

Application of effective drought index for quantification of meteorological drought events: a case study in Australia

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Abstract Drought indices (DIs) that quantify drought events by their onset, termination, and subsequent properties such as the severity, duration, and peak intensity are practical strata-gems for monitoring and evaluating the impacts of drought. In this study, the effective drought index (EDI) calculated over daily timescales was utilized to quantify short-term (dry spells) and ongoing drought events using drought monitoring data in Australia. EDI was an intensive DI that considered daily water accumulation with a weighting function applied to daily rainfall data with the passage of time. A statistical analysis of the distribution of water deficit period relative to the base period was performed where a run-sum method was adopted to identify drought onset for any day (i) with $EDI_i < 0$ (rainfall below normal). Drought properties were enumerated in terms of (1) severity (AEDI \equiv accumulated sum of $EDI_i < 0$), (2) duration (DS \equiv cumulative number of days with $EDI_i < 0$), (3) peak intensity ($EDI_{\min} \equiv$ minimum EDI of a drought event), (4) annual drought severity (YAEDI \equiv yearly accumulated negative EDI), and (5) accumulated severity of ongoing drought using event-accumulated EDI (EAEDI). The

analysis of EDI signal enabled the detection and quantification of a number of drought events in Australia: Federation Drought (1897–1903), 1911–1916 Drought, 1925–1929 Drought, World War II Drought (1937–1945), and Millennium Drought (2002–2010). In comparison with the other droughts, Millennium Drought was exemplified as an unprecedented dry period especially in Victoria (EAEDI \approx -4243, DS = 1946 days, $EDI_{\min} = -4.05$, and YAEDI = -4903). For the weather station tested in Northern Territory, the worst drought was recorded during 1925–1929 period. The results justified the suitability of effective drought index as a useful scientific tool for monitoring of drought progression, onset and termination, and ranking of drought based on severity, duration, and peak intensity, which allows an assessment of accumulated stress caused by short- and long-term (protracted) dry events.

Nomenclature

AEDI	Accumulated deficit of EDI
AWRI	Available water resources index
AWRI _{min}	Minimum value of AWRI
BMDI	Bhalme and Mooley drought index
D	Duration of summation
DEP	Deviation of EP from climatology
DI	Drought indices
DS	Drought duration
DS _t	Total dry duration (DS _t)
EAEDI	Event-accumulated value of effective drought index
EDI _{y min}	Yearly minimum effective drought index
EDI	Effective drought index
EDI _{min}	Peak intensity of drought (minimum EDI)
EDI _{y avg}	Yearly averaged effective drought index
EEDI _{min}	Event-averaged intensity
EP	Effective precipitation

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MEP	Mean EP based on climatology
P	Precipitation
P_y	Yearly precipitation
PDSI	Palmer drought severity index
PRN	Precipitation return to normal
RAI	Rainfall anomaly index
RDDI	Rainfall-decile drought index
SMDDI	Soil moisture-based deciles drought index
SPEI	Standardized precipitation and evapotranspiration index
SPI	Standardized precipitation index
ST(DEP)	Standard deviation of DEP
YAEDI	Yearly accumulated deficit of EDI
Acronyms used for drought periods	
1914–15D	1914–1915 drought
1925–29D	1925–29 drought
1967D	Drought of the year 1967
1972D	Drought of the year 1972
1982–83D	Drought during 1982/1983 period
FD	Federation Drought (1897–1903)
WWIID	World War II Drought (1937–1945)
MD	Millennium Drought (2002–2010)

1 Background

A drought is a sustained period of significant hydrometeorological imbalance caused by a cumulative occurrence of dry spells with little or no measurable rainfall. Generally, drought is classified according to the meteorological, hydrological, agricultural, and socioeconomic perspectives (Botterill and Wilhite 2006). Meteorological droughts, which occur due to a serious deficit in rainfall, are perhaps the leading cause of other categories of events, while hydrological drought stems from meteorological effects on the environmental flows (e.g., stream or river flow) (Hayes et al. 2011). The persistence of meteorological drought for a prolonged period leads to agricultural and socioeconomic consequences; thus, the longer and the more spatially extensive a meteorological drought is, the more likely is the occurrence of the other types of events (Mpelasoka et al. 2008). As drought evolves from meteorological to hydrological to agricultural, the impacts can vary by region and season, as does the need to monitor different hydrologic cycles with a variety of drought indicators that best align with the depiction of impacts. As drought is complex and insidious with a slow progressive phase, it produces detrimental impacts globally in excess of \$US6–8 billion per year (Botterill and Wilhite 2006; Pandey et al. 2008a, b; Wilhite 2000). The ability to closely monitor the initiation, termination, frequency, and accumulated stress of drought is very important from practical perspective. An obstacle in drought monitoring, however, is the lack of a universal definition and the level of detail provided by drought

monitoring tools that may be insufficient for early warning systems (Mishra and Singh 2010, 2011).

Australia is a dry continent with fragile, harsh, and extreme conditions (Deo and Şahin 2015a, b; Deo et al. 2009; Dijk et al. 2013; Timbal and Fawcett 2013; Ummenhofer et al. 2009). It is known to experience moderate to severe multi-year and multi-decadal droughts (Franks and Kuczera 2002; Kiem and Franks 2004; Kiem et al. 2003; Verdon-Kidd and Kiem 2009, 2010). In eastern Australia, drought is linked to El Niño events causing a shift of rain-bearing systems offshore into the tropical Pacific Ocean (Murphy and Timbal 2008; Trenberth et al. 2014) while in the southwest, the cool phase of the Indian Ocean Dipole moment favors the persistence of dry conditions (Ashok et al. 2003). An inventory of drought events in Australia showed its detrimental impacts on country's economy (Adams et al. 2002) (Appendix Table 7). Therefore, many studies used analytical and modelling tools to analyze the complex nature of drought (Dijk et al. 2013; Timbal and Fawcett 2013). In order to closely monitor a drought and to quantify its properties, scientific measures in terms of standardized metrics of rainfall deficiency are required (Mishra and Singh 2010, 2011).

A large body of literature shows that the monitoring of drought is performed by drought indices (DI) that are normalized statistical metrics deduced in rainfall deficit periods (Mishra and Singh (2010, 2011) and references therein). Popular rainfall-based DIs are Bhalme and Mooley drought index (BMDI) (Bhalme and Mooley 1980), rainfall decile drought index (RDDI) (Gibbs and Maher 1967), rainfall anomaly index (RAI) (Timbal and Fawcett 2013; Van Rooy 1965), and the standardized precipitation index (SPI) (Deo 2011; McKee et al. 1993), while DIs based on temperature, evapotranspiration, and soil moisture are soil moisture-based deciles drought index (SMDDI) (Mpelasoka et al. 2008), Palmer drought severity index (PDSI) (Palmer 1965), and standardized precipitation and evapotranspiration index (SPEI) (Deo and Şahin 2015a, b; Vicente-Serrano et al. 2010). DIs are able to provide multi-scale characterization of drought ranging from the smallest timescale (month) to annual, decadal, or multi-decadal scales. New evolving research has led to several DIs, including the multivariate composite drought index (CDI) which considers variables related to individual types of drought (Waseem et al. 2015), the PDSI with a coupling variable infiltration capacity (VIC) model and self-calibrating PDSI (Liu et al. 2015), the Global Precipitation Climatology Centre Drought Index (GPCC-DI) that provides estimation of water supply anomalies with respect to long-term statistics as a combination of SPI and SPEI (Ziese et al. 2014), the modified SPI for arid locations in Europe or the WMO RA VI Region (Pietzsch and Bissolli 2011), and the real-time drought index (RDI) that evaluates drought impacts on a daily basis in real-time using the concept of water shortage according to residential, agricultural, and industrial water (Oh et al. 2015).

In Australia, the SPI and RDDI are the two most popular DIs used due to their simplicity, interpretability, and applicability (Deo et al. 2009; Mpelasoka et al. 2008). The SPI provides drought information based on statistical distribution of rainfall for an aggregation length starting from 1 to 48 months (McKee et al. 1993) while RDDI compares rainfall accumulation with a climatological period of three monthly periods (Deo et al. 2009; Mpelasoka et al. 2008). However, both have limitations for continuous monitoring of drought status. They are calculated monthly so even if a drought had occurred, an index value is not available until the last day of the month. A few previous studies (Byun and Wilhite 1999; Kim et al. 2009) reported that a meteorological drought can be terminated by a single day's heavy downpour. Therefore, an objective method where rainfall is analyzed on a daily basis with larger weights assigned to recent rainfall versus, and smaller weights assigned to antecedent rainfall is particularly appealing for assessment of water resources in relation to drought. These DIs also have complications in objectively setting the base period (Byun and Wilhite 1999). Kim et al. (2009) showed the disadvantages of sliding time scales for drought classification with simple sums of rainfall used without weighted consideration of antecedent rainfall for detection of dry periods. Except for the SPEI which has evapotranspiration in its formulation, none of the other meteorological DIs consider the loss of water resources over the passage of time and can therefore undermine drought-related stress. SPI operates on probabilistic scales where its relationship with frequency depends on the time period; therefore, different time aggregations are not suitable for ranking drought (González and Valdés 2006). Also, the drought quantification over a fixed period (e.g., 1, 3, or 6 months) prevents the detection of start dates and assessment of short or ongoing events if a drought has its onset in the middle of a month and withdrawal prior to the end of the monthly period, although the impacts in that monthly period may have been severe (Morid et al. 2006; Pandey et al. 2008a, b).

In light of the necessary considerations for drought monitoring, it is argued that a versatile drought monitoring index should emphatically identify onset and termination of drought and characterize its duration (length of water deficit), severity (accumulated volume of water deficit), and peak intensity (worst water deficit situation in a given period) (Mishra and Singh 2010, 2011; Pandey et al. 2008a, b). Also, a daily index is more functional for continuous monitoring of drought or even flood (Deo et al. 2015; Lu 2009, 2012; Lu et al. 2013), although it should be interpreted with caution since impacts are normally felt after continued persistence of water deficit. Oh et al. (2015) showed that a real-time index evaluating drought on a daily basis is beneficial for calculating water shortage for short-term needs (e.g., residential, agricultural, or industrial). From this viewpoint, a quantitative definition based on statistical runs theory is appropriate to help analyze a sequential time series that defines a drought episode by a threshold value below which water deficit is sufficient to

identify the event. Originally proposed by Rice (1945), the work of Yevjevich et al. (1967a, b; Yevjevich (1991) successfully applied runs theory to quantify drought severity, duration, and peak intensity based on drought monitoring data series.

In this study, we applied the effective drought index (Byun and Wilhite 1999) as an objective measure of daily water accumulation based on weighted current and antecedent rainfall. The concept of effective drought index (EDI) follows recent research for quantifying floods and drought (Deo et al. 2015; Lu 2009, 2012; Lu et al. 2013; Oh et al. 2013, 2015). Before defining the drought severity, EDI defines the drought onset date for any i th days with $EDI_i < 0$. Consequently, the EDI has advantages over month-based DIs: (1) provision for daily severity of drought and measurement of short- and long-term events, (2) placing more weight on recent rainfall versus less on past rainfall to consider the surplus or deficit of water resources for drought assessments, (3) monitoring the continued progression of drought on a daily basis, (4) enumerating a measure for precipitation that is needed for return to normal conditions (PRN) and the available water resources index (AWRI) as supplementary parameters for assessing water scarcity, (5) allowing a methodology for drought characterization using the runs theory where accumulated stress from ongoing (continuing) drought is accounted for by cumulative deficits, duration of deficit, and peak intensity of water deficit (Cancelliere and Salas 2004; Dracup et al. 1980; Sen 1980), and (6) detection of accumulated stress due to intense (short-term) dry spells or protracted (continuing) drought events within a unified time series of the index (Kim et al. 2009; Lee et al. 2012).

The novelty of our paper is that it explores, for the first time, the suitability of EDI for drought monitoring in Australia following many investigations of EDI approach around the world (Byun et al. 2008; Byun and Wilhite 1999; Dogan et al. 2012; Kalamaras et al. 2010; Kim and Byun 2009; Kim et al. 2009; Kim et al. 2011; Lee et al. 2012; Masinde 2013; Morid et al. 2006; Oh et al. 2013; Pandey et al. 2008a, b; Smakhtin and Hughes 2004; Yamaguchi and Shinoda 2002). Merits of the EDI were outlined by Pandey et al. (2008a, 2008b) where its capability for quantifying daily water resources in a drought period was demonstrated. Morid et al. (2006) demonstrated the advantage of EDI for detecting the start and end of drought compared to the percent of normal, SPI, China Z index, and the Z score. Dogan et al. (2012) noted that the EDI was sensitive to subtle changes in rainfall, and Kim et al. (2009) used the EDI concept to develop the AWRI, a parameter for estimating the water resources in drought situations, in addition to demonstrating its superiority for continuous monitoring of short and long-term drought. Byun et al. (2008) showed the ability of EDI for drought prediction, Kim et al. (2011) developed a spatio-temporal drought map, Lee et al. (2012) performed similar work, Park et al. (2015a, b)

utilized EDI for projection of future drought using RCP 8.5 warming scenarios, and Park et al. (2015a, 2015b) developed a method for water-abundant seasons using AWRI. Recently, Jain et al. (2015) compared EDI with SPI, RDDI, Z score, China Z score, and rainfall departure in Ken River Basin (India). In this work, the EDI, which has a self-defined timescale and is free from the time-step problem faced by other indices (e.g., SPI or RDDI), was found to be highly correlated with other indices, but more importantly, it was able to better identify drought conditions than the other DIs. However, no previous work has applied the effective drought index for drought monitoring in Australia, although our recent study has developed an EDI-based predictive drought model for eastern Australia (Deo and Şahin 2015a, b).

