Assessing droughts using meteorological drought indices in Victoria, Australia

Siti Nazahiyah Rahmat, Niranjali Jayasuriya and Muhammed Bhuiyan

ABSTRACT

Droughts adversely impact rural and urban communities, industry, primary production and, thus, a country's economy. Drought monitoring is directed to detecting the onset, persistence and severity of the drought. In this study, meteorological drought indices such as the Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI) and deciles were assessed to investigate how well these indices reflect drought conditions in Victoria, Australia. The Theory of Runs was also used to identify the drought deficit. The study uses 55 years (1955–2010) of monthly precipitation and reference evapotranspiration data for five selected meteorological stations in Victoria, Australia. Results show that drought characterization using SPI and RDI provides a standardized classification of severity thus exhibiting advantages over deciles. As RDI considers both rainfall and potential evapotranspiration in calculations, it could be sensitive to climatic variability. For characterizing agricultural droughts, the application of the RDI is recommended. The use of the SPI was shown to be satisfactory for assessing and monitoring meteorological droughts. The SPI was also successful in detecting the onset and the end of historical droughts for the selected events.

Key words | deciles, drought characteristics, Reconnaissance Drought Index, Standardized Precipitation Index, Theory of Runs

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INTRODUCTION

Drought differs from other natural hazards such as cyclones and floods as it is a slow on-setting, creeping phenomenon (WMO 2006). It is difficult to determine when the drought begins and, likewise, when it ends, as urban, agricultural and industrial sectors recover from droughts differently. Monitoring droughts and forecasting persistence always present unique research challenges; however, it is essential as droughts become more common and more severe due to climate change impacts (Mishra & Singh 2009; Alexander *et al.* 2009). There are four types of droughts, commonly classified as meteorological, agricultural, hydrological and socio-economic (Wilhite & Glantz 1985). In contrast to meteorological droughts, the other three types of droughts occur less frequently because it usually takes weeks or months before precipitation deficiencies begin to produce soil moisture deficiencies, declines in streamflow, reduced reservoir levels and lower groundwater tables. Thus, for drought monitoring and early warning, meteorological drought indices (DI) provide the best initial assessment. Once meteorological indices indicate the onset of a drought, other non-meteorological indices could provide complementary additional information to the relevant sectors, describing severity and impact.

In Australia, several significant droughts have occurred in the recent past, including 1963–1968, 1972–1973, 1982–1983 and 1991–1995, costing the Australian economy billions of dollars (BoM 2011). South-eastern Australia (Victoria, parts of New South Wales and South Australia) experienced low rainfall from 1997 to 2009, known as the 'Big Dry' (Ummenhofer *et al.* 2009; Potter *et al.* 2010; Verdon-Kidd & Kiem 2010). The 12-year prolonged dry period saw four major drought years beginning in late 1997, 2002, 2006 and 2008 (Gergis *et al.* 2012). In 2010, even though widespread above-average rainfall fell across

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most of Australia, the long-term rainfall deficiencies affecting large parts of Southern Australia had still not ended (National Climate Centre 2010). The dry period had wiped out crops, decimated livestock numbers, drained rivers and dams, compromised water-dependent ecosystems and created conditions suitable for catastrophic bushfires. Tan & Rhodes (2008) reported 2006 annual inflow into four major water harvesting reservoirs supplying the greater Melbourne area to be the lowest on record, resulting in adverse socio-economic and industry impacts due to shortage of water and the imposition of restrictions.

DI have been commonly used to quantify rainfall deficits, soil moisture and water availability and to assess drought severity (Morid *et al.* 2006; Mishra & Singh 2010). Many different meteorological DI have been developed. Palmer (1965) first introduced the Palmer Drought Severity Index (PDSI) in the United States. Despite its widespread use, the PDSI has many limitations (Hayes 2003); other limitations are also discussed in Alley (1984), Hayes *et al.* (1999), Heim (2002), Mo & Chelliah (2006), Dai (2011) and van der Schrier *et al.* (2011). Other indices that have been used widely include percent of normal, deciles (commonly used in Australia (Gibbs & Maher 1967)) and the Standardized Precipitation Index (SPI) (McKee *et al.* 1993). Apart from the indices, stochastic analysis including the Theory of Runs (ToR) has also been successfully applied for characterization of droughts (Yevjevich 1967; Paulo & Pereira 2006). Tsakiris *et al.* (2007) proposed a new Reconnaissance Drought Index (RDI) which makes use of precipitation and potential evapotranspiration (PET) deficits simultaneously.

From the many indices used, the SPI has found widespread application for describing and comparing actual drought events (Mishra & Desai 2005; Paulo *et al.* 2005; Nalbantis & Tsakiris 2009; Khalili *et al.* 2011). The SPI was developed for the purpose of defining and monitoring droughts (McKee *et al.* 1993). In addition, after a comprehensive review, the World Meteorological Organization recommended the use of SPI to determine meteorological droughts and to complement local meteorological DI then in use (Hayes *et al.* 2011).

In addition, the RDI proposed by Tsakiris & Vangelis (2005) as a meteorological drought index is applied in this study to test its applicability. It makes use of precipitation and PET simultaneously as temperature, wind and relative humidity are also important factors in characterizing drought. In addition to these two DI, the ToR is applied to determine the best rainfall threshold level and to quantify the number of droughts and their characteristics.

In Australia, deciles are used to assess the status of rainfall deficiency (BoM 2007). Despite the advantages, deciles do not detect the essential characteristics of droughts (e.g., severity and intensity). However, the deciles method is also applied in this study to test its performance. Recently, Barua *et al.* (2012) developed a new drought index, namely the Nonlinear Aggregated Drought Index (NADI). NADI uses factor analysis and is complex, and has been recently developed using hydro-meteorological data from the Yarra River catchment, Victoria. However, it is yet to be tested in other regions.

