al., 2015).

Indigenous Peoples have been living across Australia for thousands of years, during which they have adapted to periodic drought conditions and developed water management strategies (Jackson 2008). Relationships with country and caring for its overall health are driving aspects of their interactions with environments and ecosystems, resulting in comprehensive holistic knowledges. This includes use of fire to manage and develop landscapes for maintenance of food and biodiversity (Vigilante, Murphy, & Bowman, 2009). Colonisation has drastically impeded Indigenous knowledge processes and practices, reducing the transmission of knowledge processes and ability to action their knowledge (Grewcock, 2018). Efforts to improve the maintenance and transmission of Indigenous knowledge processes have included the development of Indigenous seasonal calendars which detail interlinkages of season-related climate, biota, and environmental knowledge to varying degrees (Bureau of Meteorology

(BOM), 2016; CSIRO, 2021; Woodward et al., 2020). These calendars provide a glimpse into the relationship Indigenous Peoples share with country, including fire management timing and techniques and the timing of hazardous bushfires (McKemey and Banbai Rangers, 2020; McKemey et al., 2020; McKemey et al., 2022). Indigenous use of fire to manage landscapes relies on slow moving low intensity fires to reduce hazards, promote regrowth, and allow animals and insects to escape. This practice prevents the destruction of seeds, ground-level habitats, and can improve soil ability to absorb moisture (Korff, 2022).

The detailed environmental information contained within Indigenous seasonal calendars often includes hydrological conditions. This may enable the calendars to be used as approximators for periods of increased drought risk and facilitate pathways towards improving drought prediction and management.

Positionality statement

This research draws on information contained in Australian Indigenous seasonal calendars. The author acknowledges that they are a non-Indigenous Australian and do not intend to violate the intellectual property rights or make assumptions of or for the Indigenous authors of the seasonal calendars or the nations they represent. Therefore, only publicly available information is used and this information is reduced to summary level across the calendars to prevent re-representation or appropriation of the information. Best practice guidelines of collaboration and co-design (David-Chavez and Gavin, 2018; Woodward et al., 2020) have not been met in the production of this research due to time, distance, and financial constraints.

Methods

Data and region

Indigenous seasonal calendars

Holistic knowledge of patterns in weather, environment, biota, and other events, including bushfires, is available in Indigenous seasonal calendars. Public access to seasonal calendars has been granted by 25 nations across Australia (BOM, 2016; CSIRO, 2021). Each seasonal calendar is a snapshot of the rich ecological knowledge of the associated region. The diversity and level of detail in the information provided across the seasonal calendars is not uniform, in that some seasonal calendars may provide extensive details on plant or animal phenology, or may provide little information beyond meteorological observations. The majority of the seasonal calendars are located across the north of Australia.

SPEI drought index

An index of monthly drought conditions through 1951-2021 at one degree spatial resolution for each of the Indigenous seasonal calendar approximate centre regions were gathered from the SPEI Global Drought Monitor database (Beguería et al., 2022; Vicente-Serrano et al., 2015). The index uses the Thornthwaite equation for estimating potential evapotranspiration through mean temperature and monthly precipitation (Vicente-Serrano, Beguería, & López-Moreno, 2010). Positive SPEI values indicate water surpluses while negative values indicate water deficits. SPEI data cells were chosen based on the latitude and longitude of the approximate central region of each of the five Indigenous seasonal calendars with bushfire mentions (figure 4.1). The SPEI data from these cells was limited to the range of months identified as the bushfire season from the Indigenous seasonal calendars.

SOI index

Rainfall across Australia is linked with El Niño and La Niña events, with rainfall reductions associated with El Niño, and rainfall increases associated with La Niña. The Southern Oscillation Index (SOI) is an indicator of the presence and strength of El Niño (negative values) and La Niña (positive values). Droughts are more common during El Niño events, making the SOI index a good comparator for SPEI. Monthly SOI data was downloaded from the Australian Bureau of Meteorology (BOM, 2022c). The SOI data was restricted to the same time range as the SPEI data (1951-2021) and the months of data were also restricted to the bushfire season range identified by the Indigenous seasonal calendars.

IOD index

The Indian Ocean off the western coast of Australia goes through opposing patterns of warming and cooling in its eastern and western regions known as the Indian Ocean Dipole (IOD). These temperature differences between the east and west of the ocean influence climate across the Australian continent. A positive IOD is associated with reduced rainfall and higher temperatures, usually during the Australian winter and spring, while a negative IOD typically increases rainfall during the winter and spring period (BOM, 2022b). Monthly Dipole Mode Index data for the IOD was available from 1951 through 2021 (National Oceanic and Atmospheric Administration (NOAA), 2022).

SST

Sea surface temperature is a more direct measure of SOI and IOD, since SOI and IOD are indexes of ocean temperature differences. The differences in SST temperatures at one region of an ocean compared to another is indicative of thermocline cycles within the ocean downwelling warmed surface water and upwelling colder deep waters. The atmosphere above these regional differences in SST within an ocean then responds with increased or decreased heat for convection which then translates into increased or decreased rainfall. The SST data was provided by NOAA and was subject to the same year and month restrictions as the SPEI data; 1951 through 2021, and the bushfire season of October through March (Kalnay et al., 1996).

