How Effectively Do Drought Indices Capture Health Outcomes? An Investigation from Rural Australia

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ABSTRACT: Drought is a global threat to public health. Increasingly, the impact of drought on mental health and well-being is being recognized. This paper investigates the relationship between drought and well-being to determine which drought indices most effectively capture well-being outcomes. A thorough understanding of the relationship between drought and well-being must consider the (i) three aspects of drought (duration, frequency, and magnitude); (ii) different types of drought (meteorological, agricultural, etc.); and (iii) the individual context of specific locations, communities, and sectors. For this reason, we used a variety of drought types, drought indices, and time windows to identify the thresholds for wet and dry epochs that enhance and suppress impacts to well-being. Four postcodes in New South Wales (NSW), Australia, are used as case studies in the analysis to highlight the spatial variability in the relationship between drought and well-being. The results demonstrate that the relationship between drought indices and well-being outcomes differs temporally, spatially, and according to drought type. This paper objectively tests the relationship between commonly used drought indices and well-being outcomes to establish whether current methods of quantifying drought effectively capture well-being outcomes. For funding, community programs, and interventions to result in successful adaptation, it is essential to critically choose which drought index, time window, and well-being outcome to use in empirical studies. The uncertainties associated with these relationships must be accounted for, and it must also be realized that results will differ on the basis of these decisions.

SIGNIFICANCE STATEMENT: We wanted to test whether the relationship between drought and well-being changed if different drought indices were used. Our findings demonstrate that the relationship does change, based on drought type, drought index, and time window. This is significant, because it is typical for empirical drought studies to arbitrarily select which drought index to use. However, our findings highlight the need to objectively choose drought indices for individual contexts. Using the most appropriate drought indices will improve the usefulness of policy interventions and community-based programs aimed at supporting people affected by drought. Future research that investigates the relationship between drought indices and well-being should also consider the moderating sociodemographic factors of age, remoteness, and financial position.

KEYWORDS: Drought; Indices; Health

1. Introduction

a. Types of drought

Drought is a complex natural hazard (Van Loon 2015), making it inherently difficult to define (Wilhite et al. 2007). The most basic definitions consider drought as “a deficit of water

compared with normal conditions” (e.g., Sheffield and Wood 2011). However, this simple definition is vague about the parameters to define the deficit, an explanation of normal, or a method for recognizing the beginning and end of drought (Kiem et al. 2016). Complicating the situation is the confusion between the causes, impacts, and risks of drought (Kiem et al. 2016). Understanding drought is a topic of ongoing research, with advances being made in defining and categorizing drought (Peterson et al. 2013; Van Loon 2015). Five commonly used drought categories are summarized below (Heim 2002; Van Loon 2015; Kiem et al. 2016):

- 1) *Meteorological drought* is caused by atmospheric conditions that result in a precipitation deficit. It occurs over several months to years but can develop quickly and end abruptly, sometimes transitioning overnight. Meteorological drought can lead to agricultural drought.
- 2) *Agricultural or soil moisture drought* results from short-term dryness in the root zone during a critical time in the

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TABLE 1. Drought indices used in this study (Vicente-Serrano et al. 2010; Svoboda and Fuchs 2016; Askarimamani et al. 2021).

Index	Type of drought	Characteristics	Strengths	Weaknesses	Example of use
Percent of normal precipitation (relative to the long-term average 1900–2017)	Meteorological	Simple mathematical approach that ranks the frequency and distribution of precipitation	Simple and flexible method; useful in wet and dry conditions	Only uses precipitation data, so impacts of temperature and other variables are not considered	Austin et al. (2018); Morid et al. (2006)
Months below average precipitation (relative to the long-term average 1900–2017) (no. and %)	Meteorological	Counts number/percent of months with below-average precipitation	Simple and flexible method	Only uses precipitation data, so impacts of temperature and other variables are not considered	Kirono et al. (2017)
Precipitation deciles (relative to the long-term average 1900–2017)	Meteorological; agricultural; hydrological	Ranks frequency and distribution of precipitation; also has a wet scale	Method is simple and flexible	Only uses precipitation data, so impacts of temperature and other variables are not considered	Hayman and Alexander (2009); Gibbs and Maher (1967)
Months in lowest precipitation deciles (relative to the long-term average 1900–2017) (no. and %)	Meteorological; agricultural; hydrological	Counts number/percent in individual deciles	Method is simple and flexible	Only uses precipitation data, so impacts of temperature and other variables are not considered	Rahmat et al. (2014)
SPI	Meteorological	Uses historical precipitation records to calculate a probability of precipitation; can be computed at any number of time scales for any period of months; scale includes wet and dry events	Easy to use and calculate; applicable in all climate regimes	Does not account for temperature; the flexibility and availability of SPI can lead to misuse	Stagge et al. (2015b); McKee et al. (1993); Quiring and Papakryiakou (2003)
SPEI	Meteorological	Uses the basis of SPI but includes a temperature component; scale includes wet and dry events	Accounts for the impact of temperature	Requires a complete dataset; rapidly developing drought conditions may not be identified because it is a monthly index	Beguerta et al. (2014); Vicente-Serrano et al. (2010); Stagge et al. (2015a)
NDVI	Agricultural	Remote sensing index that is calculated using radiance values measured in both visible and near-infrared channels	High resolution and good spatial coverage; multispectral, which is crucial for analyzing and monitoring drought	Computational needs to process data; Short history of satellite data	Peters et al. (2002)
Self-calibrating PDSI	Meteorological; agricultural; hydrological	Constants are calculated dynamically based on characteristics present at each location; includes wet and dry scales	Reflects the situation at each site and allows for more accurate comparisons between regions	Issues with time lag and frozen precipitation and frozen soils	Quiring and Papakryiakou (2003); Wells et al. (2004); van der Schrier et al. (2013)
HDSI (count and sum)	Agricultural	Reflects government-declared agricultural drought in Australia (Hanigan et al. 2018)	Represents both drought duration and intensity	Accuracy dependent on spatial size and time frame	Hanigan et al. (2018); O'Brien et al. (2014)

FIG. 1. Three major droughts in Australia: (a) Federation, (b) World War II, and (c) Millennium (Verdon-Kidd and Kiem 2009).

crop growing season. The previous moisture status of the surface soil layers will determine the onset of agricultural drought, which may lag that of meteorological drought. When studying the human impacts of drought, it is the agricultural drought concept that is most commonly used (O'Brien et al. 2014).

