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Assessment of hydrological drought characteristics in the Yarra River catchment: a case study

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Abstract

Hydrological drought is defined by the substantial reduction of water in the hydrological cycle. This study applied the Standardised Hydrological Drought Index (SHDI) to evaluate hydrological drought events at various timescales (3, 6, 9 and 12 months) using streamflow data from the Yarra River Catchment in southeast Victoria, Australia. The easy application of the SHDI across time and space makes it a useful index for monitoring and assessing drought events. Different analysis timescales identified a different number of drought events. The longest timescale (12 months) detected a higher number of extreme drought events compared to the shortest timescale (3 months). Drought durations also changed as function of analysis timescales for the selected stations. The results showed that the peak drought intensities were not necessarily associated with the longest duration droughts, but rather drought events with comparatively short duration. The onset and end times of the drought events also varied with timescales. Finally, the SHDI threshold values were transformed into mean monthly streamflow threshold values, which are easy to use in real-time conditions for managing droughts. The longest timescale analysed (12 months) exhibited a higher threshold value as it more likely to include both dry and wet periods. Therefore, the selection of an appropriate timescale for data analysis is essential, as drought characteristics are highly influenced by the timescale. The findings from this study will assist water managers in developing appropriate drought mitigation strategies.

Keywords

hydrological drought; Standardised Hydrological Drought Index; drought duration; drought intensity

Introduction

Drought is a natural phenomenon characterised by the reduction of available water over a substantial period of time due to reduced rainfall. It is one of the main natural hazards affecting the economy and the environment in many countries (Wilhite, 2000). Drought has unique characteristics of slow onset and non-structural impacts, compared with other natural hazards. Therefore, it is difficult to assess the development and effects of droughts. Conventionally, droughts are categorized into four groups: meteorological, hydrological, agricultural, and socio-economic (Mishra and Singh, 2016). Hydrological drought is defined as the reduction of water in the land phase of the hydrological cycle. The monitoring and evaluation of drought events are extensively carried out by the use of drought indices. Such indices identify the drought onset and termination, and assess the intensity, magnitude and duration of any drought event (Todisco *et al.*, 2013; Tabari *et al.*, 2013). Numerous drought indices have been used to characterise hydrological droughts including the Surface Water Supply Index (SWSI), Streamflow Drought Index (SDI), Standardised Hydrological Index (SHI), Regional Drought Area Index (RDAI), Standardised Runoff Index (SRI) and Standardised Hydrological Drought Index (SHDI) (Shafer and Dezman, 1982; Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009; Sharma and Panu, 2010; Fleig *et al.*, 2011; Dehghani *et al.*, 2014; Rahman *et al.*, 2016).

Australia is one of the driest countries in the world and has experienced multi-year droughts over the last few decades (Tan and Rhodes, 2013). Many parts of Australia have suffered from frequent droughts. Droughts impose severe stress on water supply systems and the communities that depend on them. Therefore, drought monitoring, and forecasting play important roles in the management of droughts in Australia (Rahmat *et al.*, 2015a, 2015b, 2016).

The aim of this paper was to evaluate hydrological drought characteristics in the Yarra River catchment of Victoria, Australia using the SHDI (Dehghani *et al.*, 2014). For multiple timescales (3, 6, 9 and 12 months), drought severity classes were established based on streamflow threshold values, which are the transformation of SHDI values. This approach conveys information on drought events as streamflow values that can be easily understood by ordinary users and decision makers. Furthermore, a comparative analysis of timescales was carried out for the purpose of selecting the most appropriate timescale for the study objective. A suitable timescale is vital for evaluation of drought as its characteristics (such as initiation, intensity, duration, magnitude and frequency of occurrence) are controlled by the timescale.

