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Drought Assessment in Cai River Basin, Vietnam: a Comparison with Regard to SPI, SPEI, SSI, and SIDI

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Drought is one of the most complex natural hazards that threaten human life and property. Until recently, however, the drought phenomenon has not been fully understood. Defining droughts based on a single variable index such as precipitation, soil moisture, or evapotranspiration may not be sufficient for reliable risk assessment and decision making. In this article, a multivariate, multi–index drought–modeling approach is proposed by using the concept of copulas. The proposed model, known as Standardized Integrated Drought Index (SIDI), is a probabilistic combination of the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and the Standardized Soil Moisture Index (SSI) for drought characterization that is established by the principal components analysis method (PCA). This model was applied for analyzing in the Cai River basin, Vietnam, and is compared with SPI, SPEI, and SSI. The results show that the drought severity of the study area is relatively high during many years, with occurrences during many months of the affected years. The results of drought changes show numerous differences among indices, particularly in SPI/SPEI and SSI. The results based on the combination of SPI, SPEI, and SSI indicates that SIDI effectively shows drought onset and termination. The onset is dominated by SPI/SPEI, and drought persistence is more similar to SSI behavior. Overall, the proposed SIDI is a reasonable model for combining multiple indices probabilistically.

Key words: Drought, Standardized Integrated Drought Index, VIC model, Principal components analysis, Cai River basin

INTRODUCTION

Drought occurs throughout the world, affecting human lives more than any other major natural hazard; it is widely considered to be the most complex and least understood of all natural hazards (Dai *et al*., 2004; He *et al*., 2011). Drought hazard assessments are difficult to investigate because there is no single universally accepted method for quantifying and qualifying drought effects (Kim and Byun, 2009; Moradi *et al*., 2011). Hence, monitoring and understanding the effects of drought on water resource systems are essential to hazard preparedness and sustainable development.

Several indices have been developed for drought monitoring based on different variables, such as precipitation, soil moisture, and runoff (Mishra and Singh, 2010). For example, the Palmer Drought Severity Index (PDSI) (Palmer, 1965), derived from precipitation and temperature, has been widely used for drought characterization (Dai, 2011; Dai *et al*., 2004). McKee *et al*. (1993) proposed the Standardized Precipitation Index (SPI) as a drought indicator for meteorological drought monitoring and analysis; the index is recommended by the World Meteorological Organization (WMO) as a standard drought–monitoring index (Hayes *et al*., 2010). For researching and monitoring drought processes under the impact of global warming, Vicente–Serrano *et al*. (2010) introduced the Standardized Precipitation Evapotranspiration Index (SPEI) based on two meteorological factors, precipitation and evaporation. To reflect humidity and dryness, Hao and AghaKouchak (2013) proposed the Standardized Soil Moisture Index (SSI) as an index for drought monitoring, which is calculated basis on soil moisture events.

PDSI is one of the most commonly used indices for analyzing drought hazards and its impacts (Wu *et al*., 2010), for determining the frequency of various drought severities (Hua *et al*., 2011), and for reconstructing historical wet and dry episodes (Sousa *et al*., 2011). PDSI can be used to express the severity of a wet or dry spell because (a greater absolute value of the index relates to a more severe the dry or wet period); thus, it can help in making direct comparisons of moisture conditions among various regions (Alley, 1984; Szep *et al*., 2005). However, PDSI is traditionally calculated by using a two–layer bucket–type model to obtain data on water balance components. This model is purely empirical and does not consider the effects of factors such as spatial heterogeneity of soil, vegetation cover, and topography on watershed hydrological processes (Dai, 2011; Wells *et al*., 2004).

Drought analyses based on a single variable or indicator may not be sufficient because drought phenomena are related to multiple variables such as precipitation, runoff, and soil moisture. A meteorological drought or deficit in precipitation may not lead to an agricultural drought or deficit in soil moisture, in tropical regions, for example, where the average precipitation is relatively

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high. A complete analysis of drought events necessitates joint analyses of rainfall, runoff, and soil moisture conditions (Dracup *et al*., 1980). To characterize overall drought conditions, several joint drought indices have been proposed. Keyantash and Dracup (2004) proposed an aggregate joint index that considers all physical forms of drought, including meteorological, hydrological, and agricultural, through the selection of drought variables that are related to each drought type. Kao and Govindaraju (2010) developed a copula–based joint index with Kendall distribution to characterize drought from precipitation and streamflow. Hao and AghaKouchak (2013) proposed the Multivariate Standardized Drought Index (MSDI), which is a parametric multi–index model and is calculated on the basis precipitation and soil moisture.