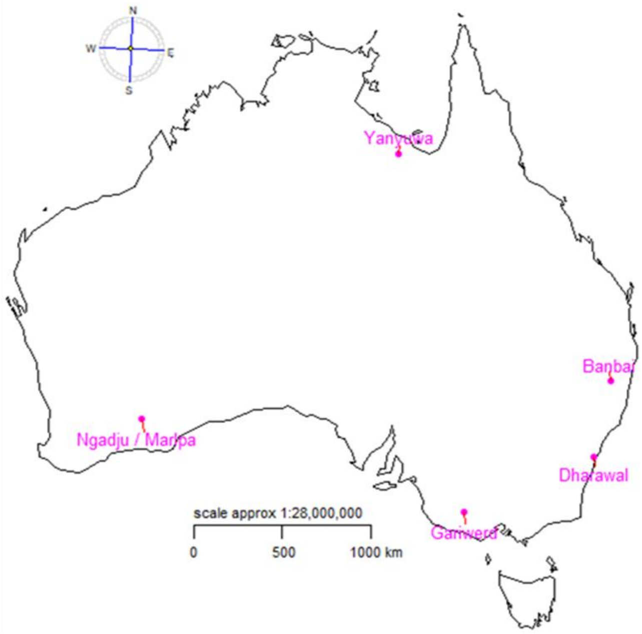
Analyses

Indigenous seasonal calendars allowed identification of an approximate bushfire season across five locations, while principal component analysis of SPEI data at the five locations provided insight into differences and similarities between the locations. Correlations between the SPEI principal components and SOI, IOD, and SST were used to reveal associations between drought values at the five locations and greater global circulation pattern trends.

Indigenous seasonal calendars

Approximate monthly presence of bushfires was gauged across 25 publicly accessible Indigenous seasonal calendars (BOM, 2016n; CSIRO, 2021). Each calendar was examined for explicit mentions of bushfires. The definition of bushfires was restricted to fires that were uncontrolled hazards and not intentionally lit or controlled fires used for cultural, preventative, and restorative purposes, such as managed grassland and wetland burning. This limitation resulted in bushfires being identified in five Indigenous seasonal calendars (BOM, 2016b; BOM, 2016d; BOM, 2016k; McKemey et al., 2022; O'Connor and Prober, 2010), shown in figure 4.1. The small sample of calendars referencing bushfires is not representative of bushfire presence across Australia or Indigenous knowledge of bushfires. The authors of each seasonal calendar tailored the information in the calendars to what was relevant to their nation and culturally appropriate to share in a public document, so the inclusion of bushfire information was up to their discretion. The approximate months associated with bushfires within the five calendars was then used to identify the bushfire season.

Figure 4.1. Map of approximate centre of seasonal calendar region used for SPEI cell data.



Indigenous seasonal calendar	SPEI coordinates for approximate centres of Indigenous seasonal calendar region	
	Latitude	Longitude
Banbai	-30.25	151.75
D'harawal	-34.25	150.75
Gariwerd	-37.25	142.25
Ngadju / Marlpa	-32.25	121.75
Yanyuwa	-17.75	138.25

SPEI drought index

Principal Component Analysis (PCA) was used on the SPEI drought index data to identify the presence of groups in the data that were not obvious pre-analysis. It reduced the years of data into principal components that are representative of aspects across those years of data, such as climatic patterns. Changes in patterns for the bushfire season was assessed through the trend in unusually wet and unusually dry years.

The annual mean SPEI values for the bushfire season of each location was found and the correlations between locations examined. A Principal Component Analysis was then applied to the annual mean bushfire season SPEI values and locally weighted scatterplot smoothing was used on the first two components to reduce interannual variability below 10 years and examined over time.

The mean upper 0.75 and lower 0.25 quartiles for the SPEI means of the five locations from 1980 to 2021 were used to determine the wet (upper) and dry (lower) thresholds. The 30-year rolling mean SPEI values for October to March for each year were then evaluated for being above the upper threshold, and therefore unusually wet, or below the threshold, and therefore unusually dry for each location. This resulted in a count of the number of unusually wet and unusually dry years which was then plotted to demonstrate the range change for the drought index for the bushfire season.

SOI index

SOI variability is anticipated to increase as climate change progresses (Power & Kociubo, 2011). The association between SOI and rainfall suggests that rainfall patterns will be impacted by the SOI response to climate change. Long-term changes in SOI were assessed because of the association between SOI and rainfall intensity patterns.

Annual mean for the bushfire season was calculated for SOI and assessed for correlation with SPEI PC1 and PC2. Long-term changes in SOI were analysed using the mean values over time with locally weighted scatterplot smoothing used again to reduce interannual variability below 10 years. The 30-year rolling standard deviation from 1980 to 2021 was also found.

IOD index

The IOD is a major climate driver in Australia and as such was assessed for relevance to the principal component most associated with the western SPEI data location. Monthly IOD index data was restricted to 1951 through 2021 and split into the bushfire season (October through March) and the non-bushfire season (April through September). Each season was averaged and assessed for correlation with the SPEI PCA components.

SST

Sea surface temperature correlations with the two primary components from the principal analysis were assessed to further assess the impact of climatic features on the drought index. The x values for PC1 and PC2 were uploaded to the NOAA via FTP as custom time series to enable correlation with their SST data. The maps were colour coded to indicate degree of correlation.

Results

Indigenous seasonal calendars

Bushfires were associated across the approximate months of October through to March within the five Indigenous seasonal calendars, as shown in table 4.1. The bushfire season increases in seasonal calendar presence from October until it reaches the maximum number of calendars in January and February, and then declines by one seasonal calendar in March.

Table 4.1. Presence of bushfires across approximate months.