The ease of application was also a factor in finalizing which indices to test and compare. This paper assesses how well the SPI, RDI and deciles can define the historical droughts in Victoria based on the data from the selected rainfall stations and ToR to identify drought properties. The results obtained by applying these three DI are presented and discussed. The SPI was also applied to identify the initiation and end of historical droughts.

METHOD

Study area

The State of Victoria in Australia has a varied climate ranging from semi-arid and hot in the north-west (300 mm/annum), to temperate and cool along the coast (1,800 mm/annum). Victoria has been split into 15 rainfall districts with relatively similar rainfall patterns (BoM 2007). The locations of the five rainfall stations selected for this study and their details are shown in Figure 1 and Table 1, respectively. Station 76031 is located in north-west Victoria in the region of Mildura, and has a long history of agriculture and irrigation. Stations 77051 and 79011 are in the Wimmera–Mallee regions of western Victoria and cover the dryland farming area. Station 81013 is located in the Goulburn Valley region, also part of the Murray–Darling Basin; this region is one of the most productive areas in

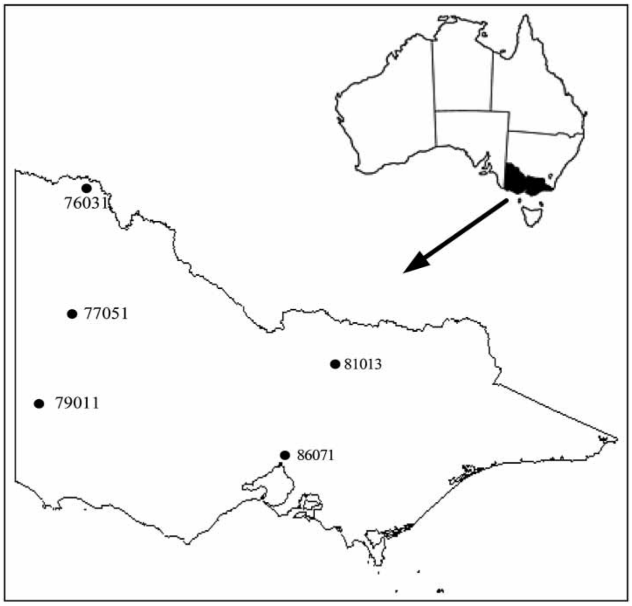

Figure 1 | Locations of the study site.

Australia and mostly irrigated. Station 86071 is within the Yarra River catchment and located in the urbanized areas. Due to the wide climatic differences prevailing in the State, the selected stations represent both drier and wetter regions of Victoria.

Rainfall and PET data

Mean annual rainfall for the five selected stations ranges from 293 to 650 mm. Rainfall data from 1955–2010 were used for the analysis and were downloaded from the Bureau of Meteorology (BoM) web site (http://www.bom.gov.au/climate/data/). Two commonly used data in-filling methods, namely the arithmetic mean and the normal ratio method were applied to calculate the missing monthly rainfall data. Data from a station's nearest neighbours were used to make the estimations. If the average annual rainfall at each of the adjacent stations differed from the average at the missing data station by ±10%, the equation used was an expression of an estimate based on the average precipitation at all stations. In contrast, if the difference between the average annual rainfall at any of the adjacent stations and the missing data station was greater than 10%, a normal ratio was used. The percentage of missing data is reported in Table 1. Figure 2 shows mean monthly temperature and precipitation for all stations. Overall, rainfall is at a maximum in late winter and early spring (i.e., July–October) and at a minimum in summer or early autumn (i.e., December–March). Similar to precipitation, temperatures in Victoria also fluctuate both on a seasonal and daily basis. High temperatures in summer (December–February) range from 24 °C to 30 °C. Mean annual rainfall is between 550 mm and 650 mm in Stations 79011, 81013 and 86071 while Stations 76031 and 77051 receive below 350 mm.

Reference evapotranspiration for these stations has been calculated using the adapted Penman–Monteith equation recommended by the United Nations Food and Agriculture Organization given in Equation (1) (Webb 2010). Daily wind speed, air temperature, humidity and solar radiation data were obtained from the BoM in Australia (BoM 2012)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{mean} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where Australian ET_o is the reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure curve (kPa$^\circ$C^{-1}), R_n is the net radiation at the crop surface (MJm^{-2}day^{-1}), G is the soil heat flux density (MJm^{-2} day^{-1}), γ is the psychometric constant (kPa$^\circ$C^{-1}), T_{mean} is

Table 1 | Description of rainfall stations

Station	Station name	Mean annual rainfall (mm)	Latitude (°S)	Longitude (°E)	AHD (m)	% of missing rainfall
76031	Mildura Airport	293	– 34.24	142.1	50	–
77051	Rainbow (Werrap (Oak-Lea))	349	– 35.94	141.9	83	0.8
79011	Edenhope (Post Office)	576	– 37.03	141.2	162	1.4
81013	Dookie Agricultural College	554	– 36.37	145.7	185	0.5
86071	Melbourne Regional Office	650	– 37.80	144.9	31	–