Defining drought based on soil moisture quires the availability of such data. Determining soil moisture events can be implemented by a field investigation method, which is generally quite difficult and costly. Nevertheless, the application of hydrographical models in simulating the hydrographical cycle of the basin can help in assessing soil moisture during various periods. In this study, the authors used the Variable Infiltration Capacity (VIC) model for simulating soil moisture events. The VIC model is a macro–scale land surface hydrology model that has been widely used to simulate watershed hydrological processes such as surface runoff, evapotranspiration, and the distribution of soil moisture in the uppermost two or three layers (Liang *et al*., 1994; Wu *et al*., 2010; Xie *et al*., 2003; Xie *et al*., 2007). Additionally, the model was designed to consider the heterogeneity of land surface properties and can provide a more realistic treatment of hydrological processes within individual grid cells than that of alternative methods (Wu *et al*., 2011).

Because the research area is located in tropical regions, with heavy rainfall and high topographical slopes, defining droughts based on a single variable index may not be sufficient for reliable risk assessment and decision making. Therefore, in this study, a multivariate, multi–index drought–modeling approach is proposed by using the concept of copulas known as the Standardized Integrated Drought Index (SIDI). SIDI was established on the basis of input variables such as precipitation, soil moisture, and evapotranspiration under SPI, SPEI, and SSI indices. The level of influence of the three types of input data on SIDI can be defined by using the principal components analysis (PCA) method. PCA, first introduced by Pearson (1901) then developed by Hotelling (1933), is a statistical algorithm that uses orthogonal transformation to transform a data set from a multidimensional space to a less multidimensional space in order to optimize the presentation of the variation of the input data (Georgemdallas, 2013; PCA, 2014).

MATERIALS AND METHODS

Study area

The studied basin lies between 12°02′49″–12°36′13″N and 108°40′03″–109°11′38″E in Khanhhoa Province, Vietnam, with a total area of 1,889 km^2 (Fig. 1). This basin is located in a tropical monsoon zone that exhibits quite unique deformational features and an oceanic climate. The average rainfall during 1982–2012 was 1,616 mm and there are two distinct seasons: rainy and dry. The rainy season usually lasts from May to December, and rainfall is largely concentrated in September, October, and November to comprise 55% of the average annual rainfall. During many dry season months, there is no rain. With a high temperature foundation, annual temperature during many years is 26.7°C, and the difference in temperature between months is relatively small. The potential evaporation in the studied area is high, averaging approximately 1,200–1,600 mm/year.

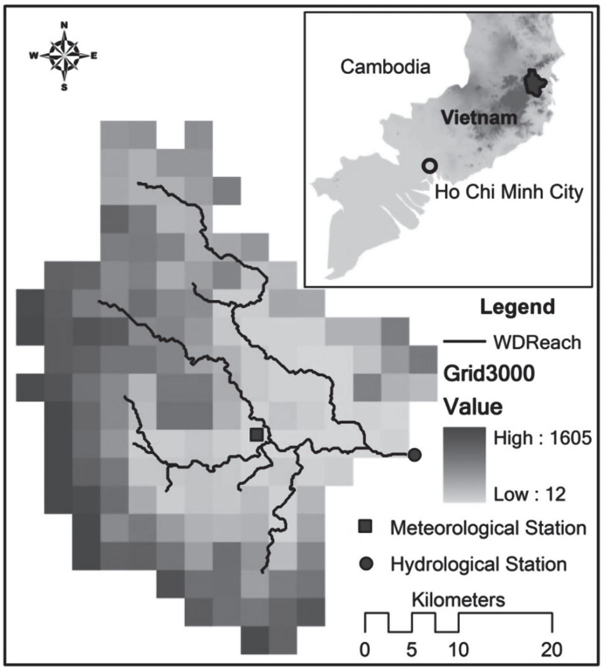

Fig. 1. Cai River basin, Vietnam.

Datasets

Meteorological and streamflow datasets

To conduct this research, the authors used meteorological data of Khanhvinh Meteorological Station in Khanhhoa Province, Vietnam, recorded from January 1982 to December 2012. The streamflow data was recorded by Dongtrang Hydrological Station in Khanhhoa Province, Vietnam, from January 1983 to December 2012.