Data and methods

Study area and data collection

The study area was the Yarra River catchment, which is located in the eastern part of Victoria (Fig. 1). Although the Yarra River is not the largest river in Victoria, it is a very productive catchment as it generates the fourth highest yield of water per hectare of catchments in Victoria (Melbourne Water, 2016). The catchment is divided into three

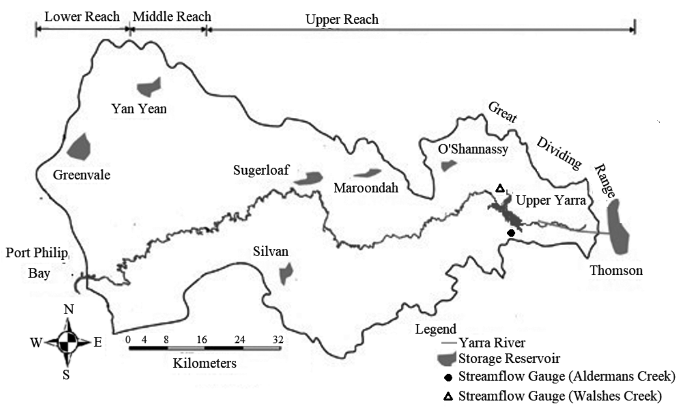

Figure 1 – Yarra River catchment

reaches: upper, middle and lower. The forested upper reach has supplied 70% of the drinking water for the Melbourne region for many years (Melbourne Water, 2016). Most of the land along the water bodies in middle and lower reach has been cleared either for agriculture or urban development. Over the last few decades, this area has been highly affected by several drought events that have generated acute water shortages in rural and urban environments. Therefore, assessing and managing drought conditions have become important issues within this catchment. Two monitoring stations in the upper reach of the Yarra River were selected to evaluate drought characteristics for this study (Fig. 1): Aldermans Creek (catchment area 24 km^2, annual average flow 8.33 GL) and Walshes Creek (catchment area 55 km^2, annual average flow 15.7 GL). Monthly streamflow data were collected from the Bureau of Meteorology Australia Website (http://www.bom.gov.au). Data from 1979 to 2014 (35 years) were used to calculate the SHDI at multiple timescales.

Standardised Hydrological Drought Index (SHDI)

The SHDI is an effective tool to quantify the streamflow deficit at multiple timescales, e.g., 1, 3, 6, 9, 12, 24 and 48 months (Labedzki, 2017). The SHDI is the transformation of the streamflow time series over a specified area into a standardised normal distribution. The calculation of SHDI requires long-term streamflow data. A gamma probability density function (PDF) is fitted to the streamflow of several time series. This is performed separately for each month. The gamma PDF is:

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

where β is a scale parameter, α is a shape parameter, x is the streamflow, and $\Gamma(\alpha)$ is the gamma function at α. The cumulative probability is obtained by integrating Equation 1 and is given by Equations 2, 3, 4 and 5:

$$G(x) = \int_0^x g\,(x)dx = \int_0^x \frac{1}{\hat{\beta}^{\hat{\alpha}}\,\Gamma(\hat{\alpha})}\, x^{\hat{\alpha}-1}\, e^{-x/\hat{\beta}}\, dx \qquad (2)$$

where

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

$$\hat{\beta} = \frac{\hat{x}}{\hat{\alpha}} \qquad (4)$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \qquad (5)$$

and n is the number of observations. The cumulative distribution is then transformed into a normal distribution with a mean of zero and variance of one (Rahmat *et al.*, 2015b) (Eq. 6):

$$SHDI = \psi^{-1}\,[G\,(x)] \qquad (6)$$

This transformed probability is the SHDI value where Ψ^{-1} is the transformation parameter (Fig. 2). A positive SHDI value indicates streamflow above average and a negative value specifies below average streamflow. The next step is to describe drought incidents by streamflow threshold values based on the SHDI formula at different timescales. The calculation of threshold values is analogous to the methods of the SHDI calculation. Assuming that the SHDI is a random normal variable, z, the SHDI drought class boundaries are transformed into probabilities as shown in Equation 7:

$$\phi\,(Z) = F\,(x) = P\,(X\ \leq x) \qquad (7)$$

where ϕ (z) is the normal distribution function and x is the cumulative streamflow value for the considered timescale. Similar to the computation of SHDI, the gamma distribution function is calculated using Equation 2. Then, the cumulative probability of a given upper bound SHDI value is made equal to the value derived from the gamma distribution function. Finally, Equation 8 is used to estimate the corresponding cumulative streamflow value *x*. If the cumulative threshold value is below the specified threshold level, the river is considered to be going through a drought period.