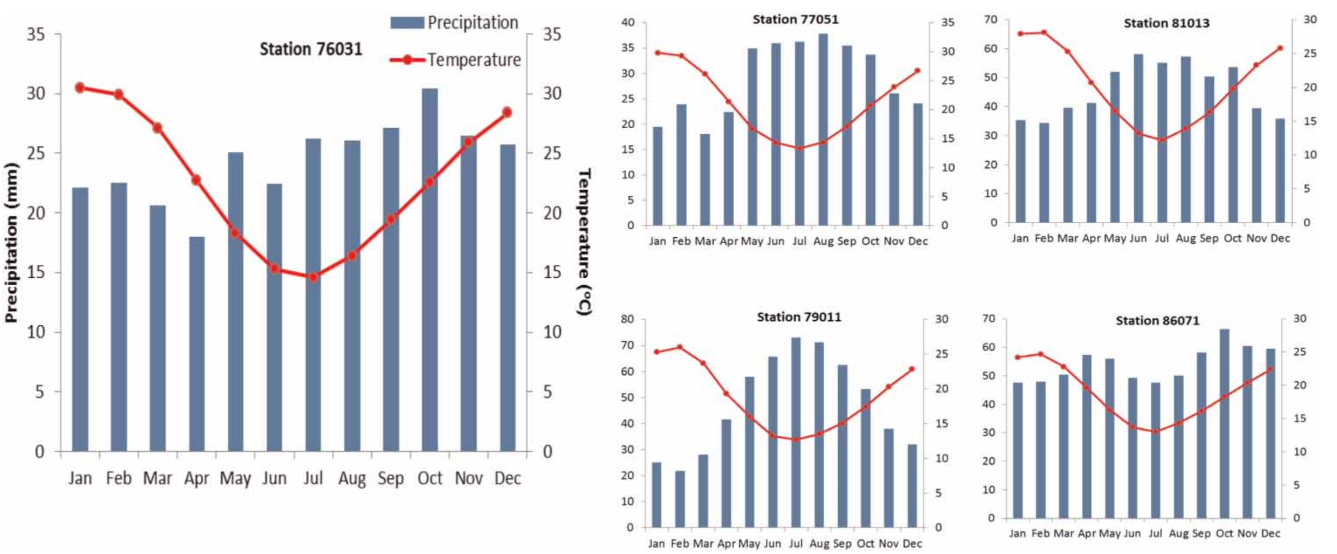

Figure 2 | Mean monthly precipitation and temperature for all stations.

the mean daily air temperature at a height of 2 m (°C), u_2 is the wind speed at a height of 2 m (ms^{-1}), e_s is the mean saturation vapour pressure (kPa) and e_a is the actual vapour pressure (kPa). The computation of ET_o followed the method described in Chapter 4 in Allen *et al.* (1998).

Drought indices

Standardized Precipitation Index

The SPI was designed by McKee *et al.* (1993) at Colorado State University to quantify the precipitation deficit for multiple time scales (i.e., 1, 3, 6, 12, 24 and 48 months). The SPI is basically the transformation of the precipitation time series into a standardized normal distribution. The computation of the SPI index requires the following steps (McKee *et al.* 1993; Wu *et al.* 2007):

(1) Fit a cumulative probability distribution function (PDF) (usually gamma distribution) on aggregated monthly (k) precipitation series (say $k = 3$, 6 and 12 months in this study). The gamma PDF ($g(x)$) is defined as

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \tag{2}$$

where β is a scale parameter, α is a shape parameter, which can be estimated using method of maximum likelihood, x is the precipitation amount and $\Gamma(\alpha)$ is the gamma function at α. The estimated parameters can be used to find the cumulative PDF of observed precipitation events for the given month and particular time scale. The cumulative distribution function (CDF) is obtained by integrating Equation (2)

$$G(x) = \int_0^x g(x)\,dx = \int_0^x \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} x^{\hat{\alpha}-1} e^{-x/\hat{\beta}}\,dx \tag{3}$$

where

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{4}$$

$$\hat{\beta} = \frac{\hat{x}}{\hat{a}} \tag{5}$$

$$A = \ln(\bar{x}) - \frac{\sum^{\ln}(x)}{n} \tag{6}$$

n = number of precipitation observations and $\bar{x}$ refers to the sample mean of the data.

(2) Transform the CDF to the CDF of the standard normal distribution with zero mean and unit variance, which is

given as follows:

$$\mathrm{SPI} = \psi^{-1}[G(x)] \tag{7}$$

This transformed probability is the SPI. A positive value of SPI indicates that precipitation is above average and a negative value denotes below average precipitation.

A drought event is defined here as a period in which the SPI is continuously negative and reaching a value of −1.0 or less (McKee *et al.* 1993; Paulo & Pereira 2006). The duration *(D)* is defined by the time between the beginning and the end (−ve SPI values); the magnitude is calculated by the sum of the SPI for every month from the initiation to the end of each drought event, and the intensity is the ratio between the magnitude and the duration of the event.

Reconnaissance Drought Index

Tsakiris & Vangelis (2005) proposed meteorological droughts to be conceptualized as water deficits representing the water balance deficit between input (precipitation) and output (reference evapotranspiration). The initial value (α_k) of RDI for a certain period, indicated by a certain month (k) during a year, could be determined as

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} \mathrm{PET}_j} \tag{8}$$

where P_{ij} and PET_{ij} are the precipitation and PET of the jth month of the year. Although this equation can be calculated starting from any month of the year, this study considered January ($k = 1$) as the starting month and not October, the month normally used in several Mediterranean countries and in the Middle East region.

The RDI can be expressed as normalized RDI (RDI_n) and Standardized RDI ($\mathrm{RDI}_{\mathrm{st}}$). The RDI_n is computed using the following equation:

$$\mathrm{RDI}_n(k) = \frac{a_k}{\bar{a}_k} - 1 \tag{9}$$

The $\mathrm{RDI}_{\mathrm{st}}$ is computed following a similar procedure to the one that is used for the calculation of the SPI. The equation is as follows:

Table 2 | Classifications scale for SPI values

SPI values	Category
0 to −0.99	Near normal
− 1.0 to −1.49	Moderate drought
− 1.5 to −1.99	Severe drought
− 2 and less	Extreme drought

$$\mathrm{RDI}_{\mathrm{st}}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k} \tag{10}$$

where y_k is ln ($a_k^{(i)}$), $\bar{y}_k$ is its arithmetic mean and $\hat{\sigma}_k$ is its standard deviation.

In this study, the RDI is fitted to a gamma PDF similar to the one used for SPI. Therefore, the $\mathrm{RDI}_{\mathrm{st}}$ could be computed following a similar procedure described for SPI and the values compared to the same threshold values as SPI (Table 2).