In this paper, we performed drought analysis using daily EDI over the period 1890–2010. A run-sum approach for quantifying the drought severity was adopted, consistent with previous viewpoints on monitoring of continuing drought (Kim et al. 2009). Therefore, the accumulated water-related stress due to ongoing drought was assessed using the cumulative sum of the drought indicators (Yevjevich et al. 1967a, b). Subsequently, the drought indicator ($EDI_i < 0$) was used to analyze the progression of an identified drought event based on negative EDI over sustained dry period (hence, the extent of a drought was assessed by accumulation of consecutively negative EDI). The aim of this research was threefold: (1) to demonstrate the applicability of the EDI for daily monitoring and quantifying short-term drought (dry spells) and ongoing drought and its comparison with SPI, RDDI, and RAI, (2) to test the potential of EDI for quantifying severity, duration, and peak intensity of long-term (continuing) drought in the context of accumulated stress caused by successively below mean rainfall ($EDI < 0$), and (3) to illustrate the efficacy of the EDI for seasonal characterization of drought events.

2 Materials and methods

2.1 Climate data and the study area

The pre-processed daily rainfall data were acquired from the Australian Bureau of Meteorology (BOM) (<http://www.bom.gov.au/climate/data-services/>) (Haylock and Nicholls 2000). The data were initially collated from 24-h observations (Jones et al. 2009; Lavery et al. 1992, 1997; Suppiah and Hennessy 1998). Quality tests conducted by Torok and Nicholls (1996) made adjustments to the raw data and corrected inhomogeneities caused by station relocations and adverse exposures to the measurement sites using various forms of objective statistical methods. As stated in Lavery et al. (1992), rainfall records were not adjusted for discontinuities but were rejected if suspected of inhomogeneity or data quality issues. Standard reliability tests were performed where

the number of missing observations was determined and frequency histograms of daily rainfall were examined for evidence of rounding errors or ignorance of small rainfall amounts. The exposure and site locations were examined with available station histories. Stations with any changes that might have had an impact on the record were rejected. Rainfall records that passed these quality checks were then tested for homogeneity using a cumulative deviation statistic for each annual rainfall series to identify years with excessive drift from the expected climate. Metadata was then examined to determine whether the change was likely to be artificial or not (BOM 2008; Haylock and Nicholls 2000; Hennessy et al. 1999; Suppiah and Hennessy 1998). The data used in this study have also been used in other climate change studies (Alexander et al. 2006; Nicholls et al. 1996; Smith 2004; Timbal and Fawcett 2013).

Following the criteria for candidate stations, (1) reasonably lengthy coverage (more than 100 years), (2) distinct climatic characteristics including drought-prone sites, and (3) the least amount of missing data, the daily rainfall data for seven meteorological stations were extracted. Table 1 shows the station, years of available data, mean annual rainfall, and drought periods for which data were missing. As the EDI was primarily calculated on a daily basis, missing data in drought-rich periods can be a matter of concern (e.g., Trenberth et al. 2014). Despite the quality checks performed in the original data portal, our preliminary inspection showed that ≈ 10 – 14 % of data for Portarlinton and Wallaroo for 1982–83D and ≈ 5 – 19 % of data for Portarlinton, Wallaroo, Cranbrook, and Katherine for 1991–95D were missing. For the Federation Drought, no data were available for Cranbrook and Fairy Mead, and only 38 % were available for Cape Grim. The discontinuities were recovered by calendar mean precipitation following the approach of Kim et al. (2011). However, due to possible erroneous effects induced in drought quantification, the drought events in periods of missing data were not measured in this study.

Figure 1 plots the study region with the candidate stations considered for drought analysis in Australia. Note that in this paper, only a sample of stations was chosen as a pilot study but a follow-up study could consider a larger set of stations depending on the availability of daily rainfall data. The five stations (Cranbrook, Portarlinton, Deniliquin, Fairy Mead, and Wallaroo) are in drought-prone regions of eastern and southwestern Western Australia (Li et al. 2005; Timbal and Fawcett 2013), and the station Katherine (Northern Territory) is located in a region that has experienced an overall reduction in drought incidences due to increased rainfall amounts after the 1950s (Hennessy et al. 2004). The precipitation patterns for Katherine and Fairy Mead are opposite in trend to the other stations (Fig. 1b); therefore, a comparison of drought for these stations is interesting. It is also acknowledged that since most stations are in the coastal region, there is a lack of stations in the central regions (120 – 130° E, 10 – 30° S) (Haylock and Nicholls 2000).

Table 1 The station characteristics for the high quality rainfall data acquired from the Australian Bureau of Meteorology (BOM)

BOM station ID	Station name/state	Location	Elevation (m)	Data start date	Period of missing days	Annual rainfall P (mm)
087053	Portarlington (Victoria)	144.64° E 38.12° S	77	1 June 1884	1982–83D (14.8 %) 1991–95D (19.2 %)	640.7
074128	Deniliquin (New South Wales)	144.95° E 35.55° S	93	1 February 1858	MD (0.19 %)	397.7
022020	Walleroo (South Australia)	137.63° E 33.93° S	10	1 January 1884	1982–83D (10.8 %) 1991–95D (10.3 %)	383.6
010537	Cranbrook (Southwest Western Australia)	117.57° E 34.30° S	255	1 January 1908	FD (100 %) 1991–95D (5.9 %)	528.7
091011	Cape Grim (Tasmania)	40.69° S 144.72° E	17	1 January 1893	FD (38.6 %)	949.8
039037	Fairy Mead Sugar Mill (Queensland)	152.36° E 24.79° S	3	1 January 1910	FD (100 %) WWIID (17.2 %)	1077.2
014902	Katherine Council (Northern Territory)	132.26° E 14.46° S	103	1 January 1888	1991–95D (11.0 %) MD (18.0 %)	1019.5

The percentage of missing daily data that was coincident with major drought periods has been shown

2.2 Theory of the effective drought index

A Fortran code available at <http://atmos.pknu.ac.kr/~intra3/> (Byun and Wilhite 1999) was used for calculating the effective drought index for the seven pilot stations in Australia (Fig. 1a). Basically, the EDI procedure utilized the concept of daily effective precipitation (EP), which is the summed precipitation, P , with a time-dependent reduction function applied to

the current and antecedent rainfall over the passage of time (Eq. 1). The daily EP, which can also be used for flood risk studies (Deo et al. 2015), was compared with the climatological mean EP (MEP) (Eq. 2) and then normalized by the standard deviation (Eq. 3). According to the original work of Byun and Wilhite (1999), if P_m was the daily rainfall and N was the duration of the preceding period, then the EP for current day can be given as:

$$\begin{aligned}
 EP &= \sum_{N=1}^D \left(\left(\sum_{m=1}^N P_m \right) / N \right) \\
 &= P_1 + \frac{(P_1 + P_2)}{2} + \frac{(P_1 + P_2 + P_3)}{3} + \dots + \frac{(P_1 + P_2 + \dots + P_{365})}{365} \\
 &= P_1 \left(1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + P_2 \left(\frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + \dots + P_{365} \left(\frac{1}{365} \right)
 \end{aligned} \tag{1}$$

$$DEP = EP - MEP \tag{2}$$

$$EDI = \frac{DEP}{ST(DEP)} \tag{3}$$

Byun and Jung (1998) found that rainfall-runoff models show a similar effect to Eq. 1. Moreover, Deo et al. (2015) utilized the same concept related to water resources, except for flood possibility studies in Brisbane and Lockyer Valley region in Australia. In Eq. 1, the D is the duration of summation ($\equiv 365$), which is the most common precipitation cycle. MEP and ST(DEP) represent the climatological mean and standard deviations. The base period for calculating MEP and ST(DEP) needs to be longer than 30 years (e.g., Kim et al. 2011), so we used 1971–2000, a normal period used for analysis of the Australian climate (Deo et al. 2009; Jones et al. 2009;

Mpelasoka et al. 2008; Smith et al. 2008). Normally, the drought range is considered extreme ($EDI \leq -2.0$), severe ($-2.0 < EDI \leq -1.5$), and moderate ($-1.5 < EDI \leq -1.0$). However, in our study, we have identified a given day (i) as a dry day when the index was in its negative phase (i.e., $EDI_i < 0$) to identify all days of below normal rainfall. For in-depth methodological description of effective drought index, readers are referred to the original work of Byun and Wilhite (1999).

It is noteworthy that the concept of daily EDI was fundamentally disparate from the other DIs where no transformation or ranking of rainfall was necessary. Instead of transformation to normal distributions (e.g., SPI) or ranked rainfall (e.g., RDDI), the drought index was computed from the weighted precipitation data (Eq. 1). Subsequently, the deviations of weighted precipitation were normalized by

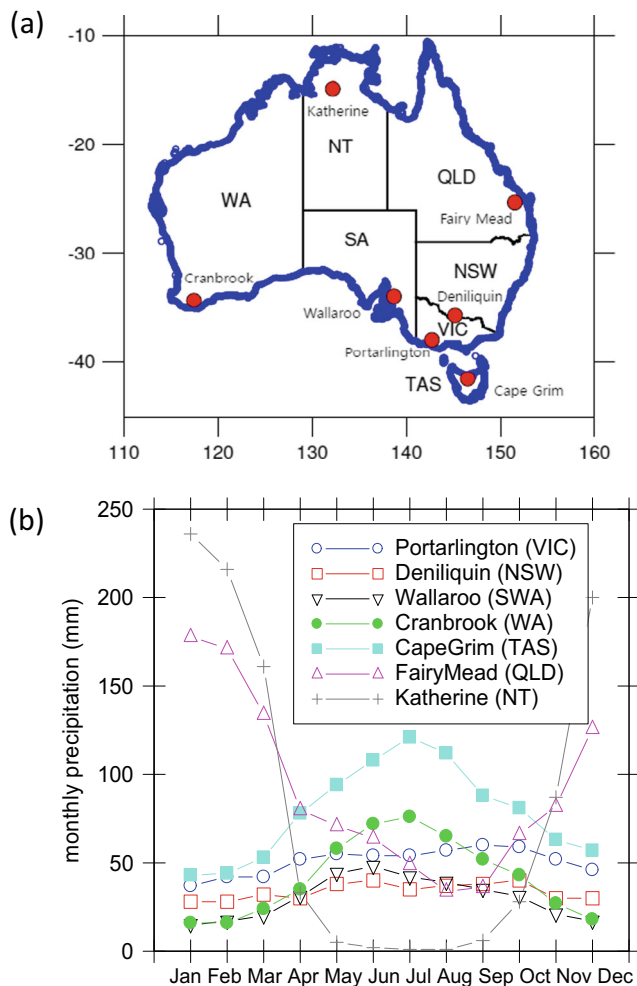


Fig. 1 **a** The study sites with candidate stations considered for drought analysis. **b** The mean monthly rainfall (P) climatology over the period 1910–2010. *NT* Northern Territory, *VIC* Victoria, *QLD* Queensland, *WA* Western Australia, *SA* South Australia, *TAS* Tasmania, *NSW* New South Wales

climatological means and standard deviations (Eqs. 2–3) so that in arid or dry climates, the normalization process makes it possible to compare the surplus or deficit of rainfall relative to a climatological period. In fact, the non-transformation of drought index or the rainfall preserved the skewness of the data series. Consequently, positively skewed rainfall is expected to produce a larger range of positive EDI than negative EDIs. Considering the negative EDI values are more important to represent rainfall that is required for a return to normal from a drought, this acts as an advantage of the method for accurate detection of the rainfall deficit period (Smakhtin and Hughes 2004). In addition, there was no need for distributional parameters or subsequent assumptions about rainfall data. Importantly, similar to the SPI, the EDI was standardized which allowed drought severity at different sites to be compared regardless of the climatic differences between them (Byun and Wilhite

1999; Lee et al. 2012; Morid et al. 2006; Oh et al. 2013; Smakhtin and Hughes 2004).

In addition to the EDI, the AWRI (total available water resources due to rainfall as source) and PRN (rainfall needed to recover prior deficit) were used to assess accumulated stress caused by the scarcity of water resources, viz.:

$$W = \sum_{N=1}^D \left(1/N\right) \quad (4)$$

$$AWRI = \frac{EP}{W} \quad (5)$$

$$PRN = \frac{DEP}{W} \quad (6)$$

where AWRI represents the available water resources in any period of consideration (Byun and Lee 2002; Byun and Wilhite 1999; Kim et al. 2009). A large value of the AWRI indicates that a large amount of water resources are available, and a small value indicates a deficiency. As it takes into account the daily reduction of water resources after precipitation, the AWRI was able to show daily changes in water-related conditions.