$$x = G^{-1}\,[(\phi(z)]\qquad(8)$$

A drought event is defined as a period in which the SHDI value is continuously negative (McKee *et al.*, 1993; Paulo and Pereira, 2006). In this paper, hydrological drought severity classes were specified based on the SHDI values (Table 1) (McKee *et al.*, 1993). Figure 3 presents a schematic description of different properties of drought events. Drought duration (*D*) is the time period between the start and end of any drought event. Drought magnitude (*M*) is the cumulative SHDI values within the drought duration. The intensity (*I*) is the ratio between the magnitude and duration of drought event. Another important characteristic of drought is inter-arrival time (*L*), which is the time period from the end of one drought event to the commencement of the next event (Shiau, 2006). However, in this paper, the inter-arrival time is not investigated.

Table 1 – Drought severity classes using the SHDI (McKee *et al.*, 1993)

SHDI values	Classification
0≥SHDI≥-0.99	Mild
-1≥SHDI≥ -1.49	Moderate
-1.5 ≥ SHDI ≥ -1.99	Severe
SHDI ≤ -2	Extreme

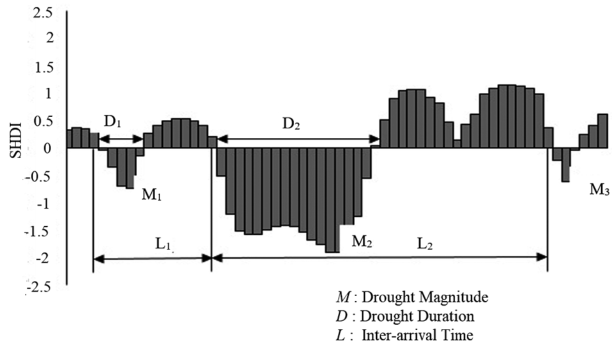

Figure 3 – Drought properties defined by the SHDI

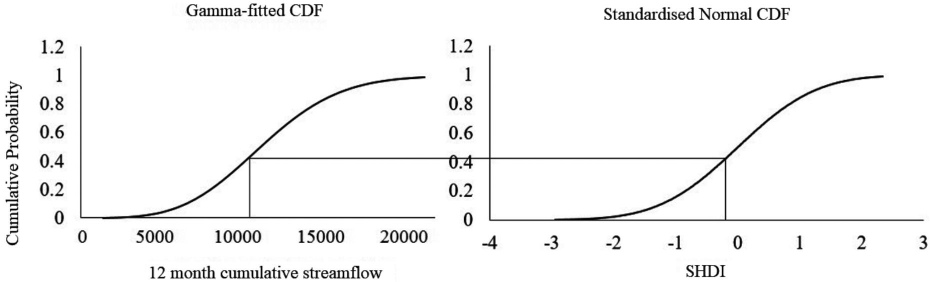

Figure 2 – Transformation of gamma-fitted CDF to the CDF standardised normal distribution (SHDI= 0) for Aldermans Creek station at a 12-month scale

Results and discussion

Temporal characteristics of drought

Victoria has experienced several droughts in the last 50 years (i.e., 1967–1968, 1972–1973, 1982–1983, 1997-2009) (Tan and Rhodes, 2013). Droughts have created immense negative impacts on human lives while causing enormous economic losses and environmental degradation. The recent 13-year drought (1997-2009), which is known as the Millennium Drought, recorded the lowest annual rainfall and streamflow in the Yarra River catchment. During this period, inflows into Melbourne Water's main four reservoirs (i.e., Thomson, Upper Yarra, O'Shannassy and Maroondah, as shown in Fig. 1) dropped well below the long-term average, which initiated the implementation of water restrictions to manage shortages in water supply systems. Therefore, analysing drought characteristics in the study catchment is one of the key issues for the proper management of water resources.