Theory of Runs

Probabilistic features of drought have been investigated extensively since Yevjevich (1967) proposed the use of the run concept as a method to identify and characterize drought events and their statistical properties in an objective way. Although ToR is not a drought index, it could be used along with other DI in identifying drought parameters. A drought event is identified as a period in which the rainfall time series is consecutively less than the critical threshold level, y_c (Figure 3).

In this study, the identification of the critical rainfall threshold level was based on the SPI drought class threshold

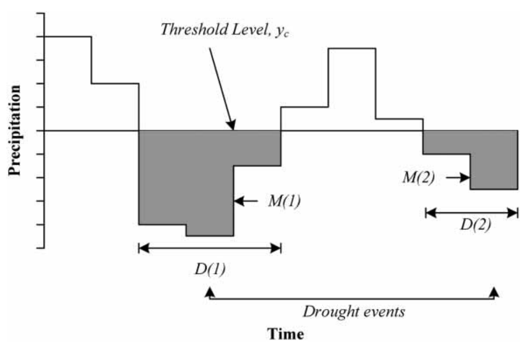

Figure 3 | Characteristics of local drought events with the ToR (Paulo & Pereira 2006).

(SPI = −1). Therefore, the rainfall threshold level, $y_c = \hat{\mu} - \hat{\sigma}$ (i.e., a rainfall below the mean corresponding to the standard deviation) was selected. This threshold level was also used in past studies by Ben-Zvi (1987) and Paulo & Pereira (2006). ToR can be computed for 3-, 6- and 12-month time scales.

Deciles

Gibbs & Maher (1967) suggested another drought-monitoring technique by arranging monthly precipitation data into deciles. The deciles are commonly used by the BoM to assess the status of rainfall deficiency throughout Australia. This technique divides the distribution of occurrences over a long-term precipitation record into tenths of the distribution, and each of these one-tenth slices is called a decile. The deciles are grouped into five classifications as shown in Table 3. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences, and so on, until the tenth decile which is the largest one-tenth of precipitation amounts within the long-term record.

In the current study, a station is considered to be suffering from drought if the sum of the observed precipitation falls within the two lowest deciles (deciles 1 and 2) of the historical distribution of 3-, 6- or 12-month totals, as suggested by Kinninmonth *et al.* (2000) and Keyantash & Dracup (2002).

RESULTS AND DISCUSSION

Drought characteristics

The SPI, RDI and deciles were applied to data from all five stations at 3-, 6- and 12-month time scales. The three methods were applied to rainfall and evapotranspiration data from 1955 to 2010. For meaningful comparison, all three indices were calculated starting at the beginning of each year for all time scales. For the ToR and deciles, the threshold values for all stations are tabulated in Table 4. It is worthwhile noting that the values vary for each station. The threshold value is critical when estimating the water shortage, especially during a drought spell or when designing water storage systems.

Droughts identified using all three indices for Station 86071 on 3-, 6- and 12-month time scales are shown in Figures 4–6, respectively. For the 3-month time scale using the RDI, eight drought events were identified during a period from 1955 to 2010. For the SPI, nine droughts were identified with one additional moderate drought event in the year 1976 with SPI at −1.16. Deciles showed 11 observed precipitation totals falling within the two lowest deciles of the historical distribution.

For the 6-month time scale, the SPI showed drought events increasing from eight to ten. However, the RDI identified only eight drought events over the period. It identified similar years of drought as the SPI did, except there were no droughts detected in the years 1983 (−0.84) and 2008 (−0.82). Similar to the 3-month time scale result, deciles identified 11 drought events giving the greatest number of droughts from all the indices. The threshold value obtained for this time scale was 210 mm.

For the 12-month time scale, in addition to Station 86071, the droughts identified for the other stations are tabulated in Table 5 for comparison. The years when drought occurred were slightly different from one station to the other. This is due to the variation in precipitation and other meteorological data for each location. For Station 76031, the SPI and RDI indices showed similar behaviour in detecting years of drought, except in 2002. However,

Table 3 | Decile classification

Value	Classification
Deciles 1–2: lowest 20%	Much below normal
Deciles 3–4: next lowest 20%	Below normal
Deciles 5–6: middle 20%	Near normal
Deciles 7–8: next highest 20%	Above normal
Deciles 9–10: highest 20%	Much above normal

Table 4 | The threshold values (mm) for each station using ToR and deciles in different time scales (3-, 6- and 12-month)

	ToR			Deciles		
Station	3	6	12	3	6	12
76031	23	68	191	31	73	202
77051	24	91	247	31	95	270
79011	43	174	472	40	175	492
81013	47	155	384	53	168	397
86071	75	212	508	77	210	503