- 3) *Ecological drought* is a deficit in soil moisture or biologically available water that imposes multiple stresses in terrestrial and aquatic ecosystems.
- 4) *Hydrological or water resources drought* results from a prolonged period of precipitation deficits that affect surface

or subsurface water supply, impacting on streamflow, reservoir and lake levels, and groundwater supply.

- 5) *Socioeconomic drought* is when the elements of meteorological, agricultural, and hydrological droughts are associated with the supply and demand of an economic good.

Data used in this paper come from participants in rural New South Wales (NSW), Australia, who are primarily affected by meteorological and agricultural drought. For this reason, the analysis focused on these two types of drought. Socioeconomic drought is not addressed specifically, because it is not a type of drought per se but rather is the combination of impacts from

TABLE 2. Distribution and impacts of historic droughts in Australia (Mpelasoka et al. 2008; Verdon-Kidd and Kiem 2009; ABARES 2011).

Drought name; period and season(s) most impacted	Date	Impact and region affected
Millennium Drought (~1997–2010); autumn and early winter	2008–10	The Millennium Drought received media attention and was labeled as the “worst drought on record” (Carnie et al. 2011); affecting southeastern Australia, it caused serious impacts to agricultural production, biodiversity, bushfire regimes, and water availability
	2002–07	Winter crop production declined sharply in 2002–03 and, after recovering, declined again in 2006–07; loss of 70 000 jobs in 2002–03; Murray–Darling Basin inflows were the lowest on record, severely affecting irrigated agriculture
	1991–95	Particularly dry in parts of Queensland, northern NSW, and central Australia; average production by rural industries fell by about 10%, leading to a possible AUD 5 billion cost to the Australian economy; the Commonwealth government provided AUD 590 million of drought relief between September 1992 and December 1995
	1982–83	One of the most intense and widespread droughts on record, with a total loss of over AUD 3 billion
	1972–73	Mainly in eastern Australia
	1963–68	Widespread drought, the last two years of which saw a 40% drop in wheat harvest, a loss of 20 million sheep, and a decrease in farm income of AUD 300–600 million
WWII/The Forties Drought (~1937–45); all seasons	1939–45	Southern Australia experienced one of the driest years on record in 1940; loss of nearly 30 million sheep between 1942 and 1945
	1918–20	Most parts of Australia, except Western Australia, in drought
	1911–16	Loss of 19 million sheep and 2 million cattle
Federation Drought (~1895–1902); late spring/summer	1895–03	The Federation Drought had several years of generally below average rainfall followed immediately by one or two years of exceptionally low rainfall; it was Australia’s most devastating drought in terms of stock losses, with sheep numbers halved and more than 40% of cattle lost
	1880–86	Southern and eastern states affected
	1864–66	All states affected except Tasmania; livestock losses included 50% of sheep and 40% of cattle populations

FIG. 2. Location of the four study sites in nonmetropolitan NSW.

other types of drought and ultimately begins with meteorological and/or agricultural drought (Kiem et al. 2016).

b. Quantifying drought

Together with this lack of universal definition, many questions remain about how best to measure and quantify drought. Droughts are typically quantified by type and in terms of severity, duration, spatial distribution, frequency, magnitude, and predictability (Zargar et al. 2011). The most prevalent method of drought quantification is the use of drought indices. Indices are practical, useful tools to quantify the different types of drought. How drought is quantified directly links to the provision of support services in terms of eligibility (e.g., spatial area covered), type (e.g., financial, counseling), and level of support (e.g., loan, income payment, and tax subsidy). This paper explores the ways drought is quantified in Australian empirical studies and considers whether current methods effectively capture well-being outcomes.

Drought indices produce a single numerical value that is more useful than raw data for analysis and decision-making. Zargar et al. (2011) found that there are more than 150 drought indices. These drought indices are all different (based on different methods, utilize different data, etc.), which creates high levels of uncertainty for users of the indices. This uncertainty results in difficulties in quantifying drought as it is not clear which indices are best for a particular location or application (e.g., Askarimarnani et al. 2021). Lack of quantification of drought has serious implications for drought adaptation, as it is not possible to engage in successful planning and adaptation when it is not clear what is being adapted to (Bachmair et al. 2016b). What is needed is increased understanding of

which index to use for specific locations and applications (Bachmair et al. 2015, 2016a; Wanders et al. 2017). The characteristics of drought and the spectrum of economic sectors it impacts makes it challenging to quantify drought using a common type of index. Table 1 shows the nine drought indices used in this paper.

Quantifying drought is an area of ongoing research (Askarimarnani et al. 2021). Wanders et al. (2017) conducted a comparison of common drought indices to determine the degree to which they are interchangeable. They found that a different index should be carefully identified for each drought type. In addition, they found indices that measure the same drought type can have considerable inconsistencies in their anomalies and therefore drought detection. Importantly, Wanders et al. (2017) and Askarimarnani et al. (2021) concluded that there is no one superior index that can accurately capture the diverse impacts of drought across the hydrological cycle. Therefore, it is essential to select the correct index for a given situation. This paper explores this by assessing how sensitive the drought–well-being association is across a range of commonly used drought indices.

c. Drought in Australia

Australia is particularly vulnerable to drought because of its extreme rainfall variability (Cleugh et al. 2011). Australia's hydroclimate is highly variable spatially and temporally, contributing to the severity of drought impacts (Kiem et al. 2016).

Since instrumental records began in the late 1880s, Australia has experienced three prolonged droughts (Verdon-Kidd and Kiem 2009) (Fig. 1), not including the current drought (Askarimarnani et al. 2021). The first of these droughts, the

TABLE 3. Community sociodemographic and climatic characteristics of the four study sites (Australian Bureau of Statistics 2019).