The SHDI was applied to evaluate hydrological drought characteristics for multiple timescales, i.e., 3, 6, 9 and 12 months. The SHDI values were derived from monthly streamflow time series. For example, the SHDI 12-month time series for any particular month is the cumulative streamflow values from the previous 12 months. Herein, two scenarios were considered when assessing drought characteristics. In the first scenario, a drought event was considered to commence as soon as the SHDI value became equal or less than zero and terminated when the SHDI value rose to more than zero (Vicente-Serrano and López-Moreno, 2005; Fiorillo and Guadagno, 2010). This scenario is described as threshold=0. In the second scenario, a drought event was defined as a period when the SHDI value reached -1 or less and continued until it rose to zero (Paulo and Pereira, 2006). This scenario is designated as threshold=-1. The two scenarios identified a different number of drought events: in the first scenario, mild drought events were included whereas in the second scenario they were not.

The drought events identified by the SHDI in Aldermans Creek and Walshes Creek for different timescales are presented in Table 2. For Aldermans Creek station, the time series of SHDI at 3-month and 12-month scales with thresholds 0 and -1 are shown in Figure 4. Using a 3-month timescale, thirty-two drought events were identified with threshold=0, including eleven mild drought events. These mild events were not included when the threshold was set to -1. The 12-month scale identified 3 mild events that were not included when the threshold changed to -1. The longest timescale (12-month) identified a higher number of extreme drought events than the shortest timescale (3-month). On the contrary, the shortest scale (3-month) detected more mild and moderate events. Three extreme events were conspicuous: 1982-1983, 1997-2003 and 2005-2011 using a 12-month scale. The corresponding SHDI values for these three events were -2, -2.15 and -2.75, respectively, for Aldermans Creek. Similarly, three extreme events were observed in Walshes Creek in the same period with SHDI values of -2.54, -2.14, -2.7, respectively, using a 12-month scale.

As shown by Figure 4, the SHDI 3-month timeseries exhibited more fluctuation than the 12-month series. As the timescales became longer, the SHDI responded more slowly to changes in streamflow. Therefore, periods with the SHDI negative and positive became fewer in number but longer in duration. As expected, droughts were more frequent with shorter durations in the 3-month scale. In Aldermans Creek station, the 3-month scale revealed several drought events of durations ranging from 1 month to 20 months. The 12-month scale exhibited longer duration droughts, ranging from 8 months to 75 months. Walshes Creek station displayed

Table 2 – Number of drought events identified using the SHDI in the Yarra catchment

Station name	Timescale (months)	Number of drought events				
			Threshold=-1			
		Mild	**Moderate**	**Severe**	**Extreme**	Total
Aldermans Creek	3	11	**15**	**5**	**1**	32
	6	4	**9**	**5**	**2**	20
	9	7	**4**	**4**	**1**	16
	12	3	**1**	**0**	**3**	7
Walshes Creek	3	12	**17**	**2**	**0**	31
	6	3	**13**	**5**	**2**	23
	9	9	**8**	**3**	**2**	22
	12	7	**0**	**1**	**3**	11

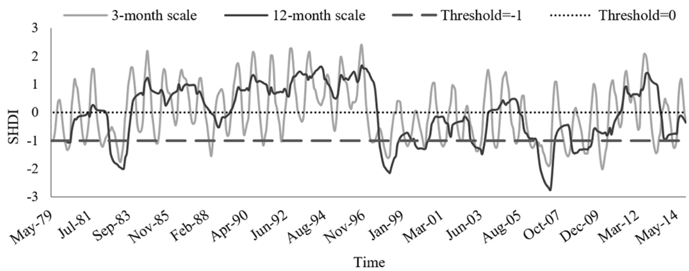

Figure 4 – Time series of SHDI at 3- and 12-month timescales for Aldermans Creek station.

drought events with durations fluctuating from 2 to 20 months and 11 to 57 months for the 3- and 12-month timescales, respectively.