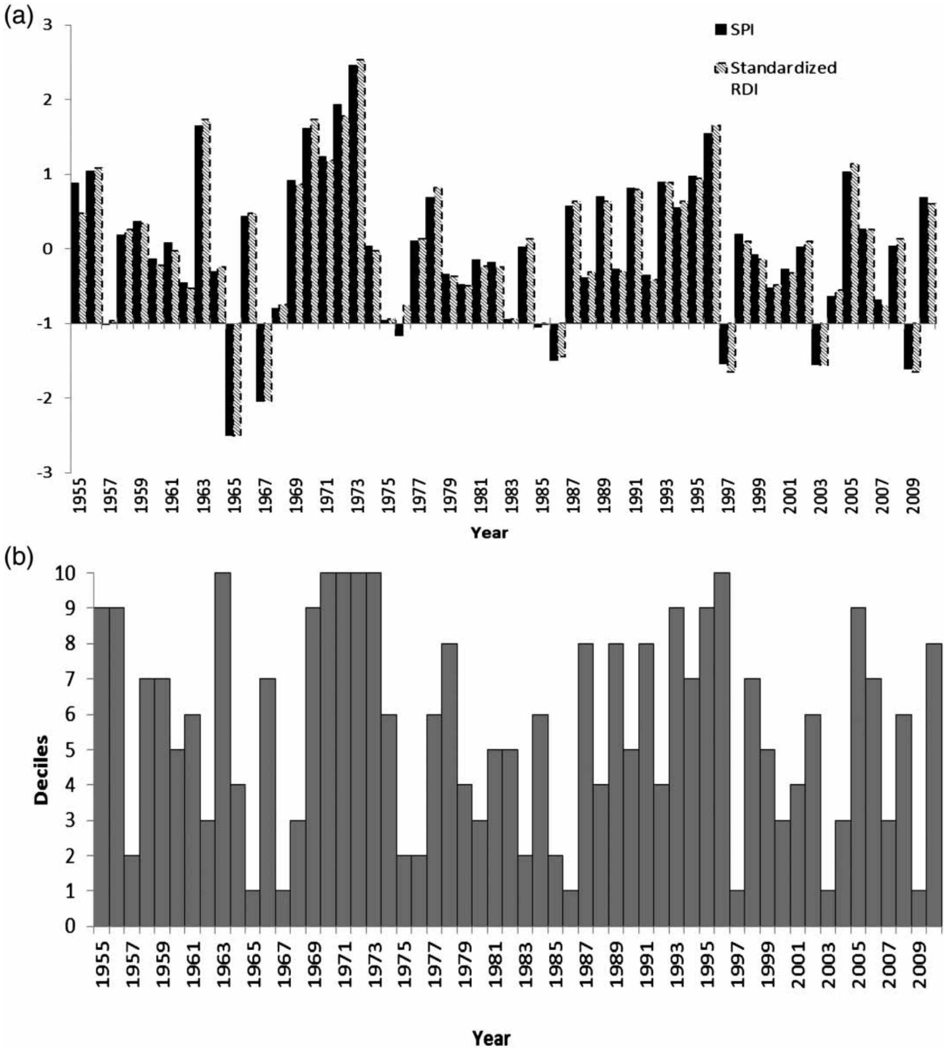

Figure 4 | Droughts identified using (a) SPI and RDI and (b) deciles on 3-month time scale for Station 86071.

while SPI does not indicate drought in 2002, RDI showed the severity to be just below the threshold level of -1.08. The 1982 and 2006 droughts are shown to be the worst among all droughts based on the results of all indices. In contrast, Station 77051 identified the 1967 drought to be the most severe, followed by the 1982 and 2006 droughts; RDI gave one additional year of drought in the year 1990 for this station. For Station 79011, the results of the SPI and RDI indices show similarities in detecting drought events. The 2006 drought was the worst amongst all of them.

Nine droughts were detected using the SPI and RDI for Station 81013. Again, the 1982 and the 2006 droughts were found to be the most severe compared to other droughts. For Station 86071, the 2003 drought was the only difference between RDI and the other two indices. However, it was a very slight difference as the SPI gave a severity of -1 and deciles showed the sum of the precipitations falls in the second decile. Similarly to Station 77051, the 1967 drought was the most severe amongst all the years. The longest duration of a drought was found at this station and was for four successive years from 2006 to 2009 detected by all three indices (Figure 6).

Overall, the 1967 and 1982 droughts, which are said to be the most widespread droughts in the State of Victoria (BoM 2011), were confirmed to be so based on the results of the current study for all stations. Furthermore, all stations

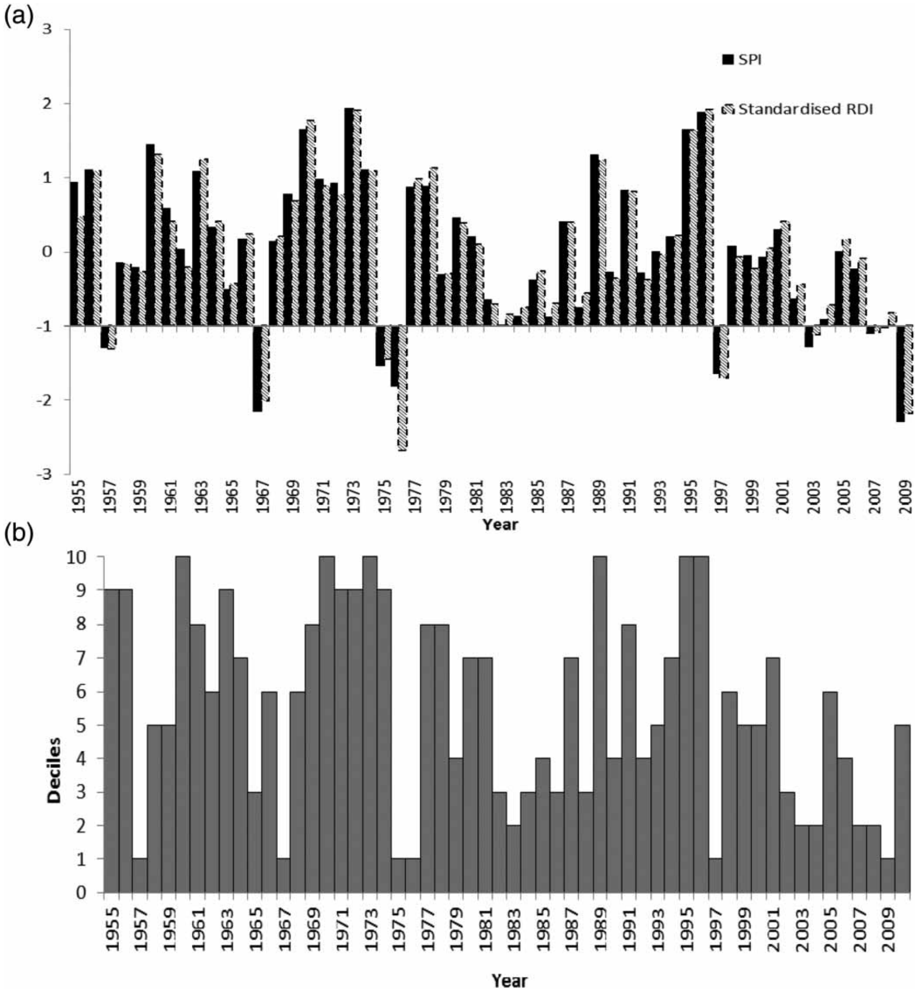

Figure 5 | Droughts identified using (a) SPI and RDI and (b) deciles on 6-month time scale for Station 86071.