Characteristic	Lismore	Bathurst	Orange	Cobar
Population (<i>n</i>)	3579	41 300	40 344	4647
Male (%)	48.8	50.1	48.6	51.5
Female (%)	51.2	49.9	51.4	48.5
Aboriginal and/or Torres Strait Islander (%)	6.1	5.4	6.3	13.7
Median age (yr)	40	37	37	36
Labor force (<i>n</i>)	1510	19 329	19 013	2139
Employed full-time (%)	47.5	57.8	59.7	66.0
Employed part-time (%)	35.1	30.6	28.8	20.9
Unemployed (%)	12.6	6.0	6.3	5.8
Most common occupations (%)	Professionals 18.9; community and personal service workers 16.4	Professionals 18.9; technicians and trade workers 14.5	Professionals 21.2; technicians and trade workers 14.6	Technicians and trade workers 15.8; machinery operators and drivers 17.8
Median weekly household income (≥ 15 yr)	AUD 485	AUD 646	AUD 667	AUD 706
Internet accessed from dwelling (%)	73.9	79.2	77.1	70.1
Climate (annual averaged)				
Mean annual rainfall (mm)	1343.1	636.8	881.9	392.3
Mean annual min temperature ($^{\circ}\text{C}$)	13.2	6.8	6.2	12.8
Mean annual max temperature ($^{\circ}\text{C}$)	25.5	19.9	18.4	25.4

Federation Drought, occurred during ~ 1895 – 1902 , followed three decades later by the World War II Drought (~ 1937 – 45) and more recently by the Millennium Drought (~ 1997 – 2010). These three droughts are named according to historical events (i.e., when Australia became a federation, the Second World War, and the turn of the twenty-first century). Droughts are considered to be prolonged after an extended period of dryness, and when they have caused significant environmental, economic, and social repercussions [refer to Verdon-Kidd and Kiem (2009) for further details]. The environmental,

economic, and social impacts and the geographical areas affected by these three droughts are summarized in Table 2 (see also Verdon-Kidd and Kiem 2009; van Dijk et al. 2013).

d. Policy and reform: Shifting paradigms

During the mid-1900s, Australian drought policy focused on “drought proofing” agriculture via expansions through irrigation (Department of Agriculture and Water Resources 2018b). This system of reform has contributed to the current situation in the Murray–Darling Basin (MDB) where overextraction of

TABLE 4. Categories of drought severity for PDSI and SPI (National Drought Mitigation Center 2019).

Drought category	Moisture category	PDSI	SPI	Possible impacts
D0	Abnormally dry	From -1.0 to -1.9	From -0.5 to -0.7	Going into drought: short-term dryness slowing planting, growth of crops or pastures; coming out of drought: some lingering water deficits, pastures or crops not fully recovered
D1	Moderate drought	From -2.0 to -2.9	From -0.8 to -1.2	Some damage to crops and pastures; streams, reservoirs, or wells low; some water shortages developing or imminent; voluntary water-use restrictions requested
D2	Severe drought	From -3.0 to -3.9	From -1.3 to -1.5	Crop or pasture losses likely; water shortages common; water restrictions imposed
D3	Extreme drought	From -4.0 to -4.9	From -1.6 to -1.9	Major crop/pasture losses; widespread water shortages or restrictions
D4	Exceptional drought	≤ -5.0	≤ -2.0	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies

TABLE 5. Categories of drought severity for SPEI (Svoboda and Fuchs 2016).

Moisture category	SPEI
Extremely wet	≥ 2.00
Very wet	1.50–1.99
Moderately wet	1.00–1.49
Near normal	From -0.99 to 0.99
Moderately dry	From -1.00 to -1.49
Severely dry	From -1.50 to -1.99
Extremely dry	≤ -2.00

natural water resources has caused significant environmental, financial, and social consequences (Kiem 2013). The early 1970s saw a shift in policy in which drought was recognized as a natural disaster, enabling support for people affected by drought. This arrangement was removed in 1989 when a review of national drought policy found previous procedures were not effective in supporting farmers to prepare for drought. The updated policy acknowledged that drought was not a one-off, unmanageable, unpredictable occurrence (Kiem 2013; Kiem and Austin 2013). The National Drought Policy, announced in 1992, focused on encouraging long-term self-reliance, by preparing for and managing climate variability. Under the National Drought Policy, the federal government had the option to classify areas as experiencing exceptional circumstances (EC), whereby the drought event was considered to be rare and severe (Department of Agriculture and Water Resources 2018a). EC was the primary mode of financial support to farmers until 2012. At this time, it became apparent that EC was inequitable and often resulted in farm businesses simply reacting to drought once they were in crisis, rather than preparing and planning for drought continuously. The last EC declarations lapsed in 2012 and EC is no longer a strategy. Since then, Australian, state and territory primary industries ministers agreed that government support needs to incentivize farmers and people in rural communities to plan and prepare for drought, especially in nondrought times (Department of Agriculture and Water Resources 2018b).

In recent years, the perception of drought as a one-off natural disaster and a crisis situation has shifted to a view of drought as a normal, recurrent, and persistent element of the Australian climate (Wilhite 2002; Rickards 2010; Askew and Sherval 2012; Kiem 2013; van Dijk et al. 2013). The abolishment of EC reflects a shift whereby drought is no longer considered as a “natural disaster” in the same context as rapid-onset extremes such as floods, bushfires, or cyclones. This change is crucial as it abandons, at least in theory, the reactionary, ad hoc crisis management approach previously used when responding to drought.

The new paradigm is one of preparedness and risk management, where drought is seen as a predictable risk, and facilitates planning for the mitigation of, and adaption to, drought impacts (Wilhite 2002; Kiem 2013; van Dijk et al. 2013; Wilhite et al. 2014). The inclusion of planning to adapt to future drought is a significant component, as it is essential to recognize that drought will return. It is imperative to learn from drought experiences and to continue to plan for the eventuality of drought, particularly during nondrought periods.

TABLE 6. Precipitation deciles in comparison with average precipitation (BOM 2019).

Decile	Rank of precipitation relative to average
1	Very much below average
2–3	Below average
4–7	Average
8–9	Above average
10	Very much above average

Despite the shift of focus, there remains a lack of successful and practical implementation of drought adaptation measures. Existing research acknowledges the need to adapt to drought and suggests potential options to do so. Javeline et al. (2019) investigate the lack of adaptation in the context of floods, storms, and sea level rise. Although their study applies to extremes with excess water, the same can be said for drought.