Table 3 summarises the drought characteristics for the longest duration and highest peak intensity drought events from 1979 to 2014 for the selected two stations using 3, 6, 9 and 12-month timescales and threshold=0. The duration and magnitude of drought events were smaller at threshold=-1 than the duration and magnitude at threshold=0. A drought event with the longest duration may not necessarily have the highest magnitude because drought intensity is defined as the ratio of drought magnitude to drought duration. Hence, if the drought magnitude is relatively low but the duration is long the intensity may be less than a high magnitude short duration drought. For example, in Aldermans Creek station, the longest drought period detected by a 12-month timescale persisted for 75 months from September 1997 to November 2003 with an intensity of 0.89. On the other hand, the peak intensity occurred during the 1982-1983 drought event, which had a 16-month duration. In a similar way, the 9-month timescale identified the 1997-2000 drought event as the longest whereas the 1982-1983 event had the maximum intensity. Despite the 1982-1983 event having the longest duration with a SHDI 3-month timescale, the 2010 drought event contained the highest intensity. For a 6-month timescale, intensity was highest in the 2006-2007 drought event, and the 2008-09 event had the longest duration. In Walshes Creek station, the 1982-1983 event exhibited the peak intensities for

Table 3 – Characteristics of the longest duration and highest peak intensity drought events for different timescales (threshold=0)

Station	Timescale (months)	Longest duration				Highest peak intensity			
		D	M	I	Drought event	D	M	I	Drought event
Aldermans Creek	3	20	18.53	0.93	1982-83	8	10.36	1.3	2010
	6	21	19.96	0.95	2008-09	18	25.54	1.42	2006-07
	9	40	42.6	1.07	1997-00	17	24.18	1.42	1982-83
	12	75	66.73	0.89	1997-03	16	23.42	1.46	1982-83
Walshes Creek	3	21	15.17	0.72	2008-09	18	20.9	1.16	1982-83
	6	20	18.21	0.91	2008-09	19	25.76	1.36	1982-83
	9	29	24.88	0.86	2008-09	18	30.2	1.68	1982-83
	12	57	58.38	1.02	2006-07	21	31.01	1.48	1982-83

D = Duration, M = Magnitude, I = Intensity

all of the timescales. In most of the cases, the peak intensities occurred in drought events with short durations rather than events with long durations. Generally, intensity is the prime consideration for developing plans to manage extreme climatic hazard (Ebi and Bowen, 2016). Thus, information on maximum intensity of drought events in the study area will help water managers with drought mitigation strategies.

Detection of onset and end of drought using the SHDI

The SHDI can be used to define the initiation (onset) and end of drought events. The starting times of drought events for different timescales at a threshold of 0 were compared for the 1982-1983 and 2002-2003 events (Table 4). In most cases, a 3-month timescale identified the onset of drought event to be earlier than other timescales. Gibbs (1984) reported that the 1982-1983 drought was between April 1982 and February 1983. For the 3-month timescale in Aldermans Creek station, the drought began in December 1981 and ended in July 1983 and for the 12-month scale the drought began July 1982 and ended in October 1983 (Figs. 5a and 5b); the drought duration varied between 16 and 20 months depending on the timescale of analysis. The onset of droughts in Walshes Creek station also varied with the timescales. The 3-month scale showed the onset and termination of the drought in December 1981 and July 1983, respectively (Fig. 6a). In this case, a mild drought began in summer 1981 (December 1981) and was followed by severe drought in the following summer (February 1983). For the 12-month scale, mild drought started in July 1982 and in October 1982 it became extreme with an SHDI of -2.13 (Fig. 6b). Bureau of Meteorology (2003) documented the 2002-2003 drought as commencing in April 2002 and ending in January 2003. In the analysis of the 2002-2003 drought event in Aldermans Creek station, the drought durations were longer with increasing analysis timescales. In Aldermans Creek station, the 3-month timescale showed two drought events in a row in the 2002-2003 period. The first one started in February 2002 and lasted until

Table 4 – Comparison of the recorded onset and end of the 1982-1983 and 2002-2003 drought events with the results obtained from the SHDI analysis

Station	Timescale (months)	1982-1983 event (recorded as April 82–February 83)			2002-2003 event (recorded as April 02–January 03)		
		Initiation	End	Duration (months)	Initiation	End	Duration (months)
Aldermans Creek	3	Dec 81	Jul 83	20	Feb 02 Oct 02	Jul 02 July 03	6 10
	6	Mar 82	Aug 83	18	May 02	Sep 03	17
	9	May 82	Sep 83	17	May 02	Oct 03	18
	12	July 82	Oct 83	16	Sep 97	Nov 03	75
Walshes Creek	3	Dec 81	Jul 83	20	Feb 02	Jul 03	18
	6	Feb 82	Aug 83	19	Apr 02	Jul 03	19
	9	May 83	Oct 83	18	Jul 01	July 03	25
	12	July 82	Oct 83	16	Aug 01	Sep 03	26