suffered from droughts in 2006. Table 6 summarizes the number of drought events and classifications that occurred in all five locations during the study periods, as discussed above. It also depicts the maximum intensity of droughts and maximum deficits for all five stations calculated for each period over 3-, 6- and 12-month time scales. As discussed earlier, the SPI and RDI identified almost the same number of drought events during each drought period but with slightly different severity, as shown in Table 6. Overall, on the 3-month time scale, Stations 76031, 77051 and 79011 gave comparable numbers of drought for these two indices, while for the 6-month time scale, Stations 76031, 77051 and 81013 showed similarities. Last but not least, for the 12-month time scale, Stations 76031, 79011 and 81013 gave similar results in identifying the number of drought events. Station 76031, which is the driest station, showed comparable results between SPI and RDI. It is also important to note that the intensity values obtained from the SPI and RDI methods were not directly comparable as each method calculated the droughts differently.

The correlation between the SPI and RDI indices were calculated and deemed to be satisfactory (Table 7) for all stations and time scales. The values ranged from 0.980 to 0.997. Station 76031 obtained the highest coefficient while Station 79011 showed the lowest. A similar result was found in Asadi Zarch et al. (2011), where SPI and RDI are more correlative in a dry climate than in a humid (wet) climate. As shown in Figure 2, Stations 79011 and 86071 receive more monthly rainfall with lower average temperature compared to the others. It also shows that the

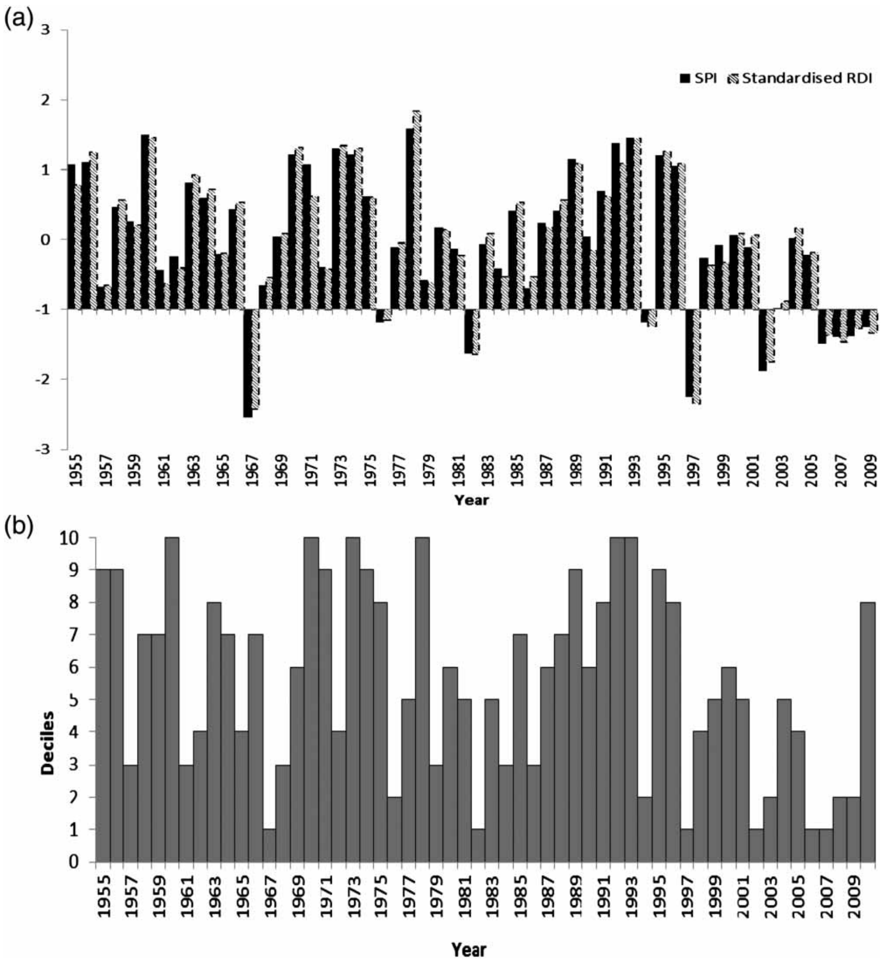

Figure 6 | Droughts identified using (a) SPI and RDI and (b) deciles on 12-month time scale for Station 86071.

correlation decreased with an increase in time scale. This is most probably due to the variability of monthly PET and the rainfall data when longer time scales were considered. The correlations were also tested for SPI and RDI values calculated starting with a month different to January. This still gave similar results.

Detecting the onset and end of droughts using SPI

The SPI was further applied to define the initiation (onset) and end of droughts in Victoria. The onset of drought times for different time scales (3, 6 and 12 months) obtained were compared with the recorded 1982 and 2002 droughts as shown in Table 8. The 1982–83 event had recorded drought periods between April 1982 and February 1983 (Gibbs 1984) based on the deciles method.

Figure 7 shows an example of SPI for Station 77051 for all time scales for the 1982–83 drought. The 3-month time scale started in November 1981 and ended in March 1983, and the duration became longer for the 6-month time scale because of less fluctuation in the SPI values given that the computation is based on a 6-month moving cumulative rainfall. As the time period is lengthened, the SPI responds more slowly to changes in precipitation, and periods with the SPI being negative and positive become fewer in number but longer in duration. The 6-month time scale showed the drought starting in January 1982 lasting until June 1983. For the 12-month time scale, the drought commenced in May 1982, which was 1 month late than recorded, and ended in September 1983.