The current ongoing drought in Australia prompted further reform during 2018: the Prime Minister held a National Drought Summit (Department of the Prime Minister and Cabinet 2018) in October 2018, and at the Council of Australian Governments (COAG) meeting in December 2018, signed a new National Drought Agreement (COAG 2018). These events demonstrate the governments’ acknowledgment of the continued need for reform in drought management in Australia. Accordingly, the federal government has released a drought response, resilience, and preparedness plan, including an investment of AUD 5 billion in the Future Drought Fund to provide drought resilience initiatives with continuous, secure funding.

e. Quantification of drought in well-being studies

There is a lack of studies that quantitatively investigate well-being as a direct outcome of drought. Of those that do exist, empirical studies of drought and well-being in Australia typically measure drought in one of two ways: either according to government agricultural drought declarations or the Hutchinson drought severity index (HDSI) (e.g., O’Brien et al. 2014; Hanigan et al. 2018). Largely, Australian investigations of drought in the health and social work domain, determine drought conditions according to government declarations of drought. However, there are issues with government drought declarations, which can be controversial, and are seen by many as arbitrary “lines on a map” that do not always reflect conditions on the ground (Botterill and Hayes 2012). Friction can arise in communities when drought declarations do not always appear to match the reality of the situation, whereby people with similar experiences of drought conditions have different declarations of drought imposed on them. In addition, each agency operating within the drought, health and social work context uses different methods for determining drought status within its jurisdiction.

The government declaration of drought method is used in both quantitative and qualitative studies. Powers et al. (2012) aimed to link drought and women’s health and well-being by using exceptional circumstances as a proxy for drought, while Stain et al. (2011) defined high drought exposure as having been drought declared for at least six months of

TABLE 7. List of indices, data, and sources.

Index	Data	Data source
Percent of normal precipitation	AWAP	http://www.csiro.au/awap/ (Raupach et al. 2009, 2012)
Months below avg precipitation (no. and %)	AWAP	http://www.csiro.au/awap/ (Raupach et al. 2009, 2012)
Precipitation deciles	AWAP	http://www.csiro.au/awap/ (Raupach et al. 2009, 2012)
Months in lowest precipitation deciles (no. and %)	AWAP	http://www.csiro.au/awap/ (Raupach et al. 2009, 2012)
SPI	AWAP	http://www.csiro.au/awap/ (Raupach et al. 2009, 2012)
SPEI	—	http://spei.csic.es/map/maps.html#months=1#month=5#year=2018
PDSI	—	Climate Research Unit, University of East Anglia (https://crudata.uea.ac.uk/cru/data/drought/)
HDSI (count and sum)	AWAP	R code: https://github.com/ivanhanigan/HutchinsonDroughtIndex
NDVI	—	http://www.bom.gov.au/jsp/awap/ndvi/archive.jsp?colour=colour&map=ndviave&year=2018&month=5&period=month&area=nat

the previous year. Although a study may be quantitative in nature, a specific reference to how drought was defined and measured may be omitted (e.g., Dean and Stain 2010; Guiney 2012). Similarly, qualitative studies are more likely not to specifically define drought (e.g., Ng et al. 2015), although some refer to government drought-declared areas and water allocations (Caldwell and Boyd 2009); while others conceptualize experiences of drought through narratives of endurance, struggle, and hope (Anderson 2009; Rich et al. 2012, 2018).

The empirical drought studies from Australia summarized in this paper were typically conducted during the last years or after the conclusion of the Millennium Drought (~1997–2010) and so time and general geographic area are the references used (e.g., Congues 2014). These studies support the notion that the repercussions of drought are not just about drought, and that rural community, sociodemographic and financial factors significantly influence individual experiences of drought (Kiem and Austin 2013).

f. ARMHS

We use health and well-being data from the Australian Rural Mental Health Study (ARMHS), a multisite longitudinal cohort study that investigated the determinants and outcomes of mental health and well-being in nonmetropolitan

NSW. Detailed methods of the ARMHS have been published previously (Kelly et al. 2010).

g. Study sites

Four study sites (Fig. 2) were selected for analysis: Lismore (postcode: 2480), Bathurst (postcode: 2795), Orange (postcode: 2800), and Cobar (postcode: 2835). Bathurst and Orange are contiguous postcodes in central NSW. Cobar is classified as remote and the other three postcodes are inner regional (Australian Bureau of Statistics 2006). Table 3 compares general community characteristics for the four locations. The four postcodes differ in their sociodemographic and climatic conditions (Table 3), which adds important context to the findings. As stated earlier, the individual nature of places, communities and sectors impacts the relationship between drought and well-being and how best to measure that relationship.

Cobar is a significantly larger postcode spatially than the other three study sites; however, Cobar has a very small population, similar to that of Lismore (Table 3). Cobar (2835) is the hottest and driest of the four postcodes, while Lismore (2480) is more tropical, with hot, wet conditions. Bathurst (2795) and Orange (2800) have very similar climatic conditions, representative of the fact that they are contiguous. Lismore, Bathurst, and Orange have very similar groupings of occupation, whereas

TABLE 8. K10 questionnaire (Kessler et al. 2002).

In the last four weeks about how often did you feel . . .	1—None of the time	2—A little of the time	3—Some of the time	4—Most of the time	5—All of the time
tired out for no good reason?					
nervous?					
so nervous that nothing could calm you down?					
hopeless?					
restless or fidgety?					
so restless you could not sit still?					
depressed?					
that everything was an effort?					
so sad that nothing could cheer you up?					
worthless?					

Cobar's most prevalent occupations are indicative of the economy of the town being dominated by mining.

While Lismore did experience impacts from the Millennium Drought, it was not one of the areas most affected, receiving average to below average rainfall from 1997 to 2009 (BoM 2015). For the purpose of this analysis, it provides insight into the different performance of indices between wet and dry, and acts in a sense as a control.

There are uncertainties around which drought index is most appropriate in any given situation, and the lack of testing into which drought index/indices are best when measuring health outcomes. Therefore, the aim of this paper is to (i) investigate how well-being outcomes differ in response to individual drought types and measures and (ii) consider the spatial variation in the relationship between drought measures and well-being. This aim will be addressed by testing the sensitivity of well-being responses to a range of drought indices.