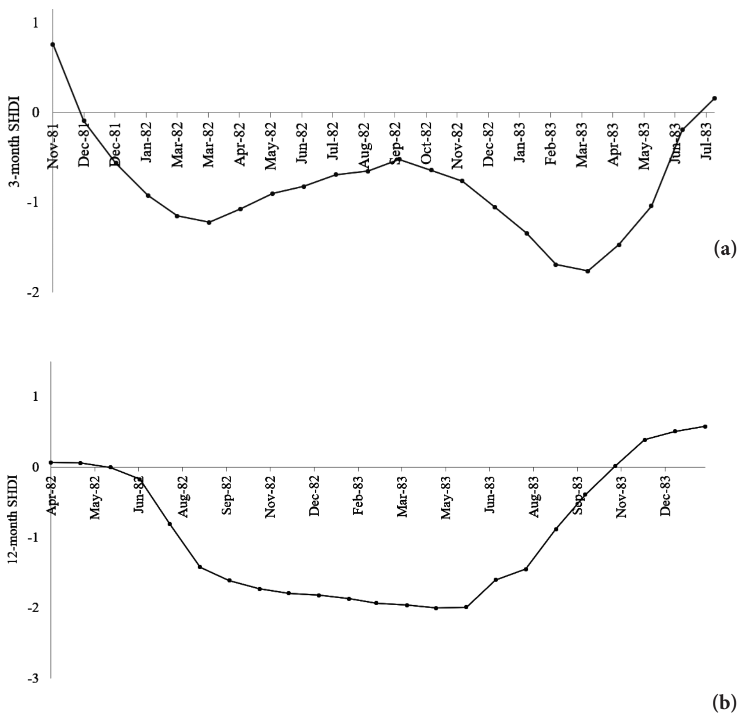

Figure 5 – Onset and termination of the 1982-1983 drought event for Aldermans Creek Station at (a) 3-month scale, (b) 12-month scale

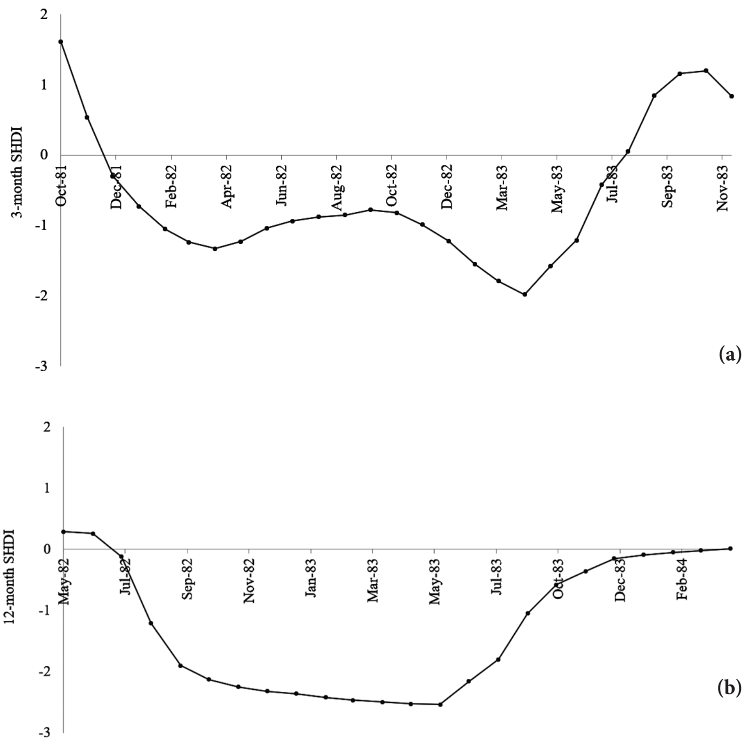

Figure 6 – Onset and termination of the 1982-1983 drought event for Walshes Creek Station at (a) 3-month scale, (b) 12-month scale