	Approximate months											
	J	F	M	A	M	J	J	A	S	O	N	D
Indigenous seasonal calendars with bushfire mentions	5	5	4							1	3	3

SPEI drought index

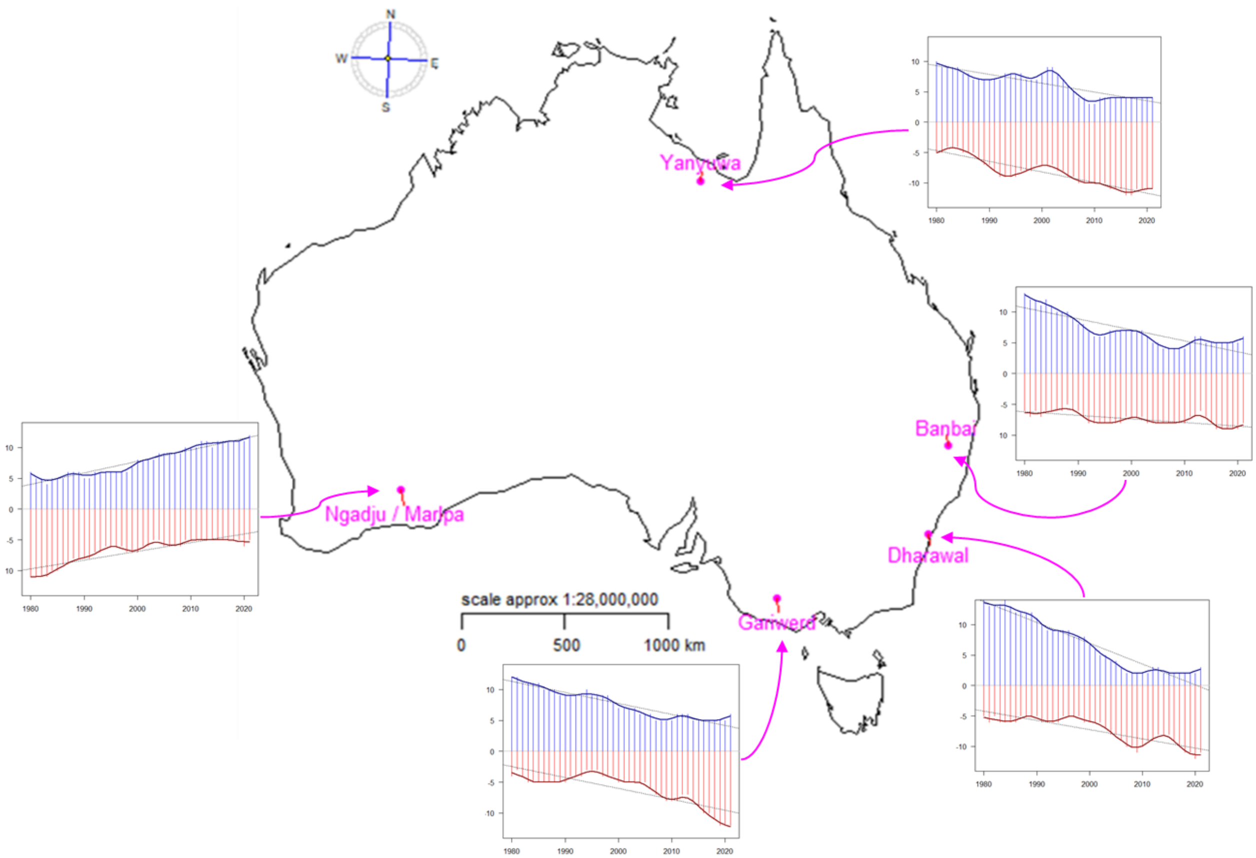
Annual mean SPEI correlation was highest between Banbai and D'harawal (0.74), followed by Banbai and Yanyuwa (0.51) (table 4.2). Banbai and D'harawal are both located on the southeastern coast and are the closest together out of all the stations so they may be subject to the similar degrees of climate influence, resulting in the high correlation. Ngadju has the lowest correlations, likely due to being the furthest from the other locations. Climate events arriving from east to west across the continent, such as the IOD, may have greater influence on Ngadju than on the more eastern locations.

Table 4.2. Correlation table for annual mean SPEI bushfire season.

	Banbai	Gariwerd	Ngadju	D’harawal	Yanyuwa
Banbai	1	0.28	0.15	0.74	0.51
Gariwerd		1	0.12	0.32	0.31
Ngadju			1	0.13	0.06
D’harawal				1	0.32
Yanyuwa					1

The count of the SPEI rolling 30-year mean above the upper threshold of 0.29 and below the lower threshold of -0.33 through 1980 to 2021 found mostly decreasing trends in unusually wet years and increases in unusually dry years (figure 4.2). The exception to this was Ngadju, with the opposite occurring with clear increases in unusually wet years and decreases in unusually dry years. Banbai has the least increasing dry trend; however, the decreasing wet trend may indicate concern for water deficiencies. The other four eastern locations have more pronounced decreasing wet trends indicating reduced water surpluses, combined with increasing dry trends.

Figure 4.2. SPEI 30-year mean bushfire season trends for wet and dry years.



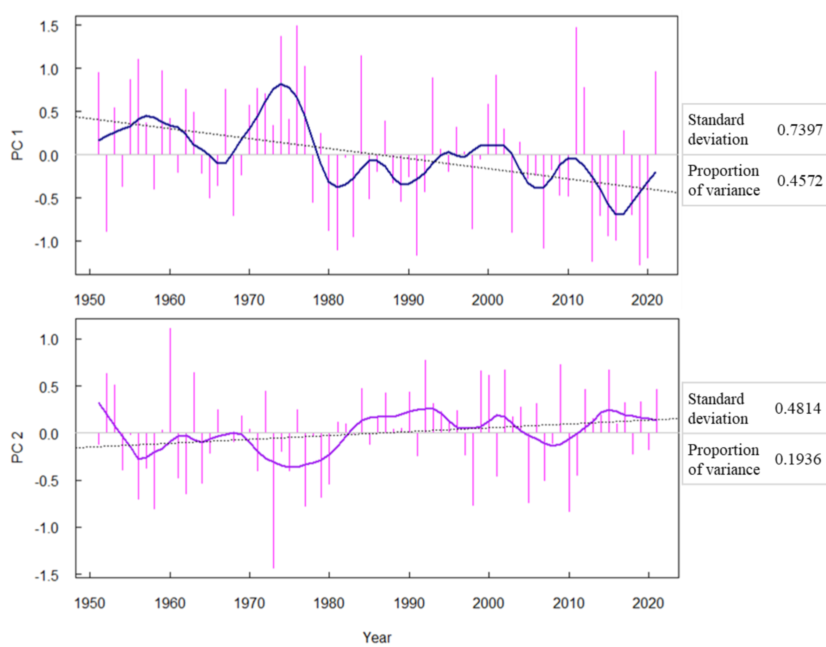
The first principal component of the PCA on the SPEI drought index data accounts for 45.72% of variance and has negative associations with all five of the locations (table 4.3), with Ngadju having the lowest strength association. The consistent sign indicates that PC1 primarily measures one factor influencing the SPEI data across the locations. The second component accounts for 19.36% of variance (figure 4.3) and has a strong negative association with Ngadju, indicating a different factor to PC1 has a large influence on the SPEI values at this location.