VIC model datasets

The meteorological forcing fields used in the VIC model were retrieved from the National Hydrometeorology Institute of Vietnam. Daily precipitation, maximum and minimum daily temperatures, and wind speed data were obtained from Khanhvinh meteorological stations. A digital elevation model (DEM) dataset was obtained from the Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model with a spatial resolution of 90 m (CGIARCSI, 2008) to delineate the boundaries of the basin. The DEM was divided into 163 grid cells in ArcGIS. This model also identified channel networks and the principal directions of flow for the regional streams, which drain a total catchment area of 1,889 km^2. Soil parameters were assigned on the basis of information obtained from the Food and Agriculture Organization (FAO) soil map for 5–foot depth (Reynolds *et al.*, 2000). A global 1–km land cover classification data-set was obtained from the University of Maryland (Hansen *et al.*, 2000).

Methodology

Applying the VIC model to simulate soil moisture events

The VIC model is used to simulate the physical exchange processes of water and energy in the soil, vegetation, and atmosphere in a surface vegetation atmospheric transfer scheme. It was developed by Liang *et al.* (1994) and was later improved by Lohmann *et al.* (1998) and De–Keersmaecker *et al.* (2014). The notable characteristics of the VIC model include the following features: (1) both water balance and energy balance parameterization; (2) two types of runoff yielding mechanisms based on saturation and infiltration excess; (3) consideration of sub–grid scale soil heterogeneity; and (4) processes of snow accumulation and melt, as well as soil freezing and thawing.

The VIC model divides study catchments into grid cells and the soil column of each grid into three layers. The upper two layers, designed to represent the dynamic responses of soil to rainfall events, were usually used by one layer. The lower soil layer is used to characterize the behavior of seasonal soil moisture. Three types of evaporation are considered including evaporation from a wet canopy, evapotranspiration from a dry canopy, and evaporation from bare soil. Stoma resistance is used to reflect the effects of radiation, soil moisture, vapor pressure deficiency, air temperature, and other factors when calculating transpiration from the canopy.

The total runoff estimations consist of surface and base flows. Surface flow, including infiltration excess and saturation excess flows, is generated only in the two top layers. To consider the heterogeneity of soil properties, soil storage capacity distribution and infiltration capacity curves were employed. The double curves are individually described as power functions with parameter B as an exponent. Base flow occurs only in the lowest layer and is described by using the ARNO method (Habets *et al.*, 1999). A dimensional Richards's equation is used to describe vertical soil moisture movement.

The VIC model includes seven hydrological parameters that need to be calibrated with the recorded daily stream flow. The Nash and Sutcliffe efficiency criterion (NSE) and the relative error of volumetric fit (RE) were employed as objective functions for calibrating the model (Nash and Sutcliffe, 1970). A good simulation result has an NSE close to 1 and an RE close to 0.

In this paper, the author used the VIC_code_4.1.1 version to simulate the concentration of streamflow of each grid cell and the route_code_1.0 versions provided by University of Washington (2009) to simulate the concentration of streamflow at the basin outlet. The monthly soil moisture events were determined by using the soil moisture events at each grid cell per day from the results of VIC model simulation.

Calculations of SPI, SPEI and SSI

SPI was introduced by McKee *et al.* (1993). Based on the high conformance of gamma distribution with rain data indices over time in numerous locations, McKee *et al.* (1993) developed SPI in the form of a stochastic variable with normal distribution (from the original accumulative probability) as

$$Z = SPI = S\left(t - \frac{c_0 + c_1 + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), \quad (1)$$

where $t = \sqrt{\ln 1/F^2}$, S = 1 when F > 0.5, S = −1 when F $\leq$ 0.5, F is an accumulative probability function, c_0 = 2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, and d_3 = 0.001308.

SPI requires a long–term precipitation record to fit the gamma probability density function to the observed data. By using the precipitation data from 1983 to 2012, we calculated SPI by using the SPI program on the Website (Beguería and Vicente–Serrano, 2009).

