18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

A comparative drought assessment of Yarra River Catchment in Victoria, Australia

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Abstract: Management of water resources in river systems is becoming more challenging in recent times because of increased frequency and intensity of droughts. In this paper, adaptation of an Aggregated Drought Index (ADI) by considering significant components of the water cycle is presented. The ADI was evaluated for the Yarra River catchment in Victoria (Australia) as the case study. The Principal Component Analysis was used to comprehensively consider hydro-meteorological variables which describe the fluctuations in the hydrologic cycle. A comparative study was carried out on ADI with two other DIs which are widely used, namely Standardized Precipitation Index (SPI) (considering only the rainfall deficiency and used in most parts in the world) and Surface Water Supply Index (SWSI) (considering several hydro-meteorological variables; these variables do not necessarily describe the whole hydrologic cycle).

The results showed that ADI was able to detect historical droughts of 1967/68, 1972/73, 1982/83, and 1997/06 occurred in Victoria (Australia). The ADI showed smooth transitional characteristics where its time series fluctuates smoothly during the droughts, and from dry to wet spells and vice versa. The main advantage of ADI includes its assessment of droughts from the aggregate perspective of meteorological, hydrological, and agricultural water shortages.

It was also found that the degree of prediction level of both SPI and SWSI was not reflected. The SPI showed rapid fluctuations over the whole period of analysis and even during the drought periods. It was difficult to completely identify historical droughts periods with the SPI. The SWSI was relatively more stable than SPI in detecting historical droughts. Comparative study of ADI with SPI and SWSI showed that historical droughts were detected more clearly with ADI, followed by SWSI and then SPI. Furthermore, ADI was more robust than both SPI and SWSI.

Keywords: *Drought index, Water cycle, Principal Component Analysis (PCA), Aggregated Drought Index (ADI), Standardized Precipitation Index (SPI), Surface Water Supply Index (SWSI).*

1. INTRODUCTION

Drought is a natural phenomenon and poses significant problems around the world. Drought places huge demands on rural and urban water resources, and enormous burdens on agricultural and energy production. In general, drought is defined as the water scarceness due to insufficient precipitation, high evapotranspiration and over-exploitation of water resources or a combination of these parameters (Bhuiyan, 2004). Timely determination of the level of drought will assist the decision making process to reduce the impacts of droughts.

Drought Indices (DIs) have been commonly used to define drought conditions. In general, DI is a function of several hydro-meteorological variables (e.g., rainfall, temperature, streamflow, snowmelt, etc.). They can be integrated in a decision support system as a drought management tool to trigger drought relief programs. Moreover, it has been used to quantify deficits in water resources and as a drought monitoring tool. However, drought researchers are confronted with the ambiguity of drought definitions, which has never been resolved to the satisfaction of all drought researchers and professionals (Redmond, 2002). Keyantash and Dracup (2004) developed an Aggregated Drought Index (ADI) which attempted to maintain a close relationship between drought and the six basic components of the hydrologic cycle, namely precipitation, streamflow, water storage volume, soil moisture status, snow water content and potential evapotranspiration. They verified the appropriateness of the ADI by comparing with the Palmer Drought Severity Index (PDSI), which is an index based on the physical theme of water balance. Furthermore, they recommended to conduct a comparative study of ADI with Standardized Precipitation Index (SPI) (McKee et al., 1993) and Surface Water Supply Index (SWSI) (Shafer & Dezman, 1982) as future work.

The aim of this study is to adapt the ADI methodology of Keyantash and Dracup (2004) to assess the historical drought conditions in the Yarra River catchment in Victoria (Australia). The paper begins with a brief description of the study area followed by data sources and processing. Then the formulation of ADI, SPI and SWSI is presented. Drought assessment in the Yarra River catchment with ADI is then discussed, followed by a comparative study of ADI with SPI and SWSI. The conclusions drawn from the study are presented at the end of the paper.

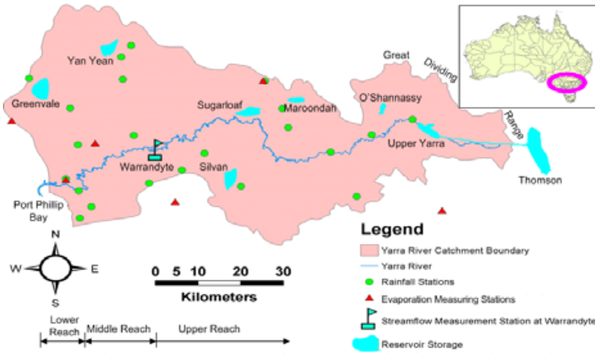

Figure 1. Yarra River catchment

2. STUDY AREA

The Yarra River catchment in Victoria (Australia) is considered for this study, since it has been researched extensively for various catchment management activities, and the river management is important in terms of downstream user requirements and environmental flows. Figure 1 shows the study area.