Table 4.3. Loadings related to the SPEI Principal components

	PC1	PC2	PC3	PC4	PC5
Banbai	0.5184	-0.0282	0.4022	0.0912	-0.7486
Gariwerd	0.3965	0.0973	-0.7791	0.4670	-0.0908
Ngadju	0.1649	0.9294	-0.0012	-0.3280	0.0386
D’harawal	0.4916	0.0364	0.4350	0.4222	0.6242
Yanyuwa	0.2252	-0.3531	-0.2050	-0.6984	0.2007

The trend for PC1 across 1951-2021 is overall negative with variance increasing slightly over time ($P < 0.01$). In comparison, PC2 has a slightly positive trend and lower variance ($P > 0.05$) (figure 4.3).

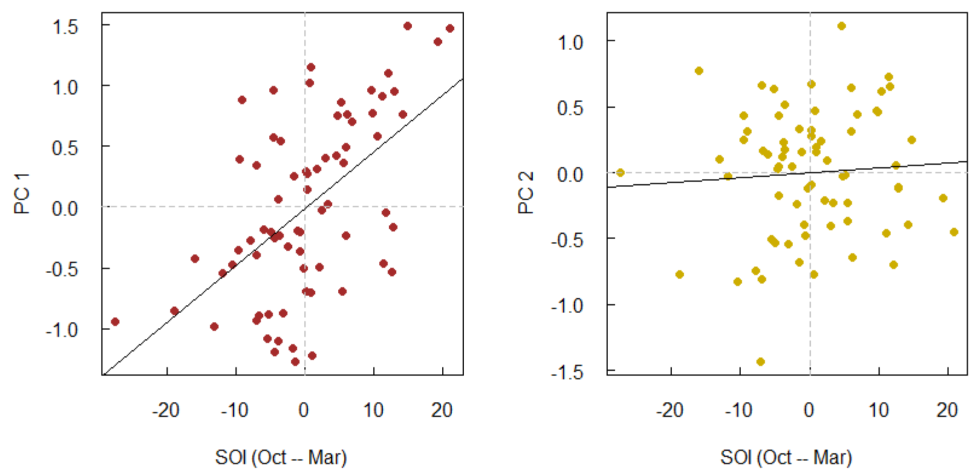
Figure 4.3. The time variation in the SPEI PC1 and PC2 for the approximate austral spring and summer seasons (October – March) over the 1951-2021 period. Long-term variability is assessed based on locally-linear smoother with a 11-year window (shown in dark blue and purple). Linear trend of the period is shown by the dashed line.



SOI index

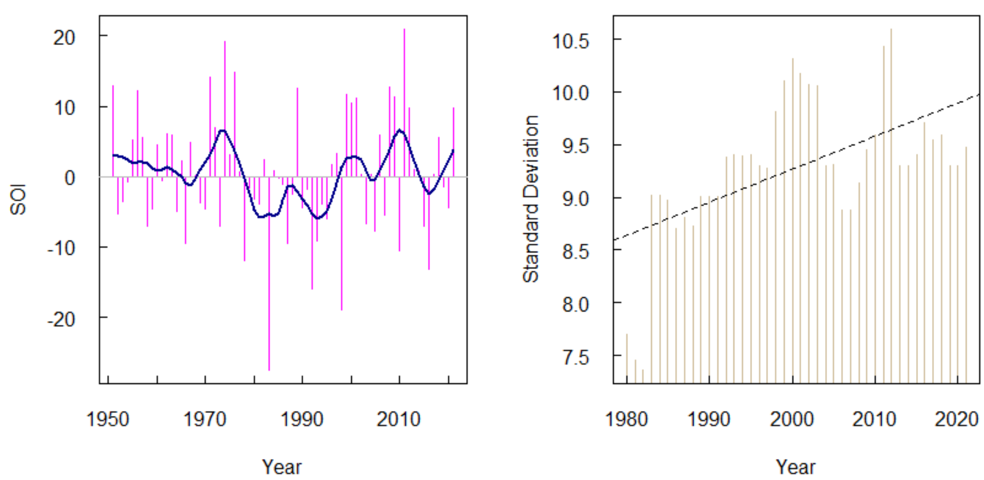
Correlations between annual mean SOI and SPEI PC1 were positive and moderate (0.56), while correlations with PC2 were positive but very weak (0.07), indicating that SOI was somewhat represented by PC1 (figure 4.4).

Figure 4.4. Correlation scatterplots for annual mean SOI and each PC1 and PC2.



The annual SOI mean values are shown to be increasing in strength over time while the rolling 30-year standard deviation is increasing. These represent increasing variation in SOI, that is, increasing intensity in El Niño and La Niña events (figure 4.5).