July 2002. Another drought event occurred between October 2002 and July 2003. For the 12-month timescale, the 2002-2003 event was a continuation of a drought that started in September 1997 and ended in November 2003. This drought event is a part of the Millennium Drought that affected Victoria severely in the period 1997-2009 (Rahmat *et al.*, 2015b). In Walshes Creek station, the drought event started in February 2002 and ended in July 2003 at the 3-month timescale. For 12-month scale, the drought events began in July 2001 and continued until July 2003. For both selected events (1982-1983 and 2002-2003), in Walshes Creek station, the 12-month scale assessed the commencement of drought events to be several months later than other timescales.

Transformation of SHDI to mean monthly streamflow thresholds

In this section, different SHDI threshold values (0, -1, -1.5, -2), which define the drought severity classes (Table 1), were considered. The calculated SHDI threshold values were converted into mean monthly streamflow threshold values for each of the selected timescales. Table 5 depicts the transformed streamflow threshold values with their corresponding SHDI threshold values. Comparing 12-month and 3-month scales indicates that longer timescales had larger streamflow threshold values than those of the shorter scale for all drought severity classes. The differences were mainly due to seasonal variation. In the case of the 12-month scale, each month accumulated streamflow values

Table 5 – Mean monthly streamflow threshold values for drought classes at different timescales

Station	Drought severity class	Mean monthly flow threshold (ML)			
		12-month scale	9-month scale	6-month scale	3-month scale
Aldermans Creek	Mild	649	630	598	553
	Moderate	383	345	272	202
	Severe	286	243	170	108
	Extreme	207	166	99	50
Walshes Creek	Mild	1196	1160	1068	963
	Moderate	680	586	418	276
	Severe	493	393	235	126
	Extreme	345	251	121	50

for the prior 12 months and is thus more likely to include both wet and dry periods than shorter timescales. In most of the cases, mean monthly streamflow threshold values for the 3-month scale were more likely to assemble only the dry months. In Victoria, rainfall is low in summer (December to February) and the impacts of lower rainfall on streams are evident over the March-April period of the year.

The 1982-1983 drought event in Aldermans Creek station was selected for detailed analysis. At a 12-month scale, the drought started in July 1982 and ended in October 1983, whereas at the 3-month scale, it started in December 1981 and terminated in July 1983. In this drought event, March 1983 was selected as a reference period as it is considered as the end of summer in Australia. At a 12-month scale, cumulated streamflow at March 1983 was 2602 ML, which gave a mean monthly threshold value of 217 ML. At a 3-month scale, the cumulated streamflow was about 247 ML giving a mean monthly threshold value of 82 ML – considerably smaller than the value at the 12-month scale. In this case, the 12-month scale assembled both dry and wet period streamflow values. However, the 3-month scale (in March) includes only the dry season. This applies to all other cases; i.e., mean monthly streamflow threshold values decreased as the timescale decreased (Table 5).

While it is logical that the mean monthly streamflow threshold values decrease as drought severity increases, the study showed that the flow difference between the 'mild' and 'extreme' class values was greatest for the shortest timescale. This can be described with the help of distribution functions. Figure 7 shows the schematic view of the

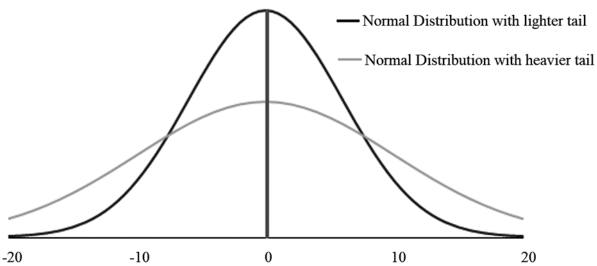

Figure 7 – Schematic view of normal distribution.

normal distribution with a lighter and heavier tail, respectively. In the former type, a statistical distribution occurs with extremely dispersed points along the x-axis resulting in a lighter tail. In the latter case, points are generally clustered along the x-axis in a statistical distribution and hence a heavier peak arises. The 3-month and 12-month scales were selected to describe the changes in flow threshold values with drought severity classes. The data for Aldermans Creek shows that the 3-month cumulative values were positively skewed with long tail on the positive side of the peak value. On the other hand, 12-month cumulative values followed almost the normal distribution with minimal skewness. This was the reason streamflow values are best fitted to the gamma distribution, which can control the skewness of the values. The gamma-fitted CDF of 3-month scale had lighter tails and a flatter peak than the normal distribution whereas CDF at 12-month scale showed heavier tails and a sharper peak. Such changes in the shape affected the transformation of the drought index to the mean monthly threshold values, as evident in Figures 8a and 8b.