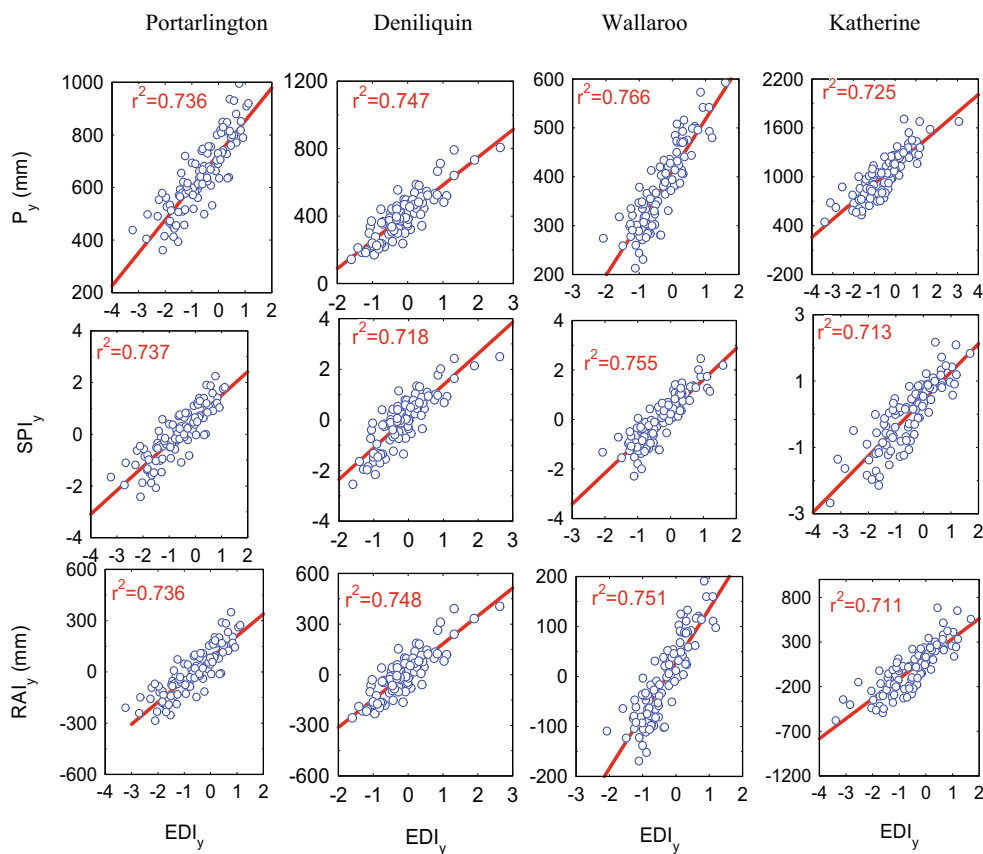
In this study, AWRI and PRN are used as supplementary parameters for assessing the available water resources based on rainfall and the estimated rainfall deficits caused by the ongoing drought (Kim et al. 2009). However, it is important to note that Eq. 5 behaves like a hydrological parameter but its fundamental derivation from rainfall makes it unsuitable for direct comparison with hydrological metrics (e.g., streamflow or soil moisture). Therefore, in the context of the present work, the AWRI should mainly be used to quantify meteorological drought events. Nevertheless, the AWRI has a general formula to represent the conversion of rainfall to available water resources (Byun and Lee 2002) based on a time-dependent reduction formula so it may therefore be used for various purposes such as comparison of drought, estimating soil moisture (Yamaguchi and Shinoda 2002), defining water-abundant seasons (Park et al. 2015a, b), defining rainy or Changma seasons (Choi et al. 2012), and flood possibility studies (Deo et al. 2015).

3 Results and discussion

3.1 Comparison of EDI with P , SPI, and RAI

A direct way to compare the first-order (visual) relationships between different DIs is a scatter plot (e.g., Kim et al. 2009). Figure 2 shows the yearly minimum EDI versus P , SPI, and RAI (Fig. 2) plotted from 1910 to 2010. For reasons of space, only four candidate stations are shown. The scatter diagram clearly displays directly proportional dependence of the EDI

Fig. 2 Scatter diagram of the annual rainfall (P_y ; mm), standardized precipitation index (SPI_y), and rainfall anomaly index (RAI_y ; mm) plotted with the annual effective drought index (EDI) from 1910 to 2010. Least square fitting with the square of Pearson correlation coefficient is shown



and the P , SPI , and RAI . Overall, a Pearson's coefficient (r) of 0.86 is obtained in all panels. Although this is only a preliminary assessment of the indices considered, it indicates that the EDI possesses similar skill to the SPI and RAI for detecting wet (or dry) conditions due to high (or low) rainfall. However, in spite of the statistical correlation of EDI with P and its corresponding DIs, a fundamental difference between the other DIs provides a rationale for its choice as a superior index. That is, the SPI is calculated from cumulative rainfall on sliding time scales (1, 3, 6 months, etc.), but the EDI is a continuous daily signal (although it may be averaged for any time-scale of interest). As shown later with the other metrics, the EDI has better skill in monitoring of continuing drought than other DIs that operate on fixed time scales.

Moreover, the SPI is based on the summation of rainfall in the period of consideration but the EDI incorporates EP that uses a time-dependent reduction function (Eq. 1) to account for the diminishing of water resources over time (Byun and Wilhite 1999; Kim et al. 2009). It is for this reason and others such as greater objectivity that a direct comparison of the EDI with the other DIs is taken cautiously, although the choice of EDI remains superior, as shown later. In fact, previous studies, for example, Morid et al. (2006), Pandey et al. (2008a, 2008b), Dogan et al. (2012), and Jain et al. (2015), showed that the EDI was more responsive to emerging drought and defined more strategically a range of water scarcity conditions compared

with the SPI or the $RDDI$. Indeed, since the EDI system of drought assessment yields discrete classifications for different drought severities or intensities, this index can be considered useful for application in various water resource environments (e.g., agriculture).

3.2 Detecting annual drought using yearly effective drought index

In drought hydrology, the departure of rainfall from a given climatological period is commonly used in drought assessment impacts. We have therefore identified historical drought events at the station, Portarlington (Victoria) for the period 1890–2010 using annual rainfall (P) and its derivative as the RAI (Fig. 3). Both statistical metrics were compared with their corresponding yearly average and minimum effective drought index ($EDI_{y\text{ avg}}$, $EDI_{y\text{ min}}$). Interestingly, the magnitudes of the $EDI_{y\text{ avg}}$ and yearly minimum effective drought index ($EDI_{y\text{ min}}$) exhibited harmonic variation with the RAI , so that the years with significantly negative anomalies coincide with drought events that are well represented by the EDI . This indicates that the annual drought is adequately detected by the annual average EDI , which concurs with the approach of previous research (Kim et al. 2009).

Merits of the EDI for its application in analyzing drought in Australia are shown in Table 2, where the drought event is

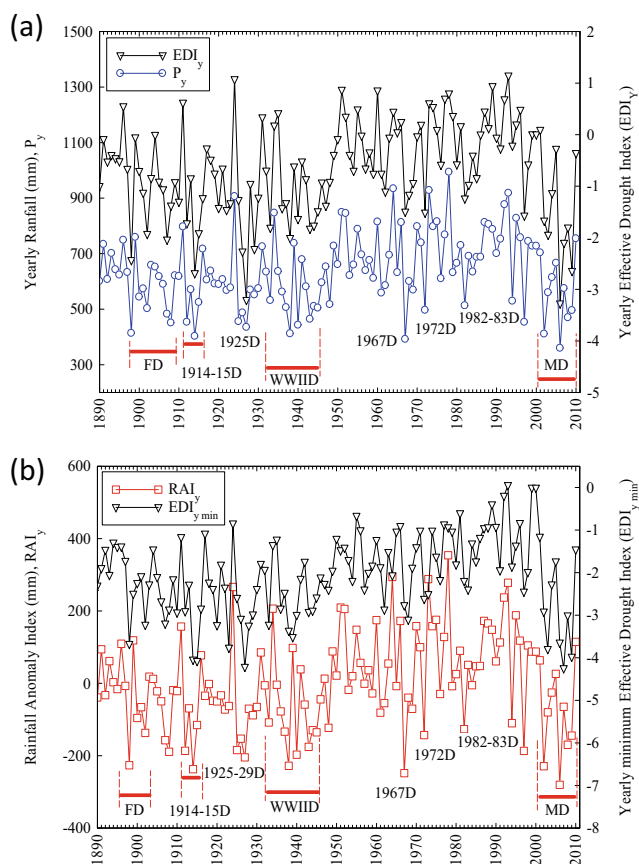


Fig. 3 The detection of annual drought years using **a** annual rainfall totals (P_y) and annual average effective drought index (EDI_y), **b** rainfall anomaly index (RAI_y), and annual minimum effective drought index ($EDI_{y\ min}$) for Portarlington (Victoria) for the period 1890–2010. Acronyms for drought years are FD (Federation Drought), 1914–15D (drought of the period 1914–1915), 1925–29D (drought of the period 1925–1929), WWIID (World War II Drought), 1967D (drought of the year 1967), 1972D (drought of the year 1972), 1982–83D (drought during 1982/1983 period), and MD (Millennium Drought)

ranked in terms of its severity (i.e., RAI). Interestingly, this ranking shows consistency with the severity ranks assigned by the $EDI_{y\ avg}$ and the $EDI_{y\ min}$. If we closely observe the

actual rainfall deficiency in the periods under concern, then the highest magnitude of the RAI_y is ≈ -281 for the Millennium Drought (MD) event, which is in agreement with the highest intensity of the drought event (i.e., $EDI_{y\ min}$ of -4.25). This event also exhibits marked shortage of water resources (of minimum value of AWRI ($AWRI_{min}$) = 30 mm) and subsequently captures the highest precipitation return to normal (173 mm). It is thus postulated that significant impacts from the Millennium Drought event and the consequent accumulated stress on water-sensitive areas (e.g., agriculture) were highly likely, as captured by the yearly averaged EDI and the AWRI.

A scrutiny of the data for the 1967D appears to exhibit an inconsistency between the $EDI_{y\ avg}$ and the P and RAI. That is, the $EDI_{y\ avg}$ was not very much negative (only -1.52) whereas the precipitation value was very low (392 mm), and the rainfall anomaly was significantly negative (≈ -249 mm). A plausible explanation is drawn from the computational methodology of the EDI, which differed from using raw P or rainfall anomaly relative to the climatology. As the EDI was responsive to the current day as well as the previous (antecedent) rainfall accumulations based on time-reduction function (Byun and Wilhite 1999), any contributory (high) rainfall from previous years is likely to impact the abundance (or shortage) of water in the current year (1967). If so, this is likely to moderate the magnitude of drought and consequently reduce the negativity of the EDI.

To verify this, we inspected rainfall data between 1964 and 1966 (not shown here) and found a positive rainfall anomaly between 54 and 293 mm and a relatively large 3-year average rainfall (769 mm). The latter was approximately 120 % of the climatological rainfall (641 mm). However, due to very low rainfall in 1967, the RAI classified the year as a dry period, whereas the EDI, which considered time-dependent rainfall accumulation rather than the gross value per year, classified it as a “not so dry” year. This is primarily because water resources in previous years acted as an offsetting factor for

Table 2 A list of annual drought events identified by the annual value of the rainfall anomaly index (RAI_y) compared with the annually averaged effective drought index (EDI_y)

Drought	RAI_y (mm)	EDI_y	$EDI_{y\ min}$	$AWRI_{y\ min}$ (mm)	PRN_{max} (mm)	P (mm)
MD	-281	-3.19	-4.25	37	173	360
1925-29D	-245	-3.21	-4.22	41	157	436
191415-D	-238	-2.65	-4.08	42	149	403
FD	-227	-2.44	-3.68	40	111	414
WWIID	-229	-2.01	-3.52	33	144	413
1967D	-249	-1.50	-2.77	56	92	392
1972D	-144	-1.52	-2.62	42	90	497
1982–83D	-128	-1.24	-2.40	46	88	514

The annual value of peak drought intensity ($EDI_{y\ min}$), annual minimum available water resources index ($AWRI_{y\ min}$), and annual maximum precipitation return to normal ($PRN_{y\ max}$) is shown. The worst annual severity of drought is in boldface

the 1967D. It should also be noted that the previous 3-year average AWRI (1964–1966) was reasonably high (74.5 mm) compared to other years, and the EDI was between 0 and 0.44, so none of those years were in fact characterized by drought. Therefore, the 1967D was flagged as a moderate dry year. This provides an example of the superiority of the EDI over anomaly indices used for detection of annual drought.