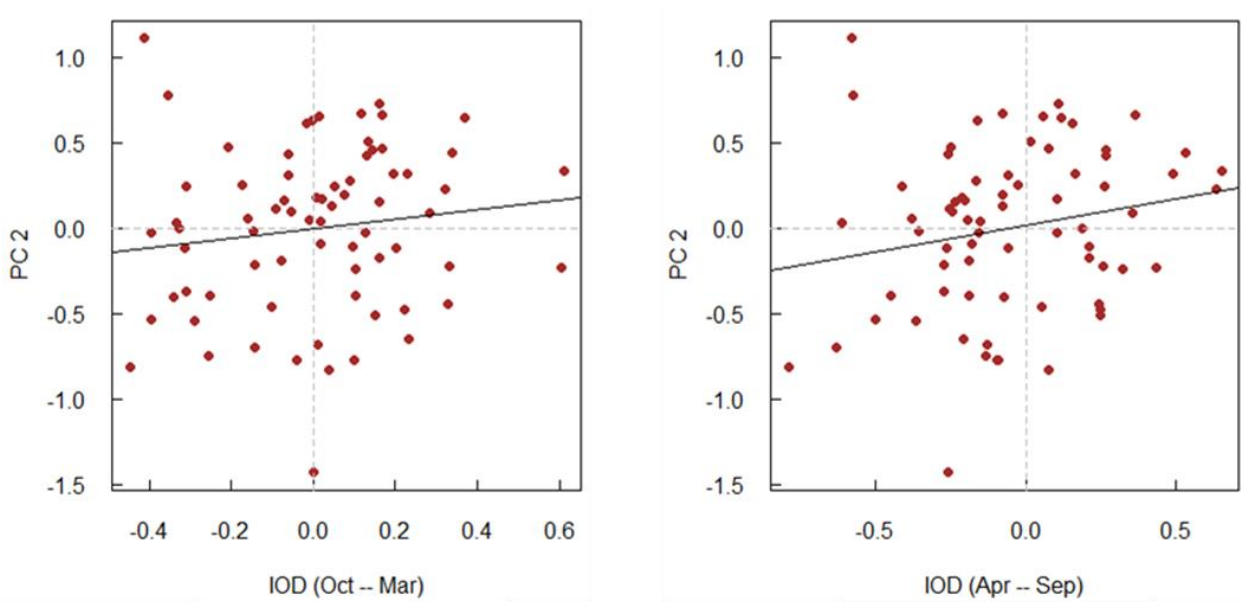
Figure 4.5. Annual mean SOI and rolling 30-year standard deviation across years.



IOD index

Ngadju having a very low strength association with PC1 but a very strong association with PC2 indicates that a climate driver that is of greater intensity on the western coast (such as IOD) may be represented in PC2. This was assessed through correlations between the annual mean IOD bushfire season (October to March) and PC2 and the annual mean non-bushfire season (April to September) and PC2 (figure 4.6). The bushfire season had a weak positive correlation (0.13) with PC2 and the non-bushfire season had a slightly stronger positive correlation (0.2).

Figure 4.6. IOD bushfire and non-bushfire season correlation with PC2.