2. Methods

a. Population and study sites

The study population is a subset of the ARMHS cohort who resided in the four NSW postcodes investigated in this study. Four postcodes were selected on the basis of two criteria: (i) the ARMHS sample size for the postcode was greater than 100 at baseline (2007) and (ii) there were fluctuations between wet and dry conditions during the study period within the spatial area of the postcode. Responses for participants who resided within these four postcodes were included. Postcode data were collected at each wave, meaning participants who changed postcodes between waves were assessed at each wave for eligibility (i.e., they were included if they had moved into the postcode and were excluded if they had moved out of the postcode). Participants who did not have a date recorded for the day the survey was completed were excluded, as it was not possible to assign them to corresponding drought data.

b. Drought indices and data

Nine indices (Table 1) and two types of drought (meteorological and agricultural drought) are used to compare the differing associations with two well-being outcomes. Indices included in the analysis were based on findings from Askarimarnani et al. (2021) and their prominence in the literature; their common use in Australian studies in particular; and their ability to measure meteorological and agricultural drought. Categories of drought severity for PDSI and standardized precipitation index (SPI), and standardized precipitation evapotranspiration index (SPEI) are shown in Tables 4 and 5, respectively, and deciles are shown in Table 6.

NDVI has been shown to effectively indicate changes in vegetation in response to drought (Condorelli et al. 2018). NDVI values range from -1 to 1 , with the following ranges representing specific types of land cover: ≤ 0 indicates nonliving material, $>0-0.33$ indicates unhealthy plant material, $>0.33-0.66$ represents healthy plant material, and >0.66 indicates very healthy plant material (Jackson and Huete 1991). However, while NDVI

TABLE 9. Characteristics of the study population. Not all participants answered every question at every wave, and therefore totals do not always sum to 1195 (100%).

Characteristic	N	%
ARMHS waves completed		
Baseline	464	38.8
1-yr follow-up	311	26.0
3-yr follow-up	222	18.6
5-yr follow-up	198	16.6
Postcode		
2480	326	27.3
2795	269	22.5
2800	324	27.1
2835	276	23.1
Gender		
Female	719	60.2
Male	476	39.8
Age (yr)		
18–34	90	7.5
35–44	133	11.1
45–54	311	26.0
55–64	326	27.3
65+	335	28.0
Employment		
Employed/studying/home duties/caring	752	62.9
Unemployed/unable to work	66	5.5
Retired	365	30.5
Financial position		
Prosperous/very comfortable	209	17.5
Reasonably comfortable	617	51.6
Just getting along/poor/very poor	283	23.8
Education (baseline only)		
Partial schooling	108	9.0
Completed high school or higher	325	27.2
Unknown	31	2.6
Marital status		
Married/de facto	894	74.8
Separated/divorced	141	11.8
Widowed	71	5.9
Never married	83	6.9
Psychological distress (K10)		
Low	863	72.2
Moderate	245	20.5
High	67	5.6
Overall physical health		
Fair/poor	277	23.2
Good	470	39.3
Very good/excellent	436	36.5
Overall mental health		
Fair/poor	188	15.8
Good	345	28.9
Very good/excellent	650	54.4
Overall relationships		
Fair/poor	113	9.5
Good	295	24.7
Very good/excellent	778	65.1

gives some insights into the spatial extent of drought conditions, there are also limitations associated with the NDVI (e.g., Sims and Gamon 2002; Adeyeri et al. 2017). These limitations are not

TABLE 10. Experiences of individual items of personal drought-related stress and community drought-related stress.

Drought-related stress	Individual items	N	%
PDS	<i>Has drought had any of these effects on you or your family?</i>		
	Money/financial pressures	514	68.17
	Business pressures	483	64.22
	Loss of contact with friends	437	58.26
	Not going out as much	475	63.16
	More work to do	495	65.91
CDS	Less time for family	415	55.63
	<i>Has drought had any of these effects on the district where you live?</i>		
	People leaving the area	575	68.78
	Losing businesses and services in town	552	65.95
	Not getting together as much	498	59.64
	Countryside has changed	724	85.98
	Reduced water quality	620	73.72

tested here, rather we use NDVI following the findings from Askarimarnani et al. (2021), who found NDVI was useful for detecting drought in Australia.

Drought indices were calculated at five time windows (6, 12, 24, 36, and 60 months to cover short, seasonal, and multiyear droughts) proceeding the survey completion. For example, if the ARMHS survey was completed in January 2008, the drought indices were calculated for 6, 12, 24, 36, and 60 months prior to January 2008. Drought indices were calculated using R statistical software (R Core Team 2013) and Python (van Rossum 1995) with data from the Australian Water Availability Project (AWAP) (Jones et al. 2009; Tozer et al. 2012), while others were downloaded directly from publicly available repositories (Table 7).

The global monthly SPEI gridded data was obtained from the SPEI Global Drought Monitor website with a 0.5° ($\sim 2500 \text{ km}^2$) spatial resolution, and the AWAP data have a spatial resolution of 0.05° (25 km^2). Because of the difference in resolution, a Python script was used to resample the rasters to 0.05° (25 km^2) spatial resolution (i.e., the same as the AWAP data). The nearest-neighbor interpolation method was used for postcodes smaller than $50 \times 50 \text{ km}^2$ (2500 km^2). This interpolation method used the closest subset of input values to the small postcodes in question (i.e., $<2500 \text{ km}^2$), and applied weights based on proportionate areas (Collins et al. 2004).

The HDSI was calculated using the AWAP monthly gridded data that was recalculated from the monthly area-averaged totals. These were then used as input files for the R code that is publicly available (Table 7). The R code was run individually for each postcode at each moving window (i.e., 20 times as a result of four postcodes for five time windows).

c. Well-being measures

Two well-being outcomes were tested: K10 and the ARMHS wellbeing index (WI). K10 is a screening scale used to rate psychological distress (Kessler et al. 2002). It is a commonly used clinical tool. K10 asks patients how they have been feeling in the past 4 weeks in terms of psychological distress. The specific questions are detailed in Table 8. Scores for each question range from 1 (none of the time) to 5 (all of the time), with final scores grouped into three levels of distress:

low (<16), moderate (16–24), and high (>24) (Kelly et al. 2010). The novel ARMHS WI is a general measure of overall well-being. The WI is an aggregate of seven validated measures: overall physical and mental health; ability to perform daily tasks; satisfaction with relationships and life overall; days out of job in the past month; and K10 (Kelly et al. 2011). The WI is a standardized score; therefore, the magnitude of response cannot be inferred. The index has been used in other ARMHS studies and has been shown to be an effective measure of well-being (e.g., Kelly et al. 2011).