The Yarra River travels 245 kilometers from its source in the Great Dividing Range to the end of its estuary at Port Phillip Bay. Over one-third of Victoria's population lives in this catchment, which has an area of 4,044 square kilometers. The upper reaches of the catchment have been reserved for water supply purposes for more than 100 years. Most of the land along rivers and creeks in the middle and lower sections has been cleared for agriculture or urban development. There are seven major storage reservoirs (i.e., Upper Yarra, Sugarloaf, Silvan, Yan Yean, Greenvale, Maroondah, and O'Shannassy) and numerous farm dams within the catchment, and water extraction from the rivers and creeks for agriculture is prevalent. The catchment supports a range of uses valued by the Victorian community, including urban water supply, agricultural and horticultural industries. Therefore, the management of water resources has great importance within the Yarra River catchment.

3. DATA SOURCES AND PROCESSING

Data used in this study were collected from a number of organizations such as Melbourne Water Corporation (i.e, streamflow and storage volume data), Bureau of Meteorology (i.e, rainfall data), and SILO database (www.bom.gov.au/silo) (i.e, evapotranspiration data). Data measurement locations for rainfall, streamflow, and evaporation are shown in Figure 1. This figure also shows the major storage reservoirs in the catchment.

The data ranged from 1960 to 2006 (47 years) were used in this study which were available for all aforementioned variables. DI was developed at monthly time scale for various reasons including easy access of monthly data and lower sensitivity to observational errors. Therefore, data processing was carried out to obtain the catchment representative monthly values. Twenty two (22) rainfall and six (6) evaporation measuring stations were used to compute the monthly evaporation values for the catchment (Figure 1). Of the 6 evaporation measuring stations, 2 were outside of the catchment area. However, they were considered in the analysis as they were very close to the study area and no other evaporation gauges were present in the southern part of the catchment. Evaporation data had been used to calculate the evapotranspiration (www.bom.gov.au/silo) which are available from the SILO database; these evapotranspiration data were used in this study. The commonly used Thiessen polygon method (Thiessen, 1911) was used to calculate the monthly rainfall and evapotranspiration values for the catchment (Keyantash & Dracup, 2004). Daily streamflow data at Warrandyte were used in this study to compute average daily data for each month; they were considered as the catchment representative data, to account for the fluctuations in streamflow discharge (Figure 1). This station was used as it had long records of flow measurements and also it is a good representative station in the Yarra River main stream. As mentioned earlier, there are seven storage reservoirs within the study area, and also a storage reservoir (Thomson) outside of the catchment area, but to the east of the Yarra River catchment, transferring water to the Upper Yarra reservoir. Of these eight storage reservoirs, only Upper Yarra and Thomson reservoirs supply water to downstream users especially for maintaining environmental flows. Therefore, these two storage reservoirs were considered in this study to account for the variation in reservoir storage level. Soil moisture measurement data were not available, and therefore a two-layer water budget model of Palmer (1965) was adopted in this study to determine the soil moisture content in the catchment.

4. THEORETICAL ASPECTS OF ADI, SPI AND SWSI

4.1. Aggregated Drought Index

The Aggregated Drought Index (ADI) is a multivariate index developed by Keyantash and Dracup (2004). Its input variables represent the fluctuations in water volume within the hydrologic cycle. There are several variables that define the hydrologic cycle, including the most important eight variables: rainfall, streamflow, reservoir storage volume, soil moisture content, potential evapotranspiration, snow water content, groundwater flow, and temperature. Of these eight variables, six influential variables namely rainfall, streamflow, reservoir storage volume, soil moisture content, snow pack and potential evapotranspiration were used for ADI formulation by Keyantash and Dracup (2004). However, snow water content was not considered in this study as it is not relevant within the study area. Reasons for excluding other variables are explained in detail in Keyantash and Dracup (2004).