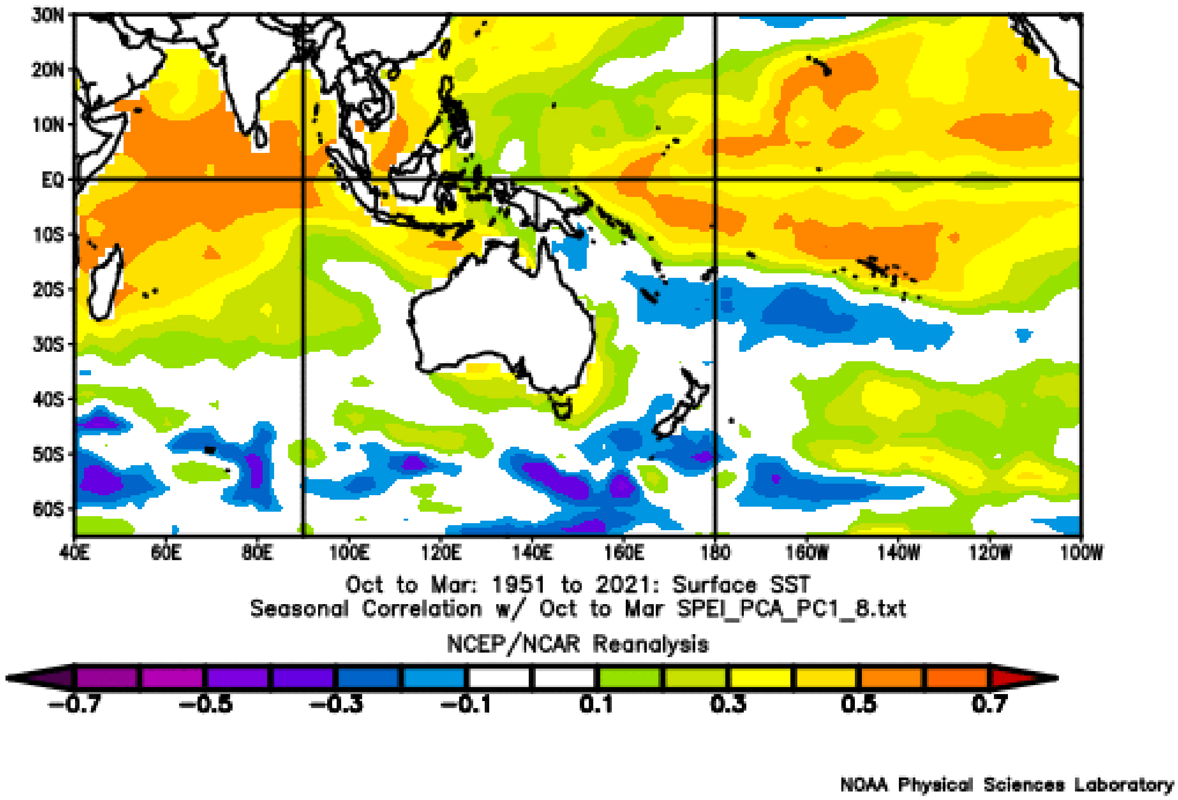
Bushfire season	PC2
Correlation	0.13

Non-bushfire season	PC2
Correlation	0.2

Sea surface temperature

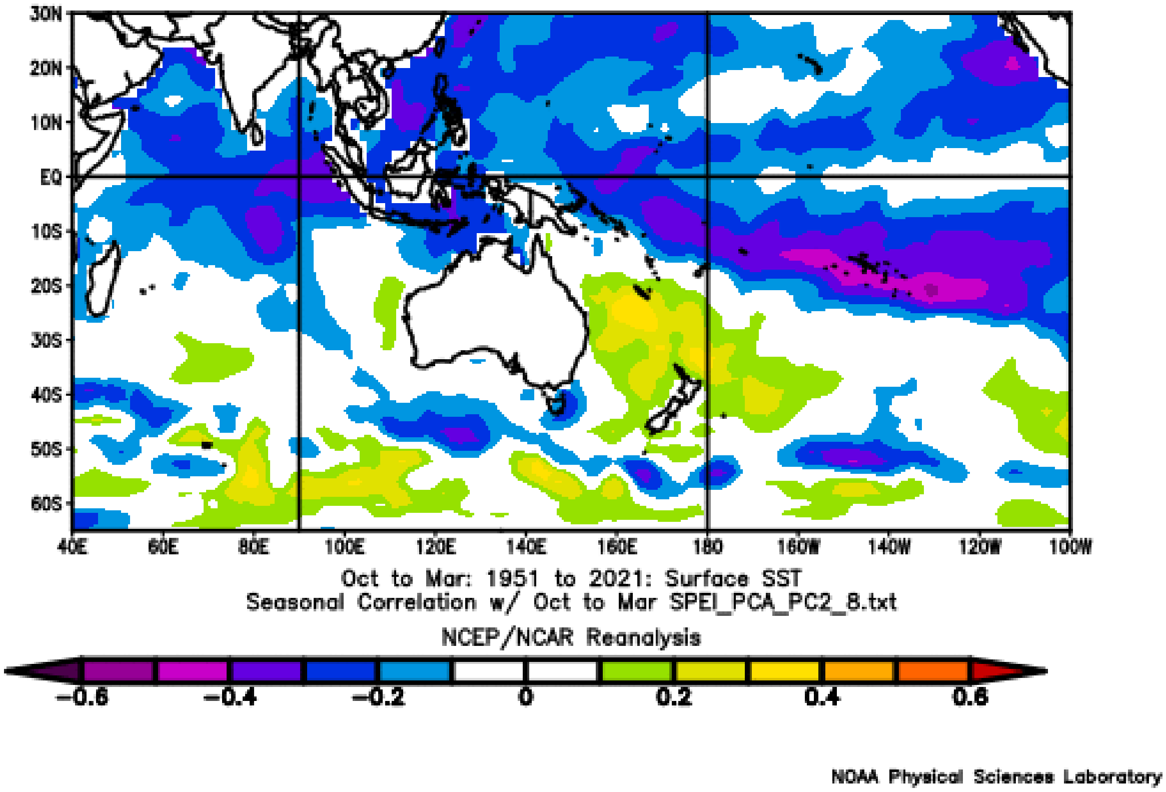
Correlations between SST and PC1 are visualised in figure 4.7, with positive correlations of 0.1 to 0.5 hugging the northern, southeastern, and southern coasts of Australia. Stronger positive correlations up to 0.7 were also visible in the northwest region of ocean on the map, with negative correlations from -0.1 to -0.5 extending off the east coast of Australia and scattered in the south with weak positive correlations below the continent. The results indicate that as SST increases in the northeast of the map (between Papua New Guinea and Tahiti), PC1 values also increase, which is supportive of increasing temperatures in this region causing El Niño conditions and associated reduced rainfall in Australia, supporting the 30-year mean SPEI trends.

Figure 4.7. Map of correlations between SPEI PC1 and sea surface temperature for the October-March season for the 1951 - 2021 period. (Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/)



Similarly to above, correlations between SST and PC2 values are demonstrated in figure 4.8. This map displays negative correlations of -0.1 to -0.6 across the mid to northern regions and scattered through the southern region. Positive correlations of 0.1 to 0.4 were visible also in the southern region, in a small region off the mid western coast of Australia, off the eastern tip of far north Queensland, and off the east coast of Australia. The pattern of correlations across the Indian ocean suggest a negative IOD phase which matches with the SPEI 30-year mean trend for the western location.

Figure 4.8. Map of correlations between PC2 and sea surface temperature. (Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/)



Discussion

Indigenous seasonal calendars offer a glimpse into extensive knowledge of environmental, ecological, hydrometeorological, and climatic patterns held by Indigenous Peoples. These knowledges can contribute to anticipation of water shortages and drought conditions. As such, a bushfire season according to five Indigenous seasonal calendars from across Australia was found to occur from October through March. The two eastern coast locations based on the approximate center of the relevant Indigenous seasonal calendars were highly correlated, indicating shared climatic factors. Principal component analysis of the SPEI drought index data for all five locations during the bushfire season indicated similarities in climate influence across all but the location in the southwestern corner of the continent. Additionally, during the bushfire season the four eastern locations had declining trends in water excesses and increasing trends in water deficits while the southwest location demonstrated trends of increasing water excesses and decreasing water deficits.

There was a moderate positive correlation between SOI and the principal component most representative of the four eastern locations, and a very weak correlation between SOI and the second principal component which was most associated with the western location. This supports that the SOI influences climate and drought conditions across Australia, with effect strongest in the eastern and southern regions.