In addition to these two outcome measures (K10 and WI), personal drought-related stress (PDS) and community drought-related stress (CDS) were analyzed to give context to the statistical findings. PDS and CDS were collected at baseline and at 3- and 5-yr follow-ups. PDS and CDS consist of six and five specific questions about the impacts of drought, respectively (Austin et al. 2018). “Yes” responses were summed to give a total score.

d. Analysis methods

Time series were plotted for the four postcodes for all drought indices at the five time windows (6, 12, 24, 36, and 60 months). Boxplots were generated using Python to assess the relationship between each drought index and the two outcome measures at each of the four postcodes for the five time windows. One-way ANOVA was used to test the statistical significance between the drought indices and the two outcome measures for each of the five time windows at the four postcodes.

3. Results

a. Population characteristics

The ARMHS sampling method has been documented previously (Kelly et al. 2010). A total of 464 participants resided across the four postcodes at baseline, and there were 1195 responses across the four ARMHS waves. There were more women (60.2%), and the majority of participants were married (67.8%) (Table 9). It was an older cohort: 55.3% of participants were 55 years or older. Additional sociodemographic characteristics of the population are shown in Table 9.

FIG. 3. (a) Comparison of drought indices at Bathurst for the 6-month time window, and (b) comparison of the “percent of months below deciles 1–4” indices at Bathurst for the 6-month time window. [Note: all indices have been standardized; HDSI (sum) and months below average have been inverted by multiplying by -1].

b. Experiences of drought-related stress

Where at least one individual item of PDS or CDS was reported, PDS was experienced by 55%–68% of participants, and 59%–85% of participants experienced CDS (Table 10). Almost 86% of participants agreed that the countryside in their local district had changed as a result of drought. This has implications for attachment to place and feelings of connection, potentially leading to members of the community experiencing feelings of *solastalgia*, disconnection from place and possibly displacement (Albrecht 2005; Austin et al. 2020).

c. Time series

Time series of each index at the four postcodes were analyzed to confirm there had been fluctuations between wet and dry epochs in the study period. The results for Bathurst are provided below as an example.

Figures 3 and 4 show comparisons of indices at Bathurst for the 6- and 60-month time windows, respectively. The time

series highlight the discrepancies between indices for wet and dry peaks and the (lack of) sensitivity of indices to depict these extremes. In addition, the variation in how indices reflect fluctuations between wet and dry epochs at different time windows is evident, supporting the need to select an appropriate time window.

The differing capabilities of indices to detect early onset of drought is also shown, with some indices lagging behind others. The time series support the aims of this paper as they demonstrate the spatial and temporal variation of drought, as well as the variation between individual indices, providing evidence for the need to rigorously select drought index and time window for any given situation.

d. Associations between drought indices and K10

K10 is a ubiquitous measure used in empirical drought studies, and therefore it is important to consider how well K10 varies under drought conditions represented by different

FIG. 4. As in Fig. 3, but for the 60-month time window.

drought indices. Based on ANOVA tests of all drought indices, at the five time windows for the four postcodes, K10 has the highest frequency of statistically significant associations (Table S1 in the online supplemental material) with the index “months below decile 1” (Table 11). The months-below-decile-1 index represents the driest 10% of months when compared with average precipitation and is ranked as very much below average (Table 5). In addition, K10 was most frequently associated with indices at the 24-month time window (Table 12). Statistically significant associations between K10 and drought indices varied spatially, where Lismore (2480), Bathurst (2795), and Orange (2800) scored 48, 45, and 49, respectively, while Cobar (2835) had a total of just 16 significant associations (Table 11).

Boxplots depicting the relationships between K10 and the number of months below decile 1 (Fig. 5) demonstrate both the spatial variability between postcodes and the temporal variability between time windows. Orange (2800) and Bathurst (2795) had statistically significant results at all the time windows except six months, with Cobar (2835) and Lismore (2480) being significant at fewer time windows. For Orange (2800), the high distress group had the largest median number of months in drought. In contrast, Bathurst (2795) had the highest median number of months in drought in the moderately distressed group. Cobar (2835) and Lismore (2480), the driest and wettest postcodes, respectively, showed the least variation in median number of months in drought across the three distress groups. These results suggest that high distress was not always

TABLE 11. Number of statistically significant associations for K10 and each drought index for the four postcodes at five time windows. The highest frequency indices for each postcode are in boldface type. Here, Met = meteorological and Ag = agricultural.

Drought	Drought type	2480		2795		2800		2835	
		<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Percent of normal	Met	3	15	3	15	3	15	0	0
Months below avg (no.)	Met	3	15	3	15	2	10	0	0
Months below avg (%)	Met	3	15	3	15	2	10	1	5
Deciles	Met/Ag	3	15	2	10	3	15	0	0
Months below decile 1 (no.)	Met/Ag	3	15	4	20	4	20	2	10
Months below decile 1 (%)	Met/Ag	3	15	4	20	4	20	2	10
Months below decile 2 (no.)	Met/Ag	2	10	2	10	3	15	1	5
Months below decile 2 (%)	Met/Ag	2	10	2	10	3	15	1	5
Months below decile 3 (no.)	Met/Ag	3	15	2	10	3	15	2	10
Months below decile 3 (%)	Met/Ag	3	15	2	10	3	15	2	10
Months below decile 4 (no.)	Met/Ag	2	10	2	10	2	10	1	5
Months below decile 4 (%)	Met/Ag	2	10	2	10	2	10	1	5
SPI	Met	1	5	1	5	1	5	1	5
SPEI	Met	3	15	3	15	3	15	0	0
NDVI	Ag	3	15	2	10	3	15	0	0
PDSI	Met/Ag	3	15	4	20	4	20	1	5
HDSI (count)	Ag	3	15	2	10	2	10	1	5
HDSI (sum)	Ag	3	15	2	10	2	10	0	0

associated with the highest number of months in drought, although the low distress group most often experienced the lowest median number of months in drought. The variation in the length of the interquartile demonstrates that the dispersion of data varies for the four postcodes and the five time windows. However, all medians fall within the interquartile of the comparison plots for a given time window, indicating there is no difference between the three groups of K10 scores. The largest median drought scores across all distress groups tended to sit higher in the quartile range (negatively skewed), indicating more participants in the sample had fewer months in drought. Findings are consistent for both the number of months below decile 1 (Fig. 5) and the percent of months below decile 1 (Fig. 6).