The Principal Component Analysis (PCA) was used to aggregate the aforementioned variables. Computation of the Principal Components (PCs) requires constructing a square ($p \times p$, where p is the number of variables) symmetric correlation matrix to describe the correlations between the original data. Twelve correlation matrices were used, one for each month. These correlation matrices then underwent PCA. An advantage of the correlation-based PCA approach used in the development of ADI is that the ADI is not impacted by the measurement units of the input data, as all input variables are standardized before they are used in the ADI computation.

The PCs are a re-expression of the original p-variable data set in terms of uncorrelated components Z_j ($1 < j \leq p$). Eigenvectors derived through PCA are unit vectors (i.e., magnitude of 1) that establish the relationship between the PCs and the original data:

$$Z = XE \tag{1}$$

where, Z is the $n \times p$ matrix of PCs (i.e. uncorrelated components); in which n is the number of observations, X is the $n \times p$ matrix of standardized observational data, and E is the $p \times p$ matrix of eigenvectors.

As was done by Keyantash and Dracup (2004), the ADI was considered as the first PC (PC1), normalized by its standard deviation:

$$\mathrm{ADI}_{i,k} = \mathrm{Z}_{i,1,k} / \sigma_k \tag{2}$$

where, $\mathrm{ADI}_{i,k}$ is the ADI value for month k in year i, $\mathrm{Z}_{i,1,k}$ is the first PC during year i for month k, and σ is the sample standard deviation of $\mathrm{Z}_{i,1,k}$ over all years for month k.

The ADI utilizes only the PC1 because it explains the largest fraction of the variance described by the full p-member, standardized data set. Since PCs are orthogonal vectors, it is not mathematically proper to combine them into a single expression (Keyantash & Dracup, 2004). Considering all 12 months, PC1 described an average of 57% of the data set variance in this study. Once the ADI values were computed for each year and each month, they were reordered into a single time series in chronological order.

The ADI thresholds values were calculated probabilistically using the empirical cumulative distribution function. These thresholds are used to classify the drought conditions. Selected low ADI percentiles were used as thresholds for drought severity as in SPI (McKee *et al.*, 1993; Keyantash & Dracup, 2002). The SPI dryness thresholds are the Gaussian variates of -2, -1.5, and -1 standard deviations, which corresponds to *2.3th*, *6.7th*, and *16th* percentiles. The ADI thresholds corresponding to these percentiles were -1.77, -1.33, and -0.95 respectively for the case study site. A similar approach was used by Keyantash and Dracup (2004). The ADI threshold ranges were then derived for the case study site as follows: -1.77 and less: extreme drought, -1.76 to -1.33: severe drought, -1.32 to -0.95: moderate drought and -0.95 to 0.92 (*84th* percentile): near-normal.

4.2. Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993) for monitoring drought conditions based on rainfall. To calculate the SPI values, first the long-term rainfall record was fitted to a probability distribution. Tsakiris et al. (2002) and Sonmez et al. (2005) used the gamma distribution as it fitted well with the rainfall time series. The gamma distribution is defined by its probability density function:

$$f(x;\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x > 0 \tag{3}$$

where, α and β are the shape and scale parameters respectively, x is the non-zero rainfall amount and $\Gamma(\alpha)$ is the gamma function. The maximum likelihood method was used to optimally estimate α and β parameters:

$$\alpha = \frac{1}{4\mathrm{A}}\left(1+\sqrt{1+\frac{4\mathrm{A}}{3}}\right), \text{ and } \beta = \frac{\bar{\mathrm{x}}}{\alpha} \tag{4}$$

where, $\mathrm{A} = \ln\left(\bar{\mathrm{x}}\right) - \frac{\sum \ln(\mathrm{x})}{\mathrm{n}}$, $\bar{\mathrm{x}}$ is the rainfall average, and n is the number of observations.

The cumulative probability for non-zero rainfalls, $F(x;\alpha,\beta)$ is then derived. The gamma function is undefined for x = 0 and data may contain zero rainfalls. Therefore, the cumulative probability $H(x)$ was calculated by the following equation:

$$H(x) = q + (1-q)F(x;\alpha,\beta) \tag{5}$$

where, q is the probability of a zero rainfall. If m is the number of zeros present in a rainfall time series, then q can be estimated by m/n. The cumulative probability is then transformed to the standard normal distribution so that the SPI mean and variance for the location and long-term record is zero and one respectively. SPI can be calculated for multiple monthly time scales (e.g., 3, 6, 12, 24, and 48 month time scales). However, in this study, SPI was calculated using monthly data to be consistent with ADI and SWSI.