Due to its proximity to the western coast and Indian Ocean, the western location was expected to have a stronger association with the IOD than the SOI. Correlations between the principal component most associated with the western location and each IOD bushfire season and non-bushfire season were positive and weak, but stronger than the correlation with SOI. These outcomes illustrate the historical and present complexity of climate interactions and drought prediction and management across Australia.

The increasing variance in the SOI indicates intensification of El Niño and La Niña events which contribute to periods of water excesses and deficits. This is likely contributing to the increasing trends in water deficits during bushfire season across the eastern four locations while other climate factors are driving an increase in water excesses in the western location. The tangible impact of these trends across all five locations is an increasing dislocation of the seasonal patterns beyond the normal variance. The positive trend in water excesses in the south western location and decreases in water deficits during the bushfire season is not representative of year-round trends, with rainfall declining in March through August (autumn and winter) since the 1970s (Keywood et al., 2016; O'Donnell et al., 2021). This could represent a shift in rainfall seasonality away from the autumn and winter months and towards spring and summer months.

The reliance of biota on seasonal patterns for regulation of phenology has extensive impacts on environment and biota when seasonal patterns are sufficiently and enduringly disrupted. The association between SPEI and hydrology has received a lot of attention, particularly for water quantity impacts. However, SPEI is linked with and is responsive to environment and biota, most obviously through its incorporation of potential evapotranspiration. The holistic impacts of SPEI on environment and biota is less well researched though has been receiving more attention through increasing awareness of drought impacts on water quality and processes associated with water quality.

Reductions in observed rainfall during autumn and winter since the 1990s in southeastern Australia (March to August) (Keywood et al., 2016) combined with the increasing trends of water deficits in the eastern locations during bushfire season indicates a drying trend of urgent concern. The drying trend increases the risk of water stress occurring in the region, particularly since water deficits are less likely to be restored due to the decreasing trends in water excesses. A drier landscape makes colonial fire management methods for reducing fuel loads riskier, increasing the likelihood of bushfires of greater intensity and destructive ability. Indigenous seasonal calendars contain insight into the cultural burning practices used to manage diverse Australian landscapes for thousands of years (McKemey et al., 2020; Vigilante et al., 2009).

There needs to be an urgent and substantial investment into equitable and respectful collaborations with Indigenous nations to enhance resource management to improve resilience to drought and bushfire events. This would include learning to have relationships with country to improve identification of most at-risk areas and adoption of Indigenous burning methods for rejuvenating areas and reducing bushfire risk. Indigenous burning methods are typically smaller, patchier in scope, and more tailored to the environment than the colonial adaptation of these methods, with colonial methods usually burning larger areas at a time with taller and hotter fires with less regard for environmental diversity and how these fires have interlinkages with ecological rejuvenation (Vigilante et al., 2009). More intense fires burn deeper roots and higher on trees and the reduced vegetation results in reduced transpiration, increased ability for moisture to evaporate from soil, and increased rainfall runoff (Kumar et al., 2020). Indigenous fire methods pose less risk to water sources, with smaller, cooler fires producing less ash to spoil water sources and the lower fire intensity promotes vegetative regrowth, increases soil permeability, reduces the risk of soil erosion and flooding (Ruthrof et al., 2019; Steffen et al., 2018), and increases biodiversity (Vigilante et al., 2009).

Conclusion

Drought risk is increasing across Australia concurrently with changes to the timing of rainfall, reducing the effectiveness of colonial land management techniques. This increases the risk of reductions in water quantity and quality available both for human uses and the broader environment. Increasing dryness then increases the risk of greater intensity bushfires which carry their own harmful effects on water quality. An approximate bushfire season was identified according to a collection of Indigenous seasonal calendars, and a principal component analysis was applied to SPEI values from the locations of the seasonal calendars that provided the approximate bushfire season. SOI, IOD, and SST were correlated with the SPEI principal components to varying degrees, indicating an association between global circulation pattern responses to climate change and drought factors in Australia. Drying trends consistent with drought and bushfire risks were found in the eastern locations, indicating an urgent need to invest in collaborative resource management with Indigenous Peoples in the region to improve resilience and reduce the negative impacts of droughts and bushfires. Indigenous Peoples have deeper understandings of the interlinkages between water, dry periods, bushfires, and the greater ecosystem and environment that they have established over thousands of years. This has allowed them to develop specialised fire management techniques that promote the health and rejuvenation of country in localised regions while also posing less risk to water quality in the short and longer term compared with colonial fire techniques of land management. Respectful and equitable collaboration with Indigenous Peoples can improve holistic understanding of interlinkages between fire, environment, biota, and climate while improving adaptation techniques to the increasing drying trends and changing seasonality across Australia.

CHAPTER 5

DISSERTATION CONCLUSIONS

Indigenous Peoples have extensive place-based knowledge, a fraction of which is reflected in seasonal calendars. This knowledge has insight into holistic interlinkages across environment, biota, weather, and climate that can contribute to climate change adaptation and management strategies. Features within the seasonal calendars can be isolated and quantified using colonial methods, such as biota, food sources, hazards, and season progression and timing, but the real value is reinserting the quantified feature back into the interlinked holistic context to better comprehend climate change impacts within a local microcosm. For example, the analysed streamflow and rainfall data from Western knowledge prcoesses indicated a hydro-metereological response to climate change of increasing severity of floods and droughts, which was supported with the results of the drought index analysis illustrating increasing drying trends in eastern Australia and increasing variability in the SOI. However, these trends at local scales need to be reinserted to their holistic ecological and environmental context for them to be appropriately actionable. Reconnecting the context within which these trends are occurring will enhance understanding of how these trends are impacting local ecosystems, environments, and communities, and allow better monitoring of such impacts.