A follow-up deduction on the practicality of the EDI can be made. Suppose rainfall in any particular year is 1200 mm and this equals the climatological value, then the RAI will not classify the year as a drought year. On the contrary, if all heavy rainfall is concentrated on 31 December and the days before this period are dry, then all of those days are classified as dry spells. However, if 12 monthly rainfalls were evenly distributed, then the EDI will not classify the year as a drought year. Indeed, a lack of rain for days prior to 30 December is expected to cause water-related stress and the danger of short-term intense dry days, irrespective of the actual value of the annual anomaly. The merit of the EDI for the encapsulation of dry conditions due to fluctuating water resources in previously dry or wet periods is a practical advantage of the effective drought index.

3.3 Definition of long-term (ongoing) drought events

In Section 3.2, the annual value of the EDI was illustrated to be a good indicator of drought measurement per year but the drought monitoring skill is limited to an overall assessment rather than the measurement of the severity of ongoing (either short- or long-term) events. However, multi-year droughts such as the Millennium Drought event (e.g., Ummenhofer et al. 2009) that progressed continuously for days, months, or years often require an objective quantitative definition to enable the measurement of accumulated severity. Following this viewpoint, the onset of a drought event was defined as the calendar date when EDI first drops below 0, and secession when it last exceeds this value while retaining negativity after onset. Following the run-sum method of Yevjevich et al. (1967a, 1967b), the properties of continuing drought events were defined as follows:

$$\text{Severity} \equiv \text{AEDI} = \sum_{i=1}^N \text{EDI}_i < 0 \tag{7}$$

$$\text{Peak drought intensity} = \min(\text{EDI})_{\text{DS}} \tag{8}$$

$$\text{Duration (DS)} \equiv \sum_{i=1}^{i=N} N \tag{9}$$

where i is the date after onset day, EDI_i is the index for a period with continuously negative Drought duration DS , EDI_N refers to EDI of the last day of drought, and the AEDI

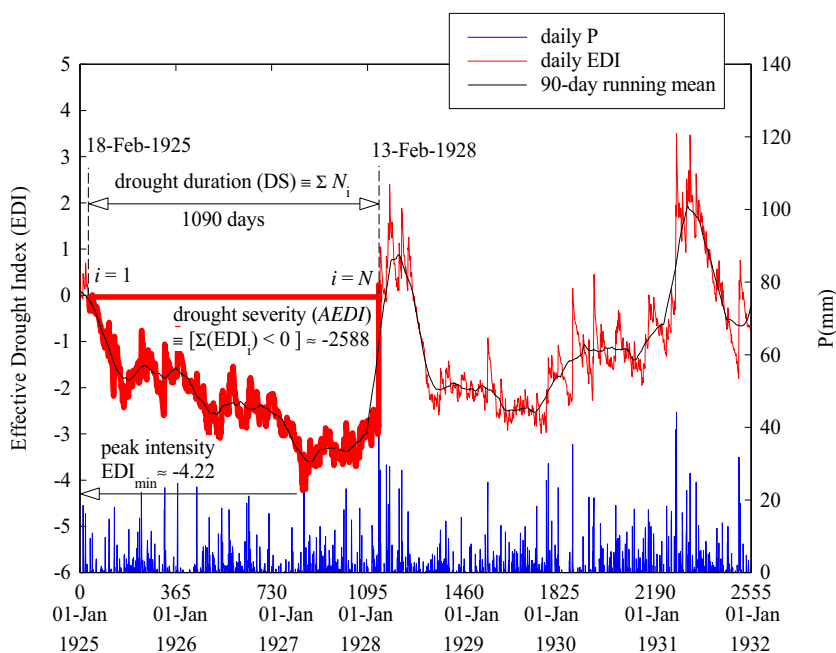
is the accumulated EDI for any continuing drought period (hereafter AEDI) (Byun and Wilhite 1999; Kim et al. 2009).

According to the drought assessment properties shown in Eqs. 7–9, it is important to clarify that the utilization of the AEDI method for continuous monitoring of drought severity considers the fact that the impact of a drought should be measured in terms of the deficit in water volume, which by this definition is quantified in terms of the cumulative value of the EDI in a drought-sustained period (Kim et al. 2009). In this context, the runs theory (Rice 1945; Yevjevich 1991; Yevjevich et al. 1967a, b), which logically measures the water deficit volume, was utilized where the drought index value for all i th days with successive deficit in water resources (i.e., $\text{EDI}_i < 0$) was considered. Likewise, the peak drought intensity represents the “worst” water deficit condition within a drought period, as measured by the most negative value of the EDI, and the duration of drought is the length of the period when EDI_i was negative, in accordance with the running-sum method of Yevjevich et al. (1967a, 1967b).

To assess the practicality of Eqs. 7–9 for quantifying the accumulated stress due to the continuing drought events, the daily EDI for 1925–29D at the Portarlinton (Victoria) station is used (Fig. 4). Drought is evident in the period from 18 February 1925 to 12 February 1928 (first episode) and 24 June 1928 to 19 March 1931 (second episode). The first episode of the drought event lasted for 1090 days and acquired peak intensity (EDI_{min}) of -4.22 (29 April 1927). Interestingly, the very high rainfall between 13 February and 23 June 1928 was mimicked by a positive phase of the EDI. In this period, cumulative rainfall was 339 mm distributed over 131 days (rain rate = 2.60 mm day^{-1}), compared to 1391 mm over 1107 days (rain rate = 1.26 mm day^{-1}) in the previous (dry) period between 02 February 1925 and 12 February 1928. Upon crosschecking the available water resources index and precipitation return to normal (not shown here), an average daily AWRI and PRN of 119 and -15 mm for the wet and 74 and 92 mm for the dry periods were found. It can be seen that the higher rainfall rate and the abundance of water were presumably responsible for easing the first drought segment, as reflected accordingly by the positive EDI.

The second episode was less intense than the first one, lasting 999 days with an intensity of $\text{EDI}_{\text{min}} = -2.99$ (24 October 1929). As argued in Section 1.0, the EDI can be very useful in detecting the onset and end dates of a given drought and consequently for deducing the severity, intensity, and duration. That is to say, considering the first episode of drought, the onset date (18 February 1925) and end date of drought (12 February 1928) would be left undetected by the monthly indices (SPI, RAI, or the RDDI) since the entire monthly statistics, rather than the start and end dates, would be used. This is an advantage of the daily EDI over the monthly indices.

Fig. 4 The definition of duration (DS), severity ($AEDI$), and peak intensity (EDI_{min}) for ongoing drought events based on Eqs. 7–9 for Portarlington (Victoria) between 01 January 1925 and 31 December 1931

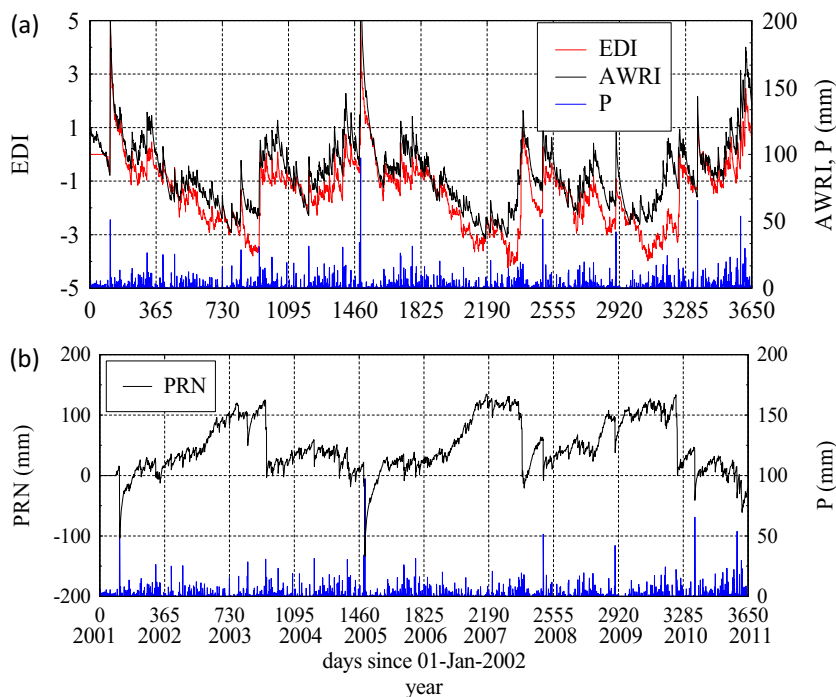


3.4 Monitoring daily patterns within the MD segment

In this section, we capitalized on the ability of the daily effective drought index for monitoring the daily changes in drought status for the MD event. This type of daily assessment of drought status is particularly useful for practical purposes such as the early detection of the onset of drought and its progression. Figure 5 shows the values of the EDI, AWRI, and the

PRN for the MD event in Portarlington (Victoria). Interestingly, the daily EDI was able to pick up dry episodes in 2002, 2006, and 2009, which was in agreement with the peak drought event based on rainfall anomaly values (e.g., Dijk et al. 2013, Timbal and Fawcett 2013, Ummenhofer et al. 2009). Based on the definition of drought onset (Fig. 4), the 2002 drought event commenced on 12 December 2001 and continued for 594 days.

Fig. 5 A daily time series plot of **a** effective drought index (EDI) and available water resources index ($AWRI$; mm) and **b** precipitation return to normal (PRN ; mm) for Millennium Drought period (MD) (2001–2010) for Portarlington (Victoria). The daily rainfall data (P_{tot}) has also been included in each panel



During this period, the drought peak intensity registered an $EDI_{\min} = -3.80$ (18 June 2003) and acquired the lowest value of available water resources Index on 20 February 2003 with a magnitude of $AWRI_{\min} = 41.54$ mm. Additionally, the rainfall needed to recover the prior deficit reached its peak value on 20 July 2003 ($PRN_{\max} = 125.08$ mm). Between 24 and 29 July 2003, a relatively high rainfall (≈ 78.9 mm) was presumably responsible for the marked increase in AWRI (54.00 to 110.65 mm) and a sharp decline in the PRN (123.00 to -3.19 mm). Consequently, the EDI was reduced from -3.66 to 0.44 in order to mimic the wetter conditions. An important deduction from this analysis is that the dry conditions persisting for several days reverted to nearly normal conditions ($EDI > 0$) with only 1 day of rainfall. This observation supports the practical utility of the EDI for monitoring a continuing drought, while taking into account drought relief that can be triggered by very heavy downpours. The monthly indices of drought (e.g., SPI) preclude such objective mechanisms for monitoring the dynamical nature of drought, particularly due to very heavy daily rainfall.

After July 2003, the dry conditions continued to become worse, reaching a peak value on 22 April 2004 although the maximum intensity of drought was lower ($EDI_{\min} \approx -2.84$), and the water scarcity conditions were lower ($AWRI_{\min} \approx 54.26$ mm) than the peak in July 2003. A close inspection of all data showed that the peak of the April 2004 segment was triggered by a dry summer (December–February) with only 86.5 mm of cumulative rainfall in this period.

The beginning of 2005 was not a drought period as the EDI was in its positive phase (4.25) as a consequence of heavy rain (97.4 mm) on 3 February 2005 and abundant water resources ($AWRI = 245$ mm). The peak of drought, however, was realized in the second phase (27 April 2007) with an EDI_{\min} of -4.25 . In response to this dry event, the available water resources index decreased to 40.8 mm and the PRN_{\max} increased to 130.9 mm. Also, the third phase was potentially catastrophic with $EDI_{\min} \approx -3.98$ and $PRN_{\max} \approx 116.6$ mm on 7 June 2006 although their magnitudes were 7 % lower than the second episode.

3.5 Dry and wet spell analysis for the MD

Using the notion of dry spells (or negative phase of the EDI) and wet spells (or positive phase of the EDI), we utilized this index for quantifying the relative frequency for the MD event and the available water resources for each class of drought experienced (Fig. 6). A dry spell (drier than normal day) was categorized into extreme ($EDI < -2.0$), severe ($-2.0 < EDI \leq -1.5$), and moderate ($-1.5 \leq EDI \leq -1.0$) and a wet spell into the synonymous categories with their positive EDI (Kim et al. 2009). The analysis yielded clear evidence that the three stations (Portarlinton, Wallaroo, and Cranbrook) encountered extreme dry spells during the MD

with relative frequency of 33.9, 7.3, and 7.8 %. For the same stations, the severe dry spells had relative frequencies of 6.6, 17.7, and 9.7 %.

Among all stations tested, Portarlinton experienced the largest impact of extreme dry spells. However, the frequency of severe dry spells for Wallaroo was the highest compared to other stations. It was interesting that less than 1 % of all days in Cape Grim, Fairy Mead, and Katherine are classified as dry spells. By contrast, their severe dry spells registered a frequency of 4.2 %, whereas those for Fairy Mead and Katherine are less than 2 %. For moderate dry spells, Portarlinton and Wallaroo exhibited nearly identical frequency (17 %), followed by Deniliquin (15 %) and Cape Grim and Fairy Mead (13 % each).