The SPI thresholds ranges are as follows (McKee et al., 1993; Tsakiris et al., 2002; Sonmez et al., 2005): 2.0+, extremely wet; 1.5 to 1.99, very wet; 1.0 to 1.49, moderately wet; -.99 to 0.99, near normal; -1.0 to -1.49, moderately dry; -1.5 to -1.99, severe dry; and -2.0 and less, extremely dry.

4.3. Surface Water Supply Index

The Surface Water Supply Index (SWSI) was developed by Shafer and Dezman (1982) as an indicator of surface water conditions. It considered rainfall, streamflow/snow water content (streamflow in summer and snow water content in winter), and reservoir storage volume in formulating SWSI. The snow water content was not considered in the current study as it is not relevant within the study region. The mathematical formulation of the SWSI is as follows:

$$\mathrm{SWSI} = \frac{\left[\left(\mathrm{a}\times\mathrm{PN}_{\mathrm{rn}}\right)+\left(\mathrm{b}\times\mathrm{PN}_{\mathrm{sf/sn}}\right)+\left(\mathrm{c}\times\mathrm{PN}_{\mathrm{rs}}\right)-50\right]}{12} \tag{6}$$

where, PN is the probability of non-exceedance (%); *rn, sf, sn,* and *rs* is refer to rainfall, streamflow, snow water content and reservoir storage volume components respectively; *a, b, c* are weights for each component and must meet the condition $a+b+c = 1$. Subtracting 50 and dividing by 12 are a centering and compressing procedure designed to make the index value have a similar magnitude to the PDSI (Palmer, 1965).

The SWSI thresholds values are as follows (Shafer & Dezman, 1982): 4.0+, abundant supply; 2.0+, Near normal; -1.0, incipient drought; -2.0, moderate drought; -3.0, severe drought; and -4.0, extremely drought.

5. DROUGHT ASSESSMENT WITH ADI

The time series of the developed ADI for the Yarra River catchment is shown in Figure 2. Different levels of drought severity are presented with the horizontal dotted lines based on ADI thresholds. The shaded vertical areas represent various historical droughts occurred in Victoria in 1967/68, 1972/73, 1982/83, 1997/98, 2002/03, and 2006 onwards, which were well documented (Keating, 1992; Tan & Rhodes, 2008). However, the shaded area was determined based on negative ADI values.

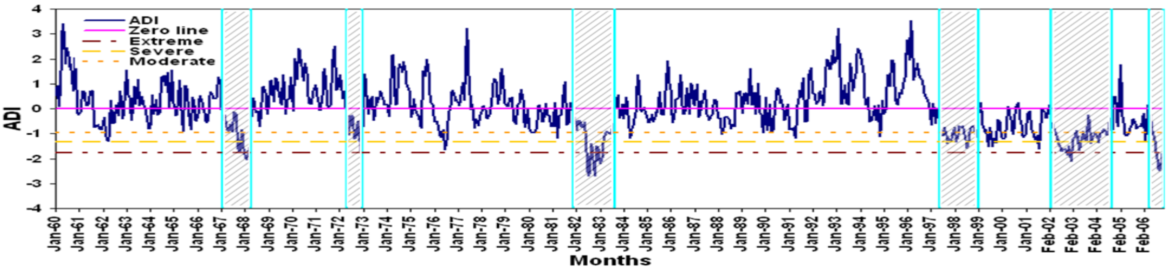

Figure 2. Time series of ADI for Yarra River catchment

Drought during 1967/68 was detected by ADI starting from February 1967 to April 1968 that exactly matches with the historical record of 15 months of dry spell (Keating, 1992). During this period, monthly rainfall had gone below 5% of normal (in February 1968) and the storage volume below 25% capacity (in April 1968). The drought condition reached the extreme condition in January-March 1968, according to the ADI results. Historical records also showed that the drought in 1967/68 was in extreme condition.

Drought in 1972/73 was relatively of shorter duration, and started in May 1972 and ended in January 1973 (9 months) according to ADI results. Keating (1992) also recorded a similar period for 1972/73 drought. During this period, monthly rainfall had gone below 6% of normal (in December 1972) and the storage volume below 55% capacity (in January 1973). Also the drought in 1972/73 was in severe condition, according to the ADI results.