The onset time of the drought for other stations, as shown in Table 8, varied with the time scale used to calculate the

Table 5 | Droughts identified at 12-month time scale for all stations

Stations	Year	SPI	RDI	Deciles
76031	1959	−1.15	−1.07	2
	1967	−1.96	−1.91	1
	1972	−1.58	−1.49	1
	1982	−2.07	−1.99	1
	1994	−1.4	−1.34	1
	1998	−1.39	−1.36	1
	2001	−1.04	−1.07	2
	2002	–	−1.08	2
	2004	−1.23	−1.28	2
	2006	−2.04	−2.06	1
	2008	–	–	2
77051	1967	−2.79	−2.68	1
	1972	–	–	2
	1977	−1.23	−1.11	1
	1982	−2.72	−2.6	1
	1990	–	−1	2
	1994	−1.42	−1.37	1
	1997	–	–	2
	2002	−1.72	−1.78	1
	2004	–	–	2
	2006	−2.31	−2.34	1
	2008	−1.03	−1.06	2
79011	1959	−1.81	−1.63	1
	1961	−1.02	−1.18	2
	1967	−2.33	−2.27	1
	1969	–	–	2
	1982	−1.82	−1.83	1
	1994	−1.07	−1.13	2
	1997	−1.35	−1.46	1
	2002	−1.53	−1.44	1
	2005	–	–	2
	2006	−2.79	−2.78	1
	2008	–	–	2
81013	1957	–	–	2
	1961	−1.02	−1	2
	1967	−1.56	−1.54	1
	1972	−1.6	−1.51	1
	1976	–	–	2
	1982	−2.37	−2.27	1
	1994	−1.52	−1.45	1
	1997	−1.13	−1.12	2
	2002	−1.76	−1.81	1
	2006	−2.54	−2.52	1
	2009	−1.18	−1.34	2
86071	1967	−2.54	−2.43	1
	1976	−1.18	−1.15	2
	1982	−1.63	−1.65	1
	1994	−1.18	−1.24	2
	1997	−2.24	−2.35	1
	2002	−1.87	−1.76	1
	2003	−1	–	2
	2006	−1.48	−1.38	1
	2007	−1.38	−1.46	1
	2008	−1.38	−1.27	2
	2009	−1.24	−1.35	2

(*continued*)

Table 5 | continued

index. For all five locations, the 3-month time scale showed the onset of the drought during the same time of the year in October–November. They show the onset of a mild drought from the beginning of the year followed by severe drought commencing later around June–July that year. The 6-month time scale indicated a drought two to three months in advance of the recorded drought. In contrast, with the exception of Station 86071, the 12-month time scale showed the onset later, in May–July, in that year. This might be because, as the time period is lengthened to 12 months, the SPI responds more slowly to changes in precipitation. Shorter or longer time scales may reflect different lags in the response to precipitation anomalies.

The 2002–2003 drought lasted from April 2002 to January 2003 (BoM 2003). Figure 8 shows the onset and end of drought for the 2002–2003 drought for all time scales. On the 3-month time scale, the SPI showed the onset of the drought starting from December 2001 and lasting until January 2003, showing the duration of the drought to be 14 months. For the 6-month time scale, it showed the onset two months earlier than the recorded drought that started from January 2002 ending in January 2003. For all five locations and for all time scales, the SPI showed the onset of the droughts well, as shown in Table 8. Based on the results it could be concluded that the SPI method would

Table 6 | Drought properties based on the SPI, RDI and ToR analysis

Stations	SPI				RDI				ToR
	No. of drought events			Max intensity	No. of drought events			Max intensity	Max deficit (mm)
	Moderate	Severe	Extreme		Moderate	Severe	Extreme		
76031	–	4	2	−3.11 (1965)	1	3	2	−3.05 (1965)	19.5 (1965)
77051	6	1	2	−3.25 (1986)	6	1	2	−3.22 (1986)	21.1 (1986)
79011	4	6	–	−1.82 (1986)	4	6	–	−1.8 (2009)	16 (1986)
81013	4	–	3	−3.28 (1965)	3	1	2	−3.24 (1965)	40.6 (1965)
86071	4	3	2	−2.51 (1965)	3	3	2	−2.51 (1965)	51 (1965)
76031	7	2	–	−1.88 (2004)	6	3	–	−1.8 (2004)	23.2 (2004)
77051	8	1	1	−2.52 (1967)	8	1	1	−2.41(1967)	48.3 (1967)
79011	4	3	2	−2.33 (1967)	3	2	2	−2.87 (1976)	67.1 (1967)
81013	2	3	1	−2.3 (1976)	2	3	1	−2.7 (1976)	51.4 (1976)
86071	5	3	2	−2.29 (2009)	4	1	3	−2.68 (1976)	85.3 (2009)
76031	5	2	2	−2.07 (1982)	7	2	1	−2.06 (2006)	65 (1982)
77051	3	1	3	−2.79 (1967)	4	1	3	−2.68 (1967)	126 (1967)
79011	3	3	2	−2.79 (2006)	4	2	2	−2.78 (2006)	164 (2006)
81013	3	4	2	−2.54 (2006)	4	3	2	−2.52 (2006)	177 (2006)
86071	7	2	2	−2.54 (1967)	6	2	2	−2.43 (1967)	171 (1967)

Table 7 | Correlation coefficient of the SPI and RDI for all stations in different time scales

Stations	Time scales 3	6	12
76031	0.997	0.994	0.994
77051	0.997	0.990	0.994
79011	0.988	0.980	0.985
81013	0.997	0.992	0.993
86071	0.995	0.980	0.991

satisfactorily identify meteorological drought events in Victoria, Australia.

Why is it important to apply DI in Australia?

To date, there are no DI applied across Australia by any Commonwealth agency except the Bureau of Meteorology (BoM) which uses deciles to assess the status of rainfall deficiency throughout Australia. A similar situation existed in the USA until the National Integrated Drought Information System Act was passed in 2006 (Public Law 109-430) addressing major droughts across America, which locked in SPI to legally define drought. In Australia, state-based agencies are responsible for operational decision-making using independently derived indices to assist operational planning.