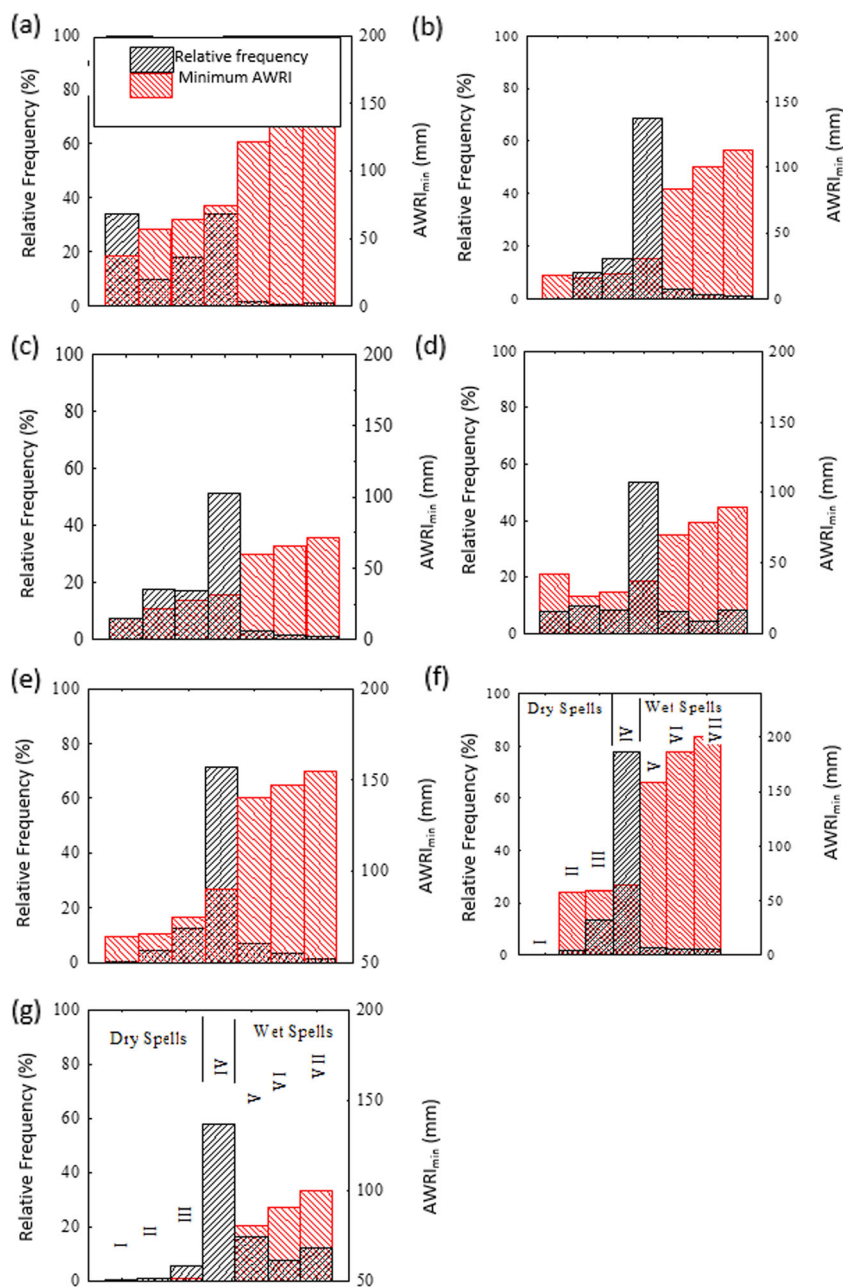
In terms of the available water resources index, the minimum value was obtained for Deniliquin and Wallaroo (~ 15.00 mm extreme, ~ 15.00 – 22.00 mm severe, and ~ 18.00 – 28.00 mm moderate) and concurred with their generally dry climate (Fig. 1b). On the other hand, Katherine and Cape Grim appeared to be immune from dry spells, but in terms of wet spells, a high frequency was evident for Katherine (~ 7 – 16 %) compared to less than 6 % at all stations except Cranbrook. By comparison, Cranbrook exhibited cases of both dry and wet spells with similar frequencies. The normal conditions for Deniliquin, Wallaroo, and Cranbrook recorded the lowest frequencies (~ 32 – 37 %).

When compared cumulatively for the entire dry period, the dry spells yielded the highest frequency for Portarlinton (~ 62 %) followed by Wallaroo (~ 43 %), Deniliquin and Cranbrook (~ 26 %), and Cape Grim and Fairy Mead (~ 16 %). Interestingly, this contrasted with the lowest frequency of dry spells for Katherine (~ 6 %). Opposite trends were evident for total wet spells, where the highest frequency of ~ 36 % was obtained for Katherine, ~ 26 % for Cranbrook, and ~ 11 % for Cape Grim. For Portarlinton, wet spells added to less than 6 % and therefore indicated its much greater vulnerability to drought. Compared with all other stations in consideration, the impact of the MD appeared to be most pronounced in Victoria and the least pronounced in Northern Territory.

3.6 Severity of long-term (continuing) drought per historical event

One may perceive that the drought severity may not solely depend on the magnitude of the index but rather on the period over which the drought has been sustained (Dogan et al. 2012; Kim et al. 2009). In Australia, for example, the MD event was sustained for several years; thus, intense accumulated stress on water resource sectors like agriculture, household water use, and consumption and the functioning of natural ecosystems was observed (Dijk et al. 2013; Ummenhofer et al. 2009). For such protracted drought events, the accumulated severity should be assessed with respect to its continuity over time

Fig. 6 The relative frequency (shown in percentage) of the dry and wet spell characteristics identified by the daily effective drought index and the minimum available water resources index ($AWRI_{min}$) from 1 January 2001 to 31 December 2010 for the Millennium Drought period. **a** Portarlinton. **b** Deniliquin. **c** Wallaroo. **d** Cranbrook. **e** Cape Grim. **f** Fairy Mead. **g** Katherine. For dry spell cases, the thresholds and/or categories of events are (I) extreme, $EDI < -2.00$; (II) severe, $-2.00 \leq EDI < -1.50$; and (III) moderate, $-1.5 \leq EDI < -1.0$ and for the wet spells (IV) moderate, $1.00 \leq EDI < 1.50$; (V) severe, $1.50 \leq EDI < 2.00$, and (VI) extreme, $EDI > 2.00$. Normal conditions are represented by $-1.00 \leq EDI < 1.00$



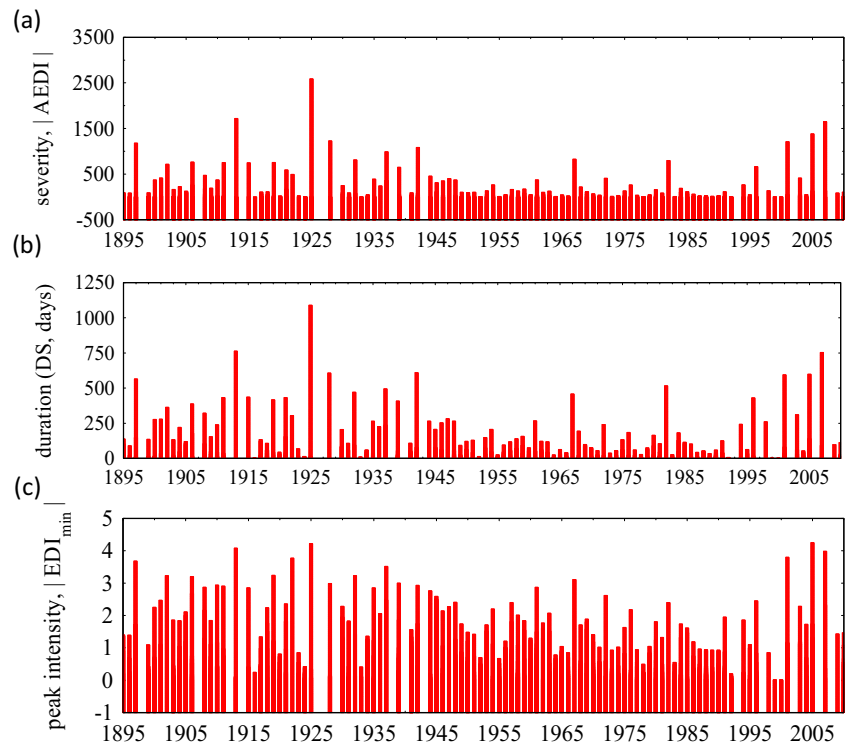
and the overall magnitude acquired by the index in that period (Kim et al. 2011).

Based on our earlier definitions (Eqs. 7–9) and the run-sum approach that allowed for the estimation of the accumulated stress caused by drought (Yevjevich et al. 1967a, b), we investigated the severity, $|AEDI|$, duration, DS and peak drought intensity, and $|EDI_{min}|$ of drought over the period 1890–2010 in Portarlinton (Victoria) (Fig. 7). The highest magnitude of all three properties was exhibited for the 1925–29D, followed by the 1914–15D and the MD which exhibited nearly identical magnitudes. Although the 1925–29D and the 1914–15D registered maximum values of the AEDI, they had single peaks in their duration and severity panels, whereas the MD

had three peaks centered on 2002, 2005, and 2006. On this basis, the latter event was a multi-year and potentially damaging drought event, with its effects compounded by the cumulatively negative EDI sustained for a longer duration. In addition, the FD (1897, 1902, and 1907), the World War II Drought (1937–1945) (WWIID) (1932, 1937, and 1942), and the 1967D were also very severe (Fig. 9), but the magnitude of these properties did not outweigh those of the MD. It is interesting to note that the duration and the severity were highly correlated, indicating that severe drought events were generally prolonged.

Information on the accumulated severity extracted from Fig. 5 was used to rank drought events recorded over the

Fig. 7 Historical diagram of properties of the drought events represented by **a** |AEDI|, **b** DS, and **c** |EDI_{min}| for Portarlinton (Victoria). Each bar was plotted at the start of dry period defined by the absolute value of accumulated EDI (|AEDI|) at the drought onset date



120-year period. Table 3 shows the onset, duration, severity, intensity, minimum AWRI, and the maximum PRN. It is important to realize that the consistent mechanism of the EDI allowed us to utilize any of these properties for ranking purposes and subsequently estimating the potential damage. In our study, the AEDI was used as a measure of accumulated severity due to drought. The results show that the 1925–29D and the 1914–15D were very severe (AEDI = -25788.90, -1721.80) and had a total duration of 1090 and 762 days and an intensity (EDI_{min}) of -4.22 and -4.08, respectively. The next case was the MD event punctuated in three segments, 2007 (AEDI = -1649.80), 2005 (-1382.50), and 2001

(-1210.30). The minimum AWRI was qualified as extreme water shortage so the damages from water shortages were perhaps very severe. Table 3 also shows that the order of drought severities based on the AEDI and the DS is different from those calculated based on the minimum EDI. In any drought comparison, one of the three methods can be adopted depending on the purpose of the comparison. Generally, the AEDI is assumed to be the most appropriate if the severity of the event in terms of its continuity over time is to be considered.

We also inspected the multi-year events using event-accumulated properties of drought. When considered

Table 3 The application of the daily effective drought index for ranking the drought events based on the accumulated value of consecutively negative effective drought index (AEDI) for Portarlinton (Victoria) over the 120-year period. The worst drought period has been shown in boldface

Rank	Drought	Onset date	Severity AEDI	Duration DS (days)	Intensity EDI _{min}	Min AWRI (mm)	Max PRN (mm)
1	1925–29D	18 February 1925	-2588.9	1090	-4.22	40.6	177
2	1914–15D	4 June 1913	-1721.8	762	-4.08	41.6	148
3	MD	6 November 2007	-1649.8	753	-3.98	47.5	134
4		16 November 2005	-1382.5	599	-4.25	37.0	135
5	1925–29D	24 June 1928	-1229.8	607	-2.99	45.5	114
6	MD	12 December 2001	-1210.3	594	-3.80	41.5	125
7	FD	02 September 1897	-1178.4	565	-3.68	40.4	110
8	WWIID	02 September 1942	-1085.4	609	-2.93	47.7	114
9		21 October 1937	-987.8	494	-3.52	32.8	144
10	1967D	27 January 1967	-828.9	458	-3.11	43.1	105

Table 4 The event-accumulated drought severity (EAEDI), total dryness (DS_t), and event-averaged peak drought intensity (EEDI_{min}) for Portarlinton (Victoria) over the 120-year period

Rank	Drought	Event-accumulated severity, EAEDI	Total dry duration, DS _t (days)	Event-accumulated intensity, EEDI _{min}
1	Millennium	-4242.6	1946	-4.01
2	1925–1928	-2588.9	1697	-3.61
3	World War II	-2073.2	1103	-3.22
4	1914–1915	-1721.8	762	-4.08
5	Federation	-1178.4	565	-3.68

The worst event-accumulated drought is in boldface

separately, the 1925–29D has been ranked in the first and the fifth category and the MD in the third, fourth, and sixth category (Table 3). In Table 4, the event-accumulated EDI (EAEDI), total dry duration (DS_t), and event-averaged intensity (EEDI_{min}) for the top five droughts are listed. The magnitude of the EAEDI and DS_t for MD were 163 and 178 % higher than 1925–29D. Likewise, the value of EEDI_{min} = -4.01 for the MD was in contrast to the value of -3.61 for the 1925–29D. Additionally, the EAEDI for the WWIID, the 1914–15D, and the FD were comparatively smaller than MD by 50, 40, and 30 %, respectively. This clearly showed that the MD was more severe compared with any other event in its 120-year drought history. Indeed, the ability to distinguish the precise nature of drought in terms of the pertinent water resource stress factors like the duration, severity, intensity, available water resources, and the precipitation return to normal is a significant benefit of the EDI approach.