Of all droughts recorded until 1990, the worst drought occurred in Victoria was in 1982/83. This drought affected most areas in eastern Australia, and sparked the Ash Wednesday bushfires, which burnt 13,000 hectares of Melbourne's water supply catchments, and caused massive dust storms (Keating, 1992). During this period monthly rainfall had gone below 8% of normal (in February 1983) and the storage volume below 20% capacity (in May 1983). The dry condition started in December 1981 and lasted until September 1983 (22 months), according to the ADI results. However, Keating (1992) recorded the duration of 1982/83 drought as approximately 11 months, which is less than the period detected with ADI. Drought was in extreme condition between August 1982 and February 1983, according to the ADI results.

Since 1997, inflows into Melbourne Water's four major harvesting reservoirs (Thomson, Upper Yarra, O'Shannassy and Maroondah) have been below the long-term average and during the ten-year (1997-2006) extended dry period three major drought years (1997/98, 2002/03 and 2006/07) have occurred (Tan & Rhodes, 2008). The ADI detected well this 10-year period dryness. During this period, the monthly average rainfall dropped to approximately 70 mm, whereas the average monthly rainfall prior to this period (1960-1996) was around 86 mm based on 22 rainfall measuring stations. In the end of the year 2004, it was relatively wet; therefore the ADI values are positive in the years of 2004/05. The overall dry condition was moderate to severe. However, it reached to the extreme conditions in the drought years in 2003/04 and 2006 onwards, according to the ADI results. Although the ADI calculations were done only until December 2006, the drought has continued until now.

6. COMPARATIVE STUDY

A comparative study was carried out comparing ADI with SPI and SWSI to investigate the appropriateness of the ADI for detecting and classifying historical droughts. The chronological comparisons of ADI with SPI and SWSI are shown in Figures 3 and 4 respectively.

As can be seen from Figure 3, SPI shows rapid fluctuations over the whole period, and even during droughts. With SPI, it is difficult to completely identify historical droughts occurred in 1967/68, 1972/73, 1982/83, and 1997/06, whereas ADI identified these droughts satisfactorily. Although SPI gave some indication of drought conditions during dry periods, it has given misleading information that the drought has ended showing higher SPI values (or, wet spells) during the drought, because of high rainfall values over a month or two. Compared to SPI, the ADI fluctuates smoothly during the droughts, and from dry to wet spells, and vice versa.

Compared to SPI, the SWSI is relatively more stable and was able to detect aforementioned historical droughts better (Figure 4). However, it showed some delay in responding to changes between dry (negative) and wet (positive) spells. Due to this characteristic, the SWSI was unable to represent shorter duration of wet spells occurred in 2000/01 in between two droughts periods (i.e., 1997/98 and 2003/04). The ADI were more strong in detecting historical drought periods compared to SWSI. Also, it was able to represent more accurately the termination of droughts.