This spatial and temporal variation is supported when we make comparisons across the different indices (Fig. 7) at the 24-month time window. From Fig. 7 it is apparent that a one-size-fits-all pattern cannot be seen across the combination of indices and locations. For example, there is not a consistent pattern in which one level of distress is more associated with increased drought condition or less associated with decreased drought condition. There is variation in the distribution of each index, for example months below average (number) is less dispersed than deciles, which has larger interquartile and minimum/maximum ranges. Postcode 2835 (Cobar) consistency

has a higher number of outliers in the wetter periods. As with the months below decile 1, all medians for all indices fall within the interquartile range of comparison plots for the given postcode, indicating there is no difference between the three levels of distress. When comparing across indices and locations, it is evident that the associations between drought index and K10 are spatially variable. This variability is also demonstrated temporally when the additional time windows are examined (Fig. 5). These findings support the concept of drought being spatially and temporally variable (Kiem et al. 2016), and hence the relationships between drought and health measures (e.g., K10) are also variable. In addition, as demonstrated in Austin et al. (2018), factors that influence drought-related stress (e.g., sociodemographics and remoteness) are spatially variable.

e. Associations between drought indices and the WI

The WI is a novel ARMHS measure, comprising seven individual well-being measures. No ARMHS studies to date have tested the impact of drought using WI as an outcome. Testing WI is important because it represents the variation possible in well-being outcome measures, and highlights that not all well-being outcomes respond the same to drought indices, i.e., the results for K10 and WI are different across time and space.

TABLE 12. Number of statistically significant associations for K10 at five time windows for the four postcodes. The highest-frequency time window for each postcode is in boldface type.

	6 months		12 months		24 months		36 months		60 months	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
2480	5	6.94	2	2.78	7	9.72	17	23.61	17	23.61
2795	0	0.00	3	4.17	17	23.61	15	20.83	10	13.89
2800	0	0.00	3	4.17	17	23.61	13	18.06	16	22.22
2835	0	0.00	2	2.78	10	13.89	3	4.17	1	1.39

FIG. 5. Associations between the number of months below decile 1 and K10 for the four postcodes at five time windows: (a) 6, (b) 12, (c) 24, (d) 36, and (e) 60 months. K10 < 16 = low distress, K10 of 16–24 = moderate distress, and K10 > 24 = high distress. Here, $n = 326$ for postcode 2480, $n = 269$ for postcode 2795, $n = 324$ for postcode 2800, and $n = 276$ for postcode 2835. The orange line in the interquartile box is the median.

The association between WI and drought was statistically significant for one postcode only—Lismore (2480) (Table 13)—where WI had the same number of associations with three drought indices (i.e., months below average; months below decile 2; and

NDVI) (Table S2 in the online supplemental material). The time window with the most associations was 12 months (Table 14).

The spatial and temporal variability of associations between drought index and K10 are consistent with the findings for WI

FIG. 6. As in Fig. 5, but for percentage of months below decile 1.

(Figs. 9–11). The percentage of months below average (Fig. 8) depicts the distribution becoming less dispersed as the time window increases. In addition, the number of outliers lessens as time window increases. Conversely, the range for months in

decile 2 (number) increases with time window (Fig. 9). Both of these indices have little variation in medians across the three distress groups, although low distress tends to be the highest or equal highest dryness score. NDVI has a different pattern, with

FIG. 7. Associations between K10 and all drought indices at the 24-month window for the four postcodes: (a) percent of normal, (b) months below average (number), (c) months below average (percent), (d) deciles, (e) months below decile 1 (number), (f) months below decile 1 (percent), (g) months below decile 2 (number), (h) months below decile 2 (percent), (i) months below decile 3 (number), (j) months below decile 3 (percent), (k) months below decile 4 (number), (l) months below decile 4 (percent), (m) SPI, (n) SPEI, (o) NDVI, (p) PDSI, (q) HDSI (count), and (r) HDSI (sum); the orange line in the interquartile box is the median.

TABLE 13. Number of statistically significant associations for WI and each drought index for the four postcodes at five time windows. The highest-frequency indices for each postcode are in boldface type. Here, Met = meteorological and Ag = agricultural.

Drought index	Drought type	2480		2795		2800		2835	
		<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Percent of normal	Met	1	5	0	0	0	0	0	0
Months below avg (no.)	Met	3	15	0	0	0	0	0	0
Months below avg (%)	Met	3	15	0	0	0	0	0	0
Deciles	Met/Ag	1	5	0	0	0	0	0	0
Months below decile 1 (no.)	Met/Ag	2	10	0	0	0	0	0	0
Months below decile 1 (%)	Met/Ag	2	10	0	0	0	0	0	0
Months below decile 2 (no.)	Met/Ag	3	15	0	0	0	0	0	0
Months below decile 2 (%)	Met/Ag	3	15	0	0	0	0	0	0
Months below decile 3 (no.)	Met/Ag	1	5	0	0	0	0	0	0
Months below decile 3 (%)	Met/Ag	1	5	0	0	0	0	0	0
Months below decile 4 (no.)	Met/Ag	1	5	0	0	0	0	0	0
Months below decile 4 (%)	Met/Ag	1	5	0	0	0	0	0	0
SPI	Met	2	10	0	0	0	0	0	0
SPEI	Met	2	10	0	0	0	0	0	0
NDVI	Ag	3	15	0	0	0	0	0	0
PDSI	Met/Ag	1	5	0	0	0	0	0	0
HDSI (count)	Ag	2	10	0	0	0	0	0	0
HDSI (sum)	Ag	2	10	0	0	0	0	0	0

narrow distributions across all postcodes, distress groups, and time windows (Fig. 10). This lack of dispersion indicates little difference between the associations between drought index and the WI.