3.7 Annual dryness index based on accumulated dry spells

In any drought studies, and especially those impacting water resource sectors, it is beneficial to compare the overall dryness per year considering the accumulated stresses caused by all dry spells recorded in the particular year. In this study, we applied the AEDI approach and calculated the sum of all

negative EDI over an annual unit (Kim et al. 2009). It is noteworthy that this approach is different from quantifying the drought year based on annual EDI (Section 3.2) as only the dry spell cases are considered in determining the AEDI per year. The benefit of this different approach is to express drought severity on an annual basis, viz. (1) sum divided by 365 days (yearly accumulated deficit of EDI (YAEDI₃₆₅; Eq. 10) and (2) sum divided by total days of negative EDI over 365 days (YAEDI_{DS}; Eq. 11) as follows:

$$YAEDI_{365} = \frac{\sum_{i=1}^{DS} EDI_i < 0}{365} \quad (10)$$

$$YAEDI_{DS} = \frac{\sum_{i=1}^{DS} EDI_i < 0}{DS} \quad (11)$$

Figure 8 displays the annual dryness index represented by Eqs. 9 and 10 for the 120-year period for the station Portarlinton (Victoria). On an annual basis, the worst years (YAEDI₃₆₅ ≥ -2.0) match the events of the 1925–29D, 1914–15D, FD, and the MD. In spite of the strongly negative YAEDI for 1898, 1914, and 1928, adjacent years did not have large magnitudes of YAEDI. By contrast, the dryness index for the MD was consistently elevated in 2006, 2007, and 2009. This indicated that on an annual basis, the MD is considered as a mega-drought event. Our findings agreed with

Fig. 8 The chronological representation of annual dryness in terms of the yearly accumulated effective drought index (YAEDI) based on total number of dry days (DS) only (i.e., YAEDI_{DS}) and all 365 days in the year (i.e., YAEDI₃₆₅) for Portarlinton (Victoria)

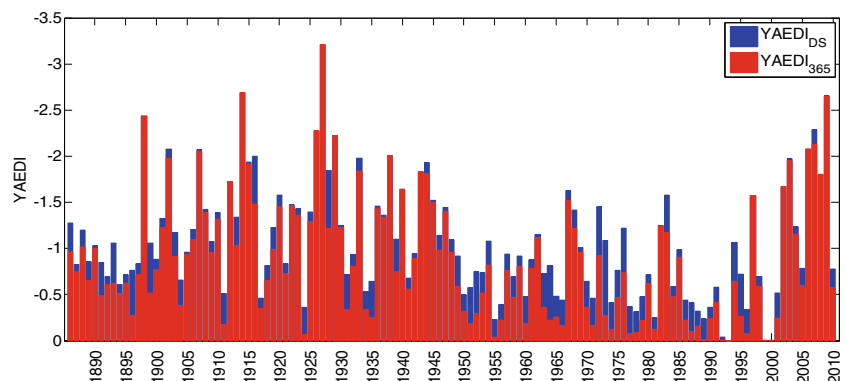


Table 5 The annual ranking of drought events based on the yearly accumulated value of the consecutively negative effective drought index (YAEDI) for Portarlinton (Victoria) over the 120-year period

Rank	Year	YAEDI ₃₆₅	YAEDI _{DS}	EDI _{min}	SPI-12	RAI	Min AWRI (mm)	Annual <i>P</i> (mm)
1	1927	-3.21	-3.21	-4.22	-1.69	-205	40.6	435.3
2	1914	-2.69	-2.69	-4.05	-2.02	-238	41.6	403.0
3	2009	-2.65	-2.65	-3.98	-1.12	-145	47.5	495.9
4	1898	-2.44	-2.44	-3.68	-1.90	-227	40.4	414.0
5	1926	-2.27	-2.27	-3.09	-1.20	-154	50.4	487.5
6	1929	-2.22	-2.22	-2.99	-0.64	-89	45.5	552.9
7	2007	-2.13	-2.29	-4.25	-0.44	-66	38.0	595.5
8	2006	-2.08	-2.08	-3.65	-2.48	-171	37.0	360.0
9	1907	-2.05	-2.07	-3.20	-1.24	-158	49.9	483.1
10	1938	-2.01	-2.01	-3.37	-1.92	-229	43.9	412.5

The YAEDI₃₆₅ is the ratio of the sum of negative EDIs to the annual time scale (365 days) and the YAEDI_{DS} is the ratio of the sum of negative EDIs to the number of dry days (DS)

previous studies (e.g., Timbal and Fawcett 2013) where the MD was extremely severe compared with either the Federation or the World War II drought events based on annual and seasonal rainfall anomalies.

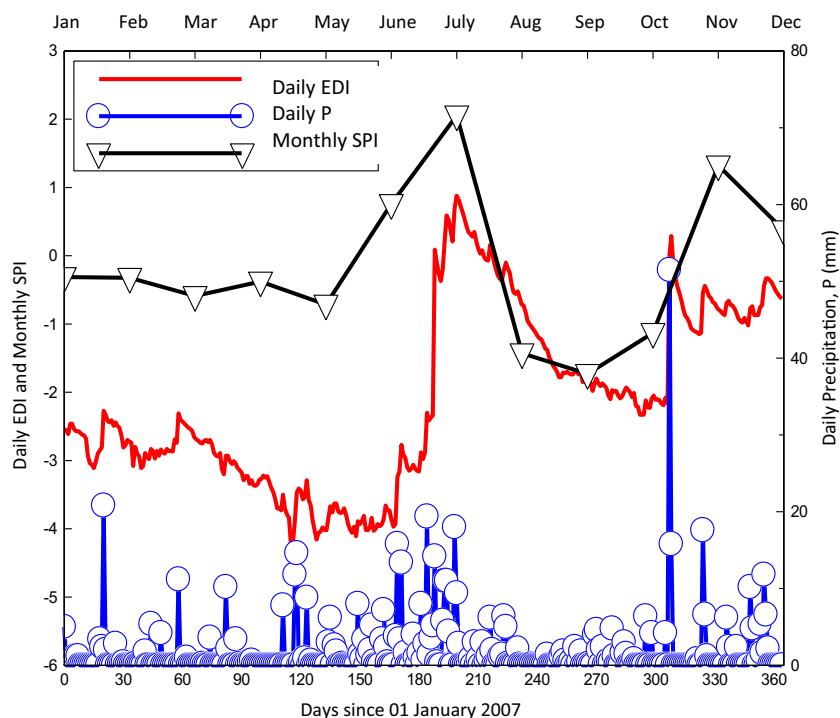
The average dryness of the drought years was quantified and ranked in Table 5. It was clear that the average dryness and intensity per year based on the dry spells were highly discernible in all the identified years. In order of their severities based on the YAEDI, the worst drought years were the 1927, 1914, 2009, 1898, 1926, 1929, 2007, 2006, 1907, and the 1938 events. For drought years ranked from the first to the sixth category, the entire year was drier than normal as reflected by the negligible difference between the YAEDI₃₆₅ and the YAEDI_{DS} (e.g., Kim et al. 2009). Interestingly, the annual minimum value of the AWRI for the two drought years (2006, 2007) qualified with an extreme shortage of water due to drought so it is likely that the actual damages were potentially very severe. This was reflected by the minimum EDI of -4.25 in the year 2007. While the eight severe drought years identified by the YAEDI were also present in continuing drought events (Table 5), the years 1907 and 1938 were excluded from the top ten ranks. This was because the negativity of the annual average drought index can be reduced when water scarcity is canceled out by excessive or rapid spurts of rainfall during other periods of the same year (Kim et al. 2009). Therefore, all drought years including 1907 and 1938 experienced prolonged dry conditions over the entire year and thus reflected overall drought conditions.

In Table 5, we compared the 12-monthly SPI, RAI, annual *P*, and the minimum AWRI for the drought years in order to check the synchronicity of these drought parameters with abnormal aberrations in yearly rainfall. It may be inferred that ranking of annual dryness based on rainfall shortage should be discerned from that of annual severity based on the YAEDI (e.g., Kim et al. 2009), as raw rainfall statistics do not generally reflect loss of water over the passage of time. That is,

annual dryness computed from the daily EDI over annual units (see Eqs. 10 and 11) was more responsive to the actual rainfall variations throughout the year as the EDI was calculated based on time-reduction functions (e.g., Eq. 1), whereas the total precipitation on drought days does not consider the gradual loss of rainfall over time. Among all drought years considered, the year 2007 received the highest rainfall (~595.5 mm), which was 93 % of the climatological mean value. This occurred despite the year being classified as a drought year with a YAEDI₃₆₅ of -2.13 and being ranked the seventh most severe case. This seemed to suggest that there was a poor distribution of rainfall in 2007, which needs further verification.

To seek a plausible explanation for this statistic, Fig. 9 plots the daily *P* and EDI together with the monthly SPI from 1 January to 31 December 2007. A check of data prior to 2007 showed that the drought actually started in the previous year and arrived with the negative SPI and EDI value on 1 January 2007. Beyond this date, occasional spurts in rainfall were received but limited to 21 January (~21.00 mm), 28 February (~11.00 mm), and 24 March (~11.00 mm). The other days were predominantly dry therefore supporting the notion of poorly distributed rainfall after 24 March. However, the majority of rainfall was received in the rainy season (28 April to 20 August), which elevated both indices (i.e., SPI and EDI) to their positive phases, and reflected partial recovery from dry conditions. Importantly, the rest of the year was dry again until about 52.00 mm of rainfall was received on 4 November. Summed up value of rainfall until December 2007 was 595.00 mm, which exceeded the value for drought years ranked between 1 and 6 (Table 5). If taken from a simple precipitation point of view, the year 2007 should be much less severe in terms of drought; however, based on the YAEDI or the minimum EDI, it was certainly a severe drought year. The analogy verified the practical merits of the daily EDI for precise representation of drought in case of poorly distributed rainfall, while the YAEDI

Fig. 9 A time series of the daily effective drought index (EDI), 1-monthly standardized precipitation index (SPI-1), and daily rainfall (P) from 1 January to 31 December 2007 for Portarlington (Victoria)



was potentially useful for estimating the gross annual dryness considering all dry spells in that annual period.

3.8 Seasonality of “big” Millennium Drought using effective drought index

Of all major droughts in Australia (Table 6), the MD event has been widely viewed as an exceptionally dry event when examined over the climate record for the last 120 years (e.g., Murphy and Timbal 2008; Sohn 2007; Timbal and Fawcett 2013). This has also been depicted in our study using the run-sum approach of drought assessment in terms of the cumulative drought severity, duration, and drought intensity (Table 4). However, any comparisons of drought-related damage (e.g., Table 6) with the drought index or its derivatives (severity, duration, or peak intensity) should be made with caution as such comparisons require additional impact assessment data (e.g., economic outlook, environmental impacts, agricultural, or other data). In this paper, we are only interested in analyzing the overall extent of droughts; any explanation of the impact of drought events would require more extensive analysis of various other datasets.

Several previous investigations that analyzed the multi-timescale behavior of historical droughts have noted distinct seasonal patterns of rainfall variability in relation to the MD, the Federation or the World War II drought (e.g., Kiem and Franks 2004; Timbal and Fawcett 2013; Verdon-Kidd and Kiem 2009). We therefore applied the EDI for the seasonal characterization of the MD event using daily rainfall data for the period 1

January 2001 to 31 December 2010. Table 5 shows the cumulative severity, duration, and average intensity based on Eqs. 7–9. It also shows the minimum available water resources index and the total rainfall needed to recover the prior deficits (PRN_{tot}) for each season and the station to provide supplementary information on its potential impacts on water resource sectors.