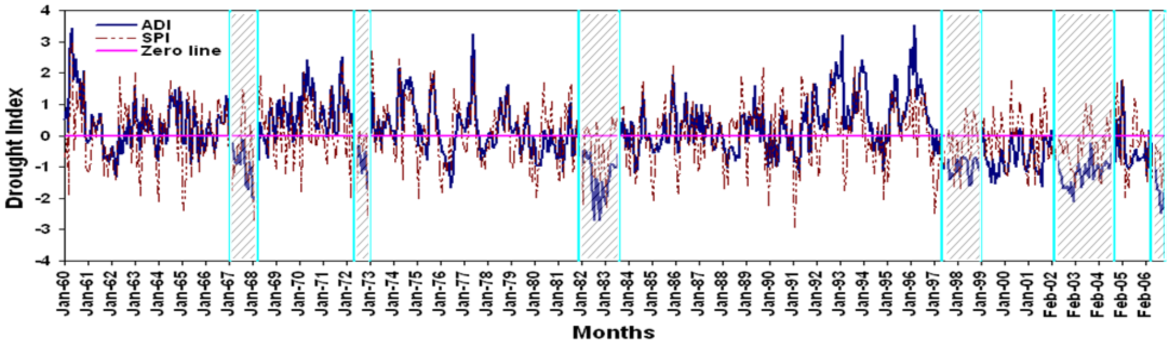

Figure 3. ADI and SPI time series for Yarra River catchment

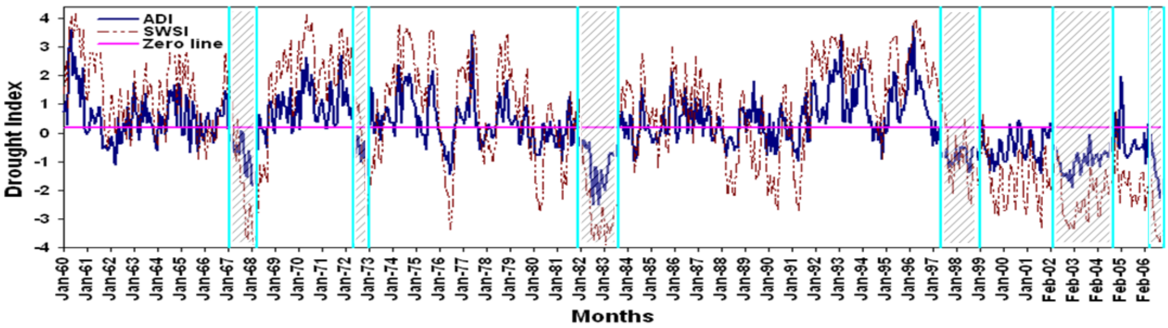

Figure 4. ADI and SWSI time series for Yarra River catchment

Determining the start and finish of droughts is a difficult task (Keyantash & Dracup, 2004). Therefore, the transitions between wet and dry spells were determined by selecting the months that show anomalies of the opposite signs. The SPI gives an early indication of drought initiation as it depends only on rainfall, whereas the drought initiations delayed in the SWSI. In detecting droughts initiation and termination periods, ADI was better than SPI and SWSI as the detected drought periods with the ADI well fitted with the historical drought records. In detecting the most intense drought month in a drought, all three indices showed almost the same month (for example, the 1982/83 drought in Figures 3 and 4). The SPI showed smaller drought durations than the ADI and SWSI because of frequent fluctuations during long drought periods. Similar drought durations were observed with ADI and SWSI in detecting the historical droughts.

As can be seen from Figures 2-4, the historical droughts were detected more clearly with ADI, followed by SWSI and then SPI. A correlation study carried out on ADI, SPI and SWSI. The strong correlation was also found between ADI and SWSI followed by ADI and SPI with the correlation coefficient of 0.84 and 0.61 respectively. The ADI has smoother transitional characteristics during droughts, and from dry to wet spells and vice versa. It is more robust than the SPI and SWSI. The SPI suffers from certain limitations, mainly because it is a rainfall based DI and it does not represent wider dry circumstances (Smakhtin & Hughes, 2004). This is because drought depends on numerous factors, such as water supply and demand, hydrological and political boundaries, and antecedent conditions. The application of SWSI is also limited as it suffers from the subjectivity of weighting factors (a, b and c in Equation (6)). Consequently, both SPI and SWSI should not be considered as the only standard methods for detecting drought conditions as stated by Keyantash and Dracup (2004). In fact, this study shows that ADI is a better index than SPI and SWSI.

7. CONCLUSIONS

Drought assessment has been a challenge amongst drought researchers and decision makers. Many argue that drought is just a deficiency in rainfall and could be defined with the rainfall as the single variable. Some others believe that rainfall based drought indices are not strong enough to define the wider drought conditions and have proposed that the drought should be defined with a number of hydro-meteorological variables which play significant roles in drought incidence. In this study, an Aggregate Drought Index (ADI) was adapted to investigate its appropriateness in describing historical droughts conditions based on water deficiencies within the hydrologic cycle, using the Yarra River catchment in Victoria (Australia). The ADI was constructed using five significant hydro-meteorological variables: precipitation, evapotranspiration, streamflow, surface reservoir storage, and soil moisture content. Principal component analysis was used to extract dominant hydrologic signals from correlations among the input variables.

Twelve ADI time series (one for each month) derived for the study catchment were chronologically ordered to produce a single time series to identify past drought. This ADI time series successfully detected past major droughts that occurred in Victoria in 1967/68, 1972/73, 1982/83, and 1997/2006. The ADI was also compared against two widely used drought indices, namely Standardized Precipitation Index – SPI (considered only rainfall deficit and used in most parts in the world) and Surface Water Supply Index – SWSI (considered multiple variables, but these variables do not completely describe the whole hydrologic cycle). The results showed that ADI was able to identify droughts more clearly than SPI and SWSI. The main advantage of ADI is that it uniquely describes the broad perspective of droughts beyond the traditional meteorological, hydrological, and agricultural subcategories.

ACKNOWLEDGMENTS

The authors wish to thank Melbourne Water Corporation and Bureau of Meteorology in Australia, for providing required data and also their valuable support and contributions.

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