Reconnecting the quantification of isolated features into the local context requires collaboration and knowledge weaving with local Indigenous knowledge holders who have developed place-based knowledges over thousands of years. Such collaboration needs to occur respectfully through the building of relationships and with a mutual desire for equitable and sustainable outcomes. These efforts will result in enhanced understanding of features and their associated interlinkages and contexts at local scales which will contribute to improved monitoring and management of variations in biota, environment, weather, and climate. An example of a management method that has great potential for improving outcomes is Indigenous cool burning methods, since these approaches have developed alongside the Australian landscape and environment and promote the health and rejuvenation of areas instead of focussing purely on reduction of flammable materials.

This research was designed to be respectful of Indigenous People's intellectual property while drawing broadly on information publicly available. Limited opportunities to collaborate with Indigenous Australians in this research process was not feasible due to time, financial, and COVID-19 limitations, though advice and feedback from an expert in the field of Indigenous Australian research was solicited and incorporated into the design of the research. As a result, broad summaries across publicly accessible Indigenous seasonal calendars were the main focus of analysis involving Indigenous knowledge. Recommendations made based on the results were also general in nature and aimed at education and policy practices to avoid perpetuating colonial violence by making recommendations for actions that could directly affect Indigenous Peoples without their equitable collaboration (David-Chavez and Gavin, 2018; Woodward et al., 2020).

In summary, collaboration and knowledge weaving with Indigenous Peoples can improve adaptability to increasingly risky conditions caused by climate change while improving equitable outcomes and encouraging resource management attitude changes towards sustainable stewardship and caring for country.

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APPENDIX: SEASONAL CALENDAR WEBSITES

Table A.1. Seasonal calendars with links to the calendars and associated references.

Seasonal calendar	Link	Reference
D'harawal	http://www.bom.gov.au/iwk/calendars/dharawal.shtml	BOM, 2016c
Gariwerd	http://www.bom.gov.au/iwk/calendars/gariwerd.shtml	BOM, 2016d
Kaurna	http://www.bom.gov.au/iwk/calendars/kaurna.shtml	BOM, 2016e
Masig	http://www.bom.gov.au/iwk/calendars/masig.shtml	BOM, 2016f
Maung	http://www.bom.gov.au/iwk/calendars/maung.shtml	Maung language contributors and BOM, 2016
Ngoorabul	http://www.bom.gov.au/iwk/calendars/ngoorabul.shtml	Ngoorabul Nation and McKemey, n.d.
Nyoongar	http://www.bom.gov.au/iwk/calendars/nyoongar.shtml	BOM, 2016g
Walabunnba	http://www.bom.gov.au/iwk/calendars/walabunnba.shtml	BOM, 2016i
Wardaman	http://www.bom.gov.au/iwk/calendars/wardaman.shtml	BOM, 2016j
Yanyuwa	http://www.bom.gov.au/iwk/calendars/yanyuwa.shtml	BOM, 2016k
Yawuru	http://www.bom.gov.au/iwk/calendars/yawuru.shtml	BOM, 2016l
Yirrganydji	http://www.bom.gov.au/iwk/calendars/yirrganydji.shtml	BOM, 2016m
Gooniyandi	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/gooniyandi	Davis et al., 2011
Jawoyn	http://www.bom.gov.au/iwk/images/jawoyn//Jawoyn-Seasons_KatherineNT_web.pdf	Jawoyn Association Aboriginal Corporation, 2019
Ngurrungurrudjba	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/ngurrungurrudjba	Lawson and McKaige, 2016

Table A.1. Continued.

Wagiman	https://healthinfonet.ecu.edu.au/key-resources/resources/28447/?title=The+Wagiman+plants+and+animals+calendar&contentid=28447_1	Liddy et al., 2012
Banbai	http://www.bom.gov.au/iwk/calendars/banbai_fire.pdf	McKemey and Banbai Rangers, 2020
Miriwoong	http://www.mirima.org.au/calendar/	Mirima Council, 2011
Kunwinjku	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/kunwinjku	Narndal et al., 2015
Walmajarri	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/walmajarri	Nuggett et al., 2011
Ngadju	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/ngadju	O'Connor and Prober, 2010
Tiwi	http://www.bom.gov.au/iwk/calendars/tiwi.shtml https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/tiwi https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/tiwi	BOM, 2016h Tipiloura et al., 2014a Tipiloura et al., 2014b
Gulumoerrgin	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/gulumoerrgin	Williams et al., 2012
Ngan'gi	https://doi.org/10.1177/1757975919832241 https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/ngangi	Woodward and McTaggart, 2019 Woodward et al., 2009
MalakMalak	https://www.csiro.au/en/research/natural-environment/land/about-the-calendars/malakmalak	Woodward et al., 2010

BIOGRAPHY OF THE AUTHOR

Rachel Coleman was born in the city of Adelaide, South Australia, Australia. She graduated Year 12 from Marrara Christian College in Darwin, Northern Territory, then later from Bond University on the Gold Coast, Queensland, Australia, with a Bachelor in Social Sciences (Psychology). While at the University of New Hampshire she achieved a Master of Public Policy and a Master of Sociology. Rachel's employment experience has encompassed retail and customer service, invasive species control, teaching, and research and report writing. Her scholarly publications include a Master's thesis ('Disparities between Indigenous and non-Indigenous educational attainment: Exploring factors related to low average school NAPLAN scores in the Northern Territory'), disability related publications ('Comparing estimates of disability prevalence using federal and international disability measures in national surveillance', third author; '2017 Disability Statistics Annual Report', third author; '2016 Annual Disability Statistics Compendium – Disability Prevalence and Highlights'), and older adult related publications ('"It helps me find balance": older adult perspectives on the intersection of caregiving and volunteering', second author; 'Supporting Older Workers and Caregivers Who Volunteer: Examples from The Field', third author; 'Juggling Multiple Roles: An Examination of Role Conflict and Its Brief Report: Relationship to Older Adult Volunteer Satisfaction and Retention'; fifth author); as well as various posters. She is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in May 2022.