From these figures, the distinct seasonality of geographically sparse data stations can be observed. In terms of the cumulative severity, duration, and peak intensity, the Victorian station (Portarlington) registered the highest value of the drought index (i.e., $AEDI = -3704$, $DS = 2012$ days, $EDI_{min} = -4.25$) during the spring and the summer seasons compared to other stations. The correspondence of this station with the region of the Murray-Darling Basin, Australia’s agricultural hub, signifies its exceptionally serious impact on agriculture and water resource sectors. Interestingly, the magnitude of the AEDI at Portarlington was more than twofold higher than the value recorded at other stations, and likewise the duration and intensity were more than 30 % larger. In contrast to the observations for Portarlington where peak impacts of the MD event have been recorded in the spring, that at Deniliquin (New South Wales), Wallaroo (South Australia), and Cranbrook (southwest Western Australia) occurred in the autumn. Among all stations under consideration, Katherine appeared to be particularly immune from the MD event, as evidenced by relatively smaller magnitude of the drought parameters. Importantly, this was consistent with observations where statistically significant increases in rainfall and the decrease in number of dry days over 1910–1990 period were

Table 6 The seasonal characterization of the Millennium Drought period using the drought monitoring data for the period 1 January 2001 to 31 December 2010

Season	Portarlinton	Deniliquin	Wallaroo	Cranbrook	Cape Grim	Fairy Mead	Katherine
EAEDI							
DJF	-1225	-488	-169	-150	-313	-949	-96
MAM	-248	-908	-1838	-1645	-364	-158	-382
JJA	-240	-637	-1040	-75	-531	-259	No drought
SON	-3704	-245	-90	-295	-347	-411	-143
DS							
DJF	637	768	272	258	480	1265	200
MAM	301	869	1482	1108	471	356	712
JJA	270	649	803	161	598	383	No drought
SON	2012	426	180	414	532	578	178
EEDI _{min}							
DJF	-3.80	-1.70	-1.71	-1.95	-1.92	-1.66	-1.70
MAM	-1.74	-2.05	-2.87	-2.86	-2.22	-1.07	-1.14
JJA	-2.33	-1.88	-2.67	-1.14	-2.62	-1.71	No drought
SON	-4.25	-1.20	-1.12	-1.16	-1.97	-1.67	-2.27
AWRI _{min} (mm)							
DJF	41.5	28.0	25.8	29.7	83.2	62.8	92.5
MAM	74.9	15.3	15.3	26.3	85.0	64.2	39.7
JJA	72.5	24.3	20.2	67.1	63.9	58.1	No drought
SON	37.0	33.0	53.1	36.9	79.5	73.8	41.0
PRN _{tot} (mm)							
DJF	126.1	135.5	49.1	96.3	160.6	753.7	336.7
MAM	109.2	180.0	269.3	300.8	307.4	320.0	109.3
JJA	168.1	149.9	243.4	100.4	363.0	246.8	No drought
SON	564.4	195.0	98.1	104.7	292.9	446.8	257.3

The extreme case per season is also highlighted in boldface

DJF December-January-February, *MAM* March-April-May, *JJA* June-July-August, *SON* September-October-November, *EAEDI* event-accumulated effective drought index, *DS_t* cumulative duration of the number of dry days, *EEDI_{min}* mean drought intensity, *AWRI* minimum available water resources index, *PRN_{tot}* total value of precipitation return to normal

evident for a number of stations in Northern Australia (Suppiah and Hennessy 1998).

Based on Eqs. 5 and 6, we estimated the water scarcity conditions and rainfall needed to recover the prior deficit caused by the persistently dry conditions for the MD event (Table 5). The severest drought (with the greatest paucity of water resources and largest precipitation needed to return to normal) was noted for the spring season ($AWRI_{min} = 37.00$ mm, $PRN_{tot} = 564.40$ mm), although the value of the $AWRI_{min}$ was less than half of Deniliquin and Wallaroo (15.30 mm) (stations located in New South Wales and South Australia). The very low availability of water resources seems to pinpoint that significant damages at these stations were potentially very severe. In fact, the intensity of drought, which concurred well with the magnitude of $AWRI_{min}$, fell in the extreme threshold category ($EDI_{min} < -2.00$) (Table 5). It is also noteworthy that the

June–July–August period in Katherine (Northern Territory) was drought-free since the EDI for this case was positive and hence did not identify any drought events.

Therefore, we aver that the MD event in eastern Australia could have been highly damaging in terms of both its severity and impacts on the hydrological balance, as also exemplified by many other studies (e.g., Dijk et al. 2013; Timbal and Fawcett 2013; Ummenhofer et al. 2009). Additionally, it is also striking to note that the rainfall needed to return to normal conditions was also the highest (i.e., $PRN = 565.4$ mm) for Portarlinton and therefore indicates the significant cumulative stress caused by dry spells in the Victorian region. To summarize, the implementation of these multiple indicators of drought as enumerated in Tables 3, 5 and 6, derived from consistent approaches, provides useful information on drought assessment, especially its potential impact on water resource environments.

4 Summary and conclusions

Our research has explored the use of the effective drought index for the first time in Australia to quantify dry spells and continuing drought events. Most previous studies in Australia have utilized monthly, seasonal, and annual indices for characterizing drought periods. In this study, a daily time-step was introduced as a useful tool for capturing the surplus, deficit, or normality of daily water resources, thus identifying both the dry spells as well as continuing drought events. Based on the daily EDI for any identified dry period, the summed negative indices measuring the severity of drought provided an effective way to compare drought severity in terms of the accumulated stress caused by the shortages of daily water resources.

The duration (number of days of consecutive dry spells), severity (accumulated negative EDI), and intensity (minimum EDI) were deduced for all candidate stations. Based on the onset and termination dates of drought determined by the first negative EDI¹, droughts of the Federation period (1897–1803), 1914–1915, 1925–1929, 1937–1945 (World War II), and the Millennium (2001–2010) were ranked according to their accumulated severity. The most severe case was the Millennium Drought event in Victoria. In the New South Wales, Western Australia, and Queensland, the World War II drought event was ranked as the most severe case. By contrast, in northern Australia, the 1925–1929 event was the worst, while in Tasmania, the 1911–1915 event exhibited the highest severity, followed by the Millennium Drought event. Several localized events which also appeared in the top ten cases were also noted. Based on the results, it may be conjectured that together with the EDI, the AWRI and the PRN allow the determination of the absolute quantity of the available water resources for a dry period, as well as enabling estimates of deficits, in addition to an analysis of the drought in terms of the year and the event. This provides crucial water deficit and a rational-based accounting measures for impact assessment in areas relevant to water resource environments. As the impacts of projected climate change are felt around the world (Adamowski et al. 2010; Belayneh et al. 2014; Halbe et al. 2013; Nalley et al. 2012, 2013; Pingale et al. 2014), accurate measures of drought properties will become increasingly important to help manage natural resources in a more sustainable manner.

In spite of the advantage of the effective drought index for continuous monitoring of drought, the requirement of daily rainfall data is a significant limitation of this method for its operational implementation. Daily data, although readily

available for many locations, may still be unreliable, unavailable, or difficult to recover in data-sparse regions. In using daily data, it may be difficult to use the EDI in an operational situation as daily updates to input data may not always be possible in real time. This was exemplified for the case of the 1982–1983 and 1991–1995 drought events in Australia where missing data raised issues in regards to the accurate quantification of drought events. While the EDI approach does allow for the missing data to be recovered from its calendar averaged values from the data available period, the assumption that daily rainfall amounts would match the missing data period may not hold true, and therefore, the estimation of the drought index would encounter significant errors. Furthermore, the EDI does not consider the distribution of rainfall and, therefore, might limit the application of this index to very arid regions. Like the SPI, the EDI requires long time series data as an input and therefore may not be suitable for drought monitoring in regions that do not have such data. With only precipitation accounted for, the impact of temperatures on drought situations is not directly acknowledged, as is normally done by the PDSI or the SPEI.

To summarize, we conclude that for data-rich regions, the application of the daily effective drought index as a unified index and its water-related derivatives (the AWRI and the PRN) as supplementary parameters for monitoring duration, severity, and intensity of dry spells is very useful for water resource management perspectives (Oh et al. 2015). However, it must be emphasized that a direct comparison of any of the drought properties (e.g., duration, severity, or peak time) and the environmental or economic impacts should be made with extreme caution as these properties only depict the meteorological character of drought (i.e., rainfall-based). A more thorough analysis of the economic and environmental data (e.g., agricultural productivity, water use demand) should be made with the framework of a complex adaptive system or multifaceted approach before any deductions of impacts based on drought properties are made. Nevertheless, the prospect of monitoring continuing drought events by the EDI approach open a window of opportunity for testing of its operational applicability by including a larger coverage area than used in this pilot study.

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¹ In some studies on the EDI, different thresholds for dry days were used. For example, Kim et al. (2009) used $EDI \leq -1.0$ for the start of a dry period.

Appendix

Table 7 A summary of the historical droughts and their impacts in Australia for the period 1890–2010

Drought period	Region	Impacts and estimated damage
1895–1903, Federation Drought (“FD”)	Australia wide	Decline in sheep flock by 50 %, cattle > 40 %, and wheat 2.4 bushels per acre. Climax in 1902 threatening drinking water supply in Sydney, 26 February 1902 as day of “humiliation and prayer,” Darling River reduced to trickle, sheep flock wipe out in Queensland (Year Book Australia 1988; Botterill 2003; Smith et al. 2007)
1915–1915 (“1915–15D”)	Western Victoria, central Tasmania, South Australia; southern, northern, central Queensland, New South Wales	18-monthly dry period, national crop failure (1914); soaring temperatures and bushfires; water flows in Murray Basin reduced to 2 % of normal value (Botterill 2003; Foley 1957)
1925–1929 (“1925–29D”)	Northern Territory, Victoria, Tasmania, New South Wales	High intensity short, affected pasture regions; persisted in New South Wales (1929–1935), Northern Territory (1926–1929), Victoria (1925–1927), and Tasmania (1925–1927) (Foley 1957)
1932–1945, World War II Drought (“WWIID”)	Widespread (New South Wales, Queensland, Victoria, and South Australia); simultaneous impacts in northwest and southeast Australia	Significant loss of crop, sheep, and cattle. By August 1940, the Nepean Dam (New South Wales) was empty and water restrictions enforced in Brisbane, Sydney, and Melbourne (Smith et al. 2007)
1965–1968 (“1967D”)	Eastern Australia although dry conditions persisted over the central continent since 1957, spread elsewhere during 1964/1965 summer	Severe in eastern Australia; peak in 1967 coinciding with Tasmanian bush fires with 62 deaths and 1400 homes lost; drop in wheat production by 40 % and loss of 30 million sheep (Year Book Australia 1988)
1972–1973 (“1973D”)	Victoria, western and central New South Wales, South Australia northeastern Tasmania	9–10 months ending February 1973; drought broke in February 1973; except in northeastern Tasmania, where it broke in autumn 1973 (Year Book Australia 1988)
1982–1983 (“1982–83D”)	Most of eastern Australia, inland New South Wales, central and Queensland and South Australia	Mostly concentrated over the low rainfall period of April 1982–February 1983 lowest 10–11-month rainfall in Victoria; decimated wheat crop and livestock worth A\$3.0 billion (Allan and Heathcote 1982; Glantz et al. 1987)
1991–1995 (“1991–95D”)	Northeastern New South Wales and Queensland	Water reservoirs below critical level. Average rural production fell by >10 %. Economic loss of A\$5.0 billion; widespread winter cropping (wheat, barley, oats, and legumes) by 50 % (1993–1994) and a decline in rural production to 10 % (1994–1995) (Year Book Australia 2012; White and O’Meagher 1995)
2002–2010 (“MD”)	Southeast Queensland, southern New South Wales, Victoria and southwest Western Australia; hit irrigated and dryland agricultural sectors in Victoria and Murray-Darling Basin	Enactment of water legislation, high electricity prices, bushfires in 2003 and 2009, and decline in GDP by 1 % between 2001 and 2003 and 0.6 % between 2006 and 2007; severe effects in 2002, 2006, and 2008 accompanied by a notable absence of wet years; systematic reduction of 10–20 % in autumn and winter rainfall. Reduction of winter crop by 36 %, worth A\$3.5 billion (Year Book Australia 2012; Adams et al. 2002; Murphy and Timbal 2008)

References

- Adamowski J, Adamowski K, Bougadis J (2010) Influence of trend on short duration design storms. *Water Resour Manag* 24:401–413
- Adams PD, Horridge M, Madden J, Wittwer G (2002) Drought, regions and the Australian economy between 2001–02 and 2004–05. Monash University, Centre of Policy Studies/IMPACT Centre
- Allan R, Heathcote R (1982) The 1982–83 drought in Australia. The societal impacts associated with the, 83:19–23
- Alexander L, Zhang X, Peterson T, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F (2006) Global observed changes in daily climate extremes of temperature and precipitation. *J Geophys Res Atmos* 111:1984–2012
- Allan R, Heathcote R (1982) The 1982–83 drought in Australia. The societal impacts associated with the, 83:19–23