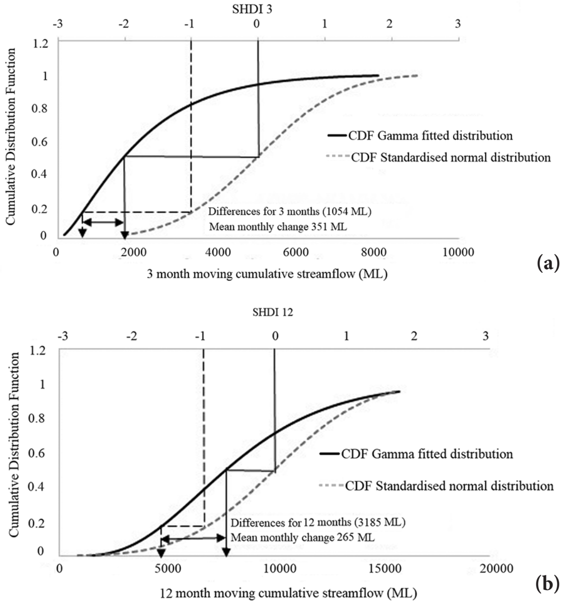

Figure 8 – Transformation of CDF standardised normal distribution to the Gamma-fitted CDF for Aldermans Creek station at (a) 3-month scale and (b) 12-month scale.

At the 3-month timescale, streamflow threshold values were 1659 ML and 605 ML for SHDI=0 (mild) and SHDI= -1 (moderate), respectively; a difference of 1054 ML (351 ML monthly average) (Table 6). For the 12-month scale, the flow difference between the mild and moderate drought threshold values was 265 ML. The 3-month timescale displayed a larger

Table 6 – Change in mean monthly streamflow threshold values, from mild drought to other drought severity classes

Station	Drought severity class	Mean monthly change from mild condition (ML)			
		12-month scale	9-month scale	6-month scale	3-month scale
Aldermans Creek	Moderate	265	285	326	351
	Severe	363	387	428	446
	Extreme	442	464	499	503
Walshes Creek	Moderate	516	574	650	687
	Severe	702	767	833	837
	Extreme	851	909	948	913

difference in flow thresholds between the mild and moderate droughts due to the flatter shape of the 3-month CDF value. Hence a change of drought severity class (from mild to moderate type) caused large changes in mean monthly threshold values for the 3-month scale compared to that of 12-month scale, where the CDF had a sharper peak (Fig. 8).

Conclusion

The study evaluated hydrological drought characteristics in the Yarra catchment using the Standardised Hydrological Drought Index (SHDI) for multiple timescales (3, 6, 9 and 12 months). The longer timescales identified a higher number of extreme drought events compared to the shorter timescale. On the contrary, a short scale detected more mild and moderate events, and more frequent droughts. As maximum drought intensity depends on both duration and magnitude, the longest duration may not result in peak intensity. The results showed that in most cases the peak intensities occurred in drought events with short durations rather than events with long durations. The SHDI was used to identify the beginning and termination of drought events. The commencement of drought events varied with the timescales. Finally, the SHDI threshold values were converted to mean monthly streamflow threshold values for different timescales. Such threshold values are easy to use in real-time conditions for defining and managing droughts. The results showed that mean monthly streamflow threshold values increased as the timescale increased. As the longest timescale (12 months) is more likely to include both dry and wet periods, its high value may misinform the early warning system. Therefore, the selection of an appropriate timescale is important for developing an effective drought mitigation strategy. The findings from this study are to be integrated with drought frequency analysis to forecast drought conditions for better management of water supply systems.

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