For example, Melbourne Water Corporation responsible for supplying four million people across the metropolis, uses 'total system storage triggers' to impose various water restriction levels. The implementation of water restriction is directly related to the severity of an evolving drought, and thus the water authority has to identify how severe a particular drought event is before planning the appropriate response. Therefore, the adaptation of SPI, which is applied in this current study, could provide essential information on droughts (e.g., lead time, duration, magnitude, the onset and end of the drought, etc.) which would help organizations to plan responses and drought impact mitigation actions.

CONCLUSIONS

This study was designed to evaluate three popular indices for the assessment of drought occurrences using data

Table 8 | Comparison of the recorded onset of the 1982–83 (April 82–February 83) and 2002–03 (April 2002–January 2003) drought events with the results obtained from the SPI

	1982–1983		2002–2003	
Stations	**Initiation**	**End**	**Initiation**	**End**
3-month				
76031	November 81	July 83	November 01	July 03
77051	November 81	March 83	December 01	January 03
79011	November 81	February 83	January 02	December 02
81013	November 81	March 83	May 01	April 03
86071	October 81	June 83	March 02	December 03
6-month				
76031	January 82	September 83	January 01	January 03
77051	January 82	June 83	January 02	January 03
79011	January 82	April 83	March 02	January 03
81013	January 82	May 83	May 01	May 03
86071	December 81	August 83	September 01	December 03
12-month				
76031	May 82	November 83	February 01	September 03
77051	May 82	October 83	February 01	July 03
79011	July 82	August 83	March 02	May 03
81013	June 82	August 83	May 01	October 03
86071	December 81	December 83	July 01	December 03

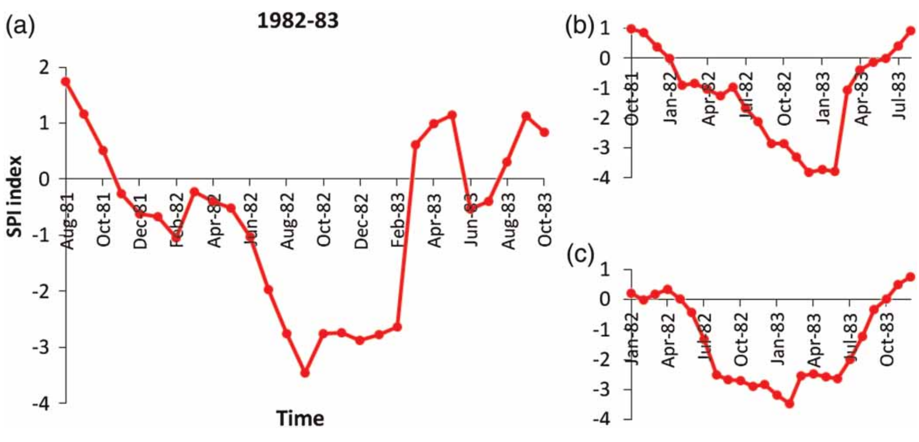

Figure 7 | Onset and end of drought obtained from the SPI on (a) 3-month, (b) 6-month and (c) 12-month time scales for Station 77051.

from five rainfall stations across Victoria, Australia. Theory of Runs (ToR) was then used to obtain drought deficit. The SPI and deciles require only rainfall data which are usually available in most countries for many locations, while the RDI method needed evapotranspiration and rainfall for its computation. Although the decile method is commonly used in Australia, it has a few limitations. One of the disadvantages is that it does not indicate the onset and end of droughts which are important features of drought monitoring. Another limitation is that droughts are defined arbitrarily based on a selected threshold and hence would be different from one location to the other. In

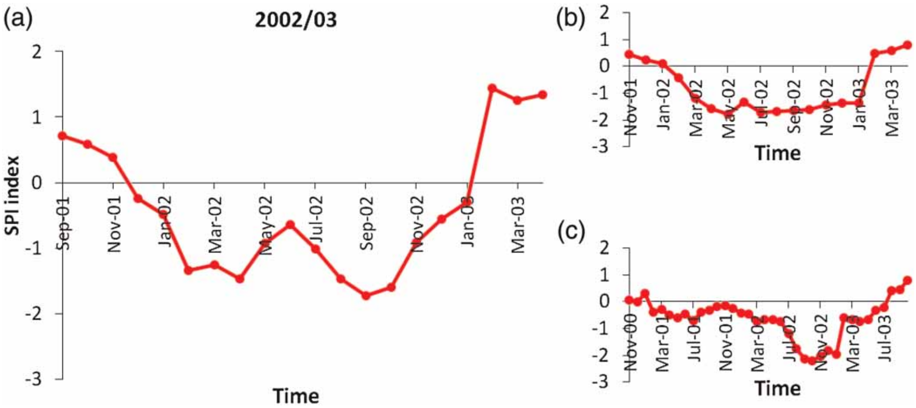

Figure 8 | Onset and end of drought for 2002–2003 on (a) 3-month, (b) 6-month and (c) 12-month time scales for Station 77051.

contrast, SPI and RDI do not rely on arbitrary selection of threshold values and the classification of when a drought occurs is clear and is set objectively. They are also applied consistently across jurisdiction (States) as the methodology has inbuilt standardization of the specific indices.

The SPI was able to identify the onset and end of meteorological droughts successfully when applied to the data. It was shown to be a good indicator and is worthy of further study to examine its use for drought monitoring and early warning, especially in other eastern states of Australia. On the other hand, utilization of the RDI might be beneficial for characterizing agricultural droughts, given that the RDI includes PET apart from precipitation in the calculation, providing an indicative deficit in soil moisture. As all three indices were calculated starting at the beginning of each year for all time scales, looking at different time scales is also necessary for comparison. In this study it was shown that the indices calculated at a longer time scale (i.e., 12 months) provided better results as the longer time scale reflected better historical drought events.

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