Figure 11 shows there were consistencies between K10 and WI for other indices also. For example, deciles again had a more dispersed distribution and Cobar (2835) tended to have more outliers. As with K10, the temporal and spatial variability of associations between drought indices and WI is evident (Fig. 11).

4. Discussion

The relationship between drought indices and well-being outcomes differs temporally, spatially, and according to drought type. This variation highlights that in any empirical drought study it is essential to consider the sensitivities and uncertainties associated with the relationship between drought and well-being. Critically, the choice of drought index, time window and well-being outcome must be objective, and it must be recognized that the results will differ based on these choices. In addition, investigations into the relationship between drought and well-being must (i) incorporate the three aspects of drought (duration, frequency, and magnitude); (ii) consider different types of drought (e.g., meteorological and agricultural); and (iii) importantly, capture the context of specific locations, communities, and sectors and be transparent about them in their results and interpretations.

This study builds on previous research (e.g., O'Brien et al. 2014; Hanigan et al. 2018) that investigated the relationship between drought and mental health. This study addressed the remaining knowledge gap by objectively testing the relationship between commonly used drought indices and well-being outcomes to establish if current methods of quantifying drought effectively capture well-being outcomes.

Findings indicate that several commonly used drought indices are not correlated to well-being outcomes, for example the HDSI (agricultural drought) may not be the most appropriate index to use if K10 is the outcome measure. This is significant because K10 is a common measure used in well-being studies (Kessler et al. 2002). In addition, while the ARMHS WI has been shown to be an effective measure of well-being in some contexts (Kelly et al. 2011), it is not well correlated with the commonly used drought indices investigated in this study. These findings highlight the need to identify, or if needed develop, drought indices that realistically represent the location- or sector-specific relationship between drought and health outcomes (Van Loon et al. 2016).

Limitations of the study include the spatial resolution of postcodes and the inability to account for heterogeneous drought conditions within individual postcodes. There is the potential for reporter bias in the ARMHS as it was a self-reported survey. As demonstrated in Austin et al. (2018) sociodemographic factors, age, remoteness, and financial position, influence the relationship between drought and well-being. Future research that investigates the relationship

TABLE 14. Number of statistically significant associations for WI at five time windows for each postcode. The highest-frequency time window for each postcode is in boldface type.

	6		12		24		36		60	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
2480	5	6.94	15	20.83	4	5.56	9	12.50	1	1.39
2795	0	0	0	0	0	0	0	0	0	0
2800	0	0	0	0	0	0	0	0	0	0
2835	0	0	0	0	0	0	0	0	0	0

FIG. 8. Associations between the percentage of months below average and WI for the four postcodes at the five time windows: (a) 6, (b) 12, (c) 24, (d) 36, and (e) 60 months; H = high well-being, M = moderate well-being, and L = low well-being. The orange line in the interquartile box is the median.

between drought indices and well-being should include these moderators.

Comparisons between groups of distress as measured by K10 did not reveal a consistent pattern. For example, the high distress group did not consistently have the driest

drought score. This is possibly explained by the health impacts of drought persisting long after drought has technically ended (e.g., people continue to be distressed because of financial hardship or breakdown of community networks that persists after the drought) (Austin et al. 2018). Also

FIG. 9. As in Fig. 8, but for associations between the number of months below decile 2 and WI.

interesting was that moderate distress often occurred with the driest or equal driest conditions for both agricultural and meteorological drought. This may be explained by people having started to adapt as the drought develops and approaches its peak (e.g., via changes to household budget, securing off-

farm income, changes to farming practices or lifestyle, or accessing government funding that has become available) (Sartore et al. 2008). A significant contributor to well-being is the feeling of control over your life (Kelly et al. 2011), so by beginning some adaptive activities as listed above, which in

FIG. 10. As in Fig. 8, but for associations between NDVI and WI.

turn provides a sense of control, may explain the moderate distress levels even when the drought is at its peak.

The most appropriate drought index for any given situation, depends on the drought aspects (duration, frequency, and magnitude) (Van Loon et al. 2016), drought type, location,

well-being measure, and time frame. This paper demonstrates that there is no universal, optimal drought index for use with a given well-being outcome. Rather, when quantifying the relationship between drought and well-being, we must acknowledge the uncertainty associated with measuring drought and

FIG. 11. Associations between WI and all drought indices at the 12-month window for the four postcodes: (a) percent of normal, (b) months below average (number), (c) months below average (percent), (d) deciles, (e) months below decile 1 (number), (f) months below decile 1 (percent), (g) months below decile 2 (number), (h) months below decile 2 (percent), (i) months below decile 3 (number), (j) months below decile 3 (percent), (k) months below decile 4 (number), (l) months below decile 4 (percent), (m) SPI, (n) SPEI, (o) NDVI, (p) PDSI, (q) HDSI (count), and (r) HDSI (sum); the orange line in the interquartile box is the median.

the use of indices, consider the range of drought impacts, and account for the potential resulting variations produced as a result of using different indices (Wanders et al. 2017).

5. Conclusions

This paper demonstrates the complexity of the relationship between drought and well-being. It provides evidence that drought varies spatially and temporally and that, when quantifying drought in health studies, the choice of drought type, drought index, time window, and well-being outcome must be rigorously selected. This selection needs to be made according to location and context. An important point is that researchers need to be justified and transparent about these choices so as to build a better evidence-based empirical understanding of health and drought.

This paper reinforces the key point from Wanders et al. (2017) and Askarimarnani et al. (2021), that drawing conclusions using one drought index is not recommended, given that one index cannot cover the breadth of drought impacts. Rather, an index needs to be selected on the basis of drought characteristics, drought type, spatial location, impacts, and the individual context of the community and sector. This paper offers one method for making such a selection when using drought indices in studies with well-being outcomes. To date, existing empirical drought and well-being studies appear to use an arbitrarily chosen drought index, based on the index's performance in another context, rather than its capacity to predict well-being outcomes. It must be acknowledged that just because a drought index is useful/accurate in one given situation it is not necessarily useful or accurate in another, including in a well-being context.

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