- Ashok K, Guan Z, Yamagata T (2003) Influence of the Indian Ocean Dipole on the Australian winter rainfall. *Geophys Res Lett*
- Belayneh A, Adamowski J, Khalil B, Ozga-Zielinski B (2014) Long-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet neural network and wavelet support vector regression models. *J Hydrol* 508:418–429
- Bhalme HN, Mooley DA (1980) Large-scale droughts/floods and monsoon circulation. *Monthly Weather Review*. 1197–1211. doi: 10.1175/1520-0493(1980)108<1197:lsdamc>2.0.co;2
- BOM (2008) High-quality Australian daily rainfall dataset. National Climate Centre, Bureau of Meteorology, Melbourne
- Botterill L (2003) Beyond drought in Australia: the way forward In: Fisher LBA (ed) *Beyond drought: people, policy and perspectives*. CSIRO Publishing, Collingwood, Victoria pp 197–207
- Botterill LC, Wilhite DA (2006) From disaster response to risk management: Australia's National Drought Policy. Springer
- Byun H-R, Jung J (1998) Quantified diagnosis of flood possibility by using effective precipitation index. *J Kor Water Resour Assoc* 31: 657–665
- Byun H-R, Lee D-K (2002) Defining three rainy seasons and the hydrological summer monsoon in Korea using available water resources index. *J Meteorol Soc Japan* 80:33–44
- Byun H-R, Wilhite D (1999) Objective quantification of drought severity and duration. *J Clim* 12:2747–2756
- Byun H-R, Lee S-J, Morid S, Choi K-S, Lee S-M, Kim D-W (2008) Study on the periodicities of droughts in Korea. *Asia-Pac J Atmos Sci* 44:417–441
- Cancelliere A, Salas JD (2004) Drought length properties for periodic-stochastic hydrologic data. *Water Resour Res*
- Choi K-S, Wang B, Kim D-W (2012) Changma onset definition in Korea using the available water resources index and its relation to the Antarctic oscillation. *Climate Dyn* 38:547–562
- Deo RC (2011) On meteorological droughts in tropical Pacific Islands: time-series analysis of observed rainfall using Fiji as a case study. *Meteorol Appl* 18:171–180
- Deo RC, Şahin M (2015a) Application of the Artificial Neural Network model for prediction of monthly Standardized Precipitation and Evapotranspiration Index using hydrometeorological parameters and climate indices in eastern Australia. *Atmos Res* 161-162:65–81
- Deo RC, Şahin M (2015b) Application of the extreme learning machine algorithm for the prediction of monthly Effective Drought Index in eastern Australia. *Atmos Res* 153:512–525. doi:10.1016/j.atmosres.2013.11.002
- Deo RC, Syktus J, McAlpine C, Lawrence P, McGowan H, Phinn SR (2009) Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia. *Geophys Res Lett*
- Deo RC, Byun H-R, Adamowski JF, Kim D-W (2015) A real-time flood monitoring index based on daily effective precipitation and its application to Brisbane and Lockyer Valley flood events. *Water Resour Manag* 29:1–19. doi:10.1007/s11269-015-1046-3
- Dijk AI, Beck HE, Crosbie RS, Jeu RA, Liu YY, Podger GM, Timbal B, Viney NR (2013) The Millennium Drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resour Res* 49: 1040–1057
- Dogan S, Berktaş A, Singh VP (2012) Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey. *J Hydrol* 470-471:255–268
- Dracup JA, Lee KS, Paulson EG (1980) On the definition of droughts. *Water Resour Res* 16:297–302
- Foley JC (1957) Droughts in Australia: review of records from earliest years of settlement to 1955. Director of Meteorology
- Franks SW, Kuczera G (2002) Flood frequency analysis: evidence and implications of secular climate variability, New South Wales. *Water Resour Res* 38:20-1–20-7
- Gibbs W, Maher J (1967) Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin
- Glantz MH, Katz R, Krenz M (1987) The societal impacts associated with the 1982-83 worldwide climate anomalies. Report based on the Workshop on the economic and societal impacts associated with the 1982-83 worldwide climate anomalies, 11-13 November 1985, Lugano, Switzerland
- González J, Valdés JB (2006) New drought frequency index: definition and comparative performance analysis. *Water Resour Res*
- Halbe J, Pahl-Wostl C, Sendzimir J, Adamowski J (2013) Towards adaptive and integrated management paradigms to meet the challenges of water governance. *Integrated Water Resources Management in a Changing World: Lessons Learnt and Innovative Perspectives*. 211
- Hayes M, Svoboda M, Wall N, Widhalm M (2011) The Lincoln declaration on drought indices: universal meteorological drought index recommended. *Bull Am Meteorol Soc* 92:485–488
- Haylock M, Nicholls N (2000) Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910–1998. *Int J Climatol* 20:1533–1541
- Hennessy K, Suppiah R, Page C (1999) Australian rainfall changes, 1910–1995. *Australian Meteorological Magazine*. 1–13
- Hennessy K, Page C, McInnes K, Walsh K, Pittock B, Bathols J, Suppiah R (2004) Climate change in the Northern Territory. Consultancy report for the Northern Territory Department of Infrastructure, Planning and Environment. 64.
- Jain VK, Pandey RP, Jain MK, Byun H-R (2015) Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin. *Weather Climate Extremes* 8:1–11
- Jones, DA, Wang, W and Fawcett, R (2009) High-quality spatial climate data-sets for Australia. *Aust Meteorol Oceanogr* J. 233
- Kalamaras, N, Michalopoulou, H and Byun, H-R (2010) Detection of drought events in Greece using daily precipitation
- Kiem AS, Franks SW (2004) Multi-decadal variability of drought risk, eastern Australia. *Hydrol Process* 18:2039–2050
- Kiem AS, Franks SW, Kuczera G (2003) Multi-decadal variability of flood risk. *Geophys Res Lett*
- Kim D-W, Byun H-R (2009) Future pattern of Asian drought under global warming scenario. *Theor Appl Climatol* 98:137–150
- Kim D-W, Byun H-R, Choi K-S (2009) Evaluation, modification, and application of the Effective Drought Index to 200-year drought climatology of Seoul Korea. *J Hydrol* 378:1–12
- Kim D-W, Byun H-R, Choi K-S, Oh S-B (2011) A spatiotemporal analysis of historical droughts in Korea. *J Appl Meteorol Climatol* 50: 1895–1912
- Lavery B, Kariko A, Nicholls N (1992) A historical rainfall data set for Australia. *Aust Met Mag* 46:33–39
- Lavery B, Joung G, Nicholls N (1997) An extended high-quality historical rainfall dataset for Australia. *Aust Meteorol Mag*. 27–38
- Lee S-M, Byun H-R, Tanaka HL (2012) Spatiotemporal characteristics of drought occurrences over Japan. *J Appl Meteorol Climatol* 51: 1087–1098
- Li Y, Cai W, Campbell E (2005) Statistical modeling of extreme rainfall in southwest Western Australia. *J Clim* 18:852–863
- Liu Y, Yang X, Ren L, Yuan F, Jiang S, Ma M (2015) A new physically based self-calibrating Palmer drought severity index and its performance evaluation. *Water Resour Manag* 29:4833–4847
- Lu E (2009) Determining the start, duration, and strength of flood and drought with daily precipitation: rationale. *Geophysical Res Lett*
- Lu E (2012) Monitoring and maintenance of a cold-season drought. *Science and Technology Infusion Climate Bulletin*. NOAA's National Weather Service, Fort Collins
- Lu E, Cai W, Jiang Z, Zhang Q, Zhang C, Higgins RW, Halpert MS (2013) The day-to-day monitoring of the 2011 severe drought in China. *Clim Dyn* 43:1–9

- Masinde M (2013) Artificial neural networks models for predicting effective drought index: factoring effects of rainfall variability. *Mitig Adapt Strateg Glob Chang* 19:1–24
- McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology*. American Meteorological Society Boston, MA. pp 179–183
- Mishra AK, Singh VP (2010) A review of drought concepts. *J Hydrol* 391:202–216
- Mishra AK, Singh VP (2011) Drought modeling—a review. *J Hydrol* 403:157–175
- Morid S, Smakhtin V, Moghaddasi M (2006) Comparison of seven meteorological indices for drought monitoring in Iran. *Int J Climatol* 26:971–985
- Mpelasoka F, Hennessy K, Jones R, Bates B (2008) Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management. *Int J Climatol* 28:1283–1292
- Murphy BF, Timbal B (2008) A review of recent climate variability and climate change in southeastern Australia. *Int J Climatol* 28:859–879
- Nalley D, Adamowski J, Khalil B (2012) Using discrete wavelet transforms to analyze trends in streamflow and precipitation in Quebec and Ontario (1954–2008). *J Hydrol* 475:204–228
- Nalley D, Adamowski J, Khalil B, Ozga-Zielinski B (2013) Trend detection in surface air temperature in Ontario and Quebec, Canada during 1967–2006 using the discrete wavelet transform. *Atmos Res* 132–133:375–398
- Nicholls N, Lavery B, Frederiksen C, Drosowsky W, Torok S (1996) Recent apparent changes in relationships between the El Niño–Southern Oscillation and Australian rainfall and temperature. *Geophys Res Lett* 23:3357–3360
- Oh S-B, Byun H-R, Kim D-W (2013) Spatiotemporal characteristics of regional drought occurrence in East Asia. *Theor Appl Climatol*. 1–13
- Oh K, Yu I, Kim H, Kim S, Kim L-h, Jeong S (2015) Drought assessment based on real-time drought index. *Desalin Water Treat* 53:3111–3117
- Palmer WC (1965) *Meteorological drought*. US Department of Commerce, Weather Bureau, Washington, DC
- Pandey R, Dash B, Mishra S, Singh R (2008a) Study of indices for drought characterization in KBK districts in Orissa (India). *Hydrol Process* 22:1895–1907
- Pandey R, Mishra S, Singh R, Ramasastri K (2008b) Streamflow drought severity analysis of Betwa river system (India). *Water Resour Manag* 22:1127–1141
- Park C-K, Byun H-R, Deo R, Lee B-R (2015a) Drought prediction till 2100 under RCP 8.5 Climate Change Scenarios for Korea. *J Hydrol* 526:221–230. doi:10.1016/j.jhydrol.2014.10.043
- Park S-R, Oh S-B, Byun H-R (2015b) Definition and characteristics of the water abundant season in Korea. *Theor Appl Climatol* 120:249–258
- Pietzsch S, Bissolli P (2011) A modified drought index for WMO RAVI. *Adv Sci Res* 6:275–279
- Pingale SM, Khare D, Jat MK, Adamowski J (2014) Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. *Atmos Res* 138:73–90
- Rice S (1945) Mathematical analysis of random noise. *Bell System Technical Journals*, 23–24 (reprinted in “Selected Papers on Noise and Stochastic Processes”, ed. Wax, 1954). New York: Dover
- Sen Z (1980) Statistical analysis of hydrologic critical droughts. *J Hydraul Div* 106:99–115
- Smakhtin V, Hughes D (2004) Review, automated estimation and analyses of drought indices in South Asia. International Water Management Institute
- Smith I (2004) An assessment of recent trends in Australian rainfall. *Aust Meteorol Mag* 53:163–173
- Smith DMS, McKeon GM, Watson IW, Henry BK, Stone GS, Hall WB, Howden SM (2007) Learning from episodes of degradation and recovery in variable Australian rangelands. *Proc Natl Acad Sci* 104(52):20690–20695
- Smith TM, Reynolds RW, Peterson TC, Lawrimore J (2008) Improvements to NOAA’s historical merged land-ocean surface temperature analysis (1880–2006). *J Clim* 21:2283–2296
- Sohn E (2007) The big dry: prolonged drought threatens Australia’s people, wildlife, and economy. *Sci News* 172:266–268
- Suppiah R, Hennessy KJ (1998) Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. *Int J Climatol* 18:1141–1164
- Timbal B, Fawcett R (2013) A historical perspective on southeastern Australian rainfall since 1865 using the instrumental record. *J Clim* 26:1112–1129
- Torok S, Nicholls N (1996) A historical annual temperature dataset. *Aust Meteorol Mag*
- Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global warming and changes in drought. *Nat Clim Chang* 4:17–22
- Ummenhofer CC, England MH, McIntosh PC, Meyers GA, Pook MJ, Risbey JS, Gupta AS, Taschetto AS (2009) What causes southeast Australia’s worst droughts? *Geophys Res Lett*
- Van Rooy M (1965) A rainfall anomaly index independent of time and space. *Notos*. 43–48
- Verdon-Kidd DC, Kiem A (2009) On the relationship between large-scale climate modes and regional synoptic patterns that drive Victorian rainfall. *Hydrol Earth Syst Sci* 13:467
- Verdon-Kidd DC, Kiem AS (2010) Quantifying drought risk in a nonstationary climate. *J Hydrometeorol* 11:1019–1031
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Clim* 23:1696–1718
- Waseem M, Ajmal M, Kim T-W (2015) Development of a new composite drought index for multivariate drought assessment. *J Hydrol* 527:30–37
- Wilhite DA (2000) Drought as a natural hazard: concepts and definitions. *Drought, a global assessment*. 3–18
- Yamaguchi Y, Shinoda M (2002) Soil moisture modeling based on multi-year observations in the Sahel. *J Appl Meteorol* 41:1140–1146
- Year Book Australia (1988) Australian Bureau of Statistics, Canberra
- Year Book Australia (2012) Australian Bureau of Statistics, Canberra
- Yevjevich V (1991) Tendencies in hydrology research and its applications for 21st century. *Water Resour Manag* 5:1–23
- Yevjevich V, Ingenieur J, Ingénieur Y, Engineer Y (1967) An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University Fort Collins
- Yevjevich V, Ingenieur J, Yevjevich V, Ingénieur Y, Yevjevich V, Engineer, Y (1967) An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University Fort Collins
- Ziese M, Schneider U, Meyer-Christoffer A, Schamm K, Vido J, Finger P, Bissolli P, Pietzsch S, Becker A (2014) The GPCC Drought Index—a new, combined and gridded global drought index. *Earth Syst Sci Data* 6:285–295