To study and follow up the drought process under the effects of global warming, SPEI was introduced by Vicente–Serrano *et al.* (2010) on the basis of index (D), which is the difference between rainfall (P) and potential evaporation (PET). Index (D) indicates the redundancy or shortage of humidity, from which we can determine wet or dry conditions. Each period of increase or decrease in water discharge can be defined as

$$D_i = P_i - PET_i. \quad (2)$$

PET uses the Thornthwaite method for calculation. In the incremental or decremental series of water discharge, negative values may occur. Therefore, SPEI uses three parameters of log–logistic probability distribution function to describe the probability of an event. The form of accumulative probability function is expressed as

$$F(x) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1}, \quad (3)$$

where parameters α, β, and γ may use the linear moments method to determine conformance. By using the precipitation and temperature data from 1983 to 2012, SPEI was calculated by using the SPEI program on the Website (Beguería and Vicente–Serrano, 2009).

The SSI proposed by Hao and AghaKouchak (2013) was calculated on the basis of soil moisture events of the VIC model from 1983 to 2012. The calculation method of SSI is the same as that of SPI.

SPEI/SSI was calculated in the same manner as SPI. The calculation of SPI, SPEI, and SSI have different time scales, such as 1–, 3–, 6–, and 12–month periods. SPI, SPEI, and SSI were classified according to WMO climatic conditions of drought or wet, as shown in Table 1 (WMO, 2012a).

Table 1. Standard Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Soil Moisture Index (SSI) classifications

SPEI/SPI	Classification	SPEI/SPI	Classification
2.00 or more	Extremely wet	–0.50 to –0.99	Mild drought
1.50 to 1.99	Very wet	–1.00 to –1.49	Moderate drought
1.00 to 1.49	Moderately wet	–1.5 to –1.99	Severe drought
0.50 to 0.99	Mildly wet	–2,0 or less	Extreme drought
–0.49 to 0.49	Normal		

Applying PCA to define SIDI

In this research, a multivariate, multi–index drought–modeling approach is proposed by using the SIDI concept of copulas, which was established on the basis of input variables such as precipitation, soil moisture, and evapotranspiration under SPI, SPEI, and SSI. The following steps were used to calculate SIDI

(1) Calculate Integrated Drought Index (IDI) on the basis of three types of data such as SPI, SPEI, and SSI. SPI events are designated as x_1, SPEI events are x_2, and SSI events are x_3. Variation of IDI will be subject to the variation of the initial space of data x_1, x_2, and x_3. Applying PCA the rate of contribution of the components to IDI events is determined from that used to determine the linear equation for IDI. As previously mentioned, PCA is a statistical algorithm that uses orthogonal transformation to transform a dataset from a multidimensional space to a less multidimensional space in order to optimize the presentation of the variation of the input data (Georgemdallas, 2013; PCA, 2014).

IDI is defined by

$$IDI = ay_1 + by_2, \quad (4)$$

$$y_1 = cx_1 + dx_2 + ex_3, \quad (5)$$

$$y_2 = fx_1 + gx_2 + hx_3, \quad (6)$$

where y_1, y_2 are the values of the first and second main components, respectively; a and b are the contribution rates of the first and second main components, respectively; and c, d, e and f, g, h are the contribution rates of x_1, x_2, x_3 in the first and second main components, respectively.

(2) Standardize IDI to define SIDI according to the formula $SIDI = (IDI - \overline{IDI})/\sigma_{IDI}$, in which is $\overline{IDI}$ the mean value of IDI, and σ_{IDI} is the standard deviation. SIDI with SPI, SPEI, and SSI is computed for the same durations (i.e., 1–, 3–, 6– and 12–month periods) and is used for cross–comparison. SIDI is classified by climatic condition (drought or wet) with the same SPI (Table 1).

RESULTS AND DISCUSSION

Streamflow simulation, regional parameterization, and monthly soil moisture events

Streamflow at the outlet of the basin between 1983 and 2000 was simulated to adjust and determine the parameters of the model. The result of streamflow simulation at the basin outlet is presented in Fig. 2, and the parameters of the model are presented in Table 2.

The NSE was 76%, and the RE was –6.4%, according to WMO standards (WMO, 2012b); therefore, the model was evaluated as good.

The parameters of the found model were used to simulate the streamflow at the basin outlet between 2001 and 2012 for model calibration, the results of which are presented in Fig. 3. The NSE was 67%, and RE was 3.5%; therefore, the model was evaluated as good.

The set of parameters was simulated by the model; the calculation results of the streamflow were completely conformable to the actual observed streamflow, according to the NSE assessment.

Results of SPI, SPEI, SSI, and SIDI

The results of the value parameters for determining IDI events are shown in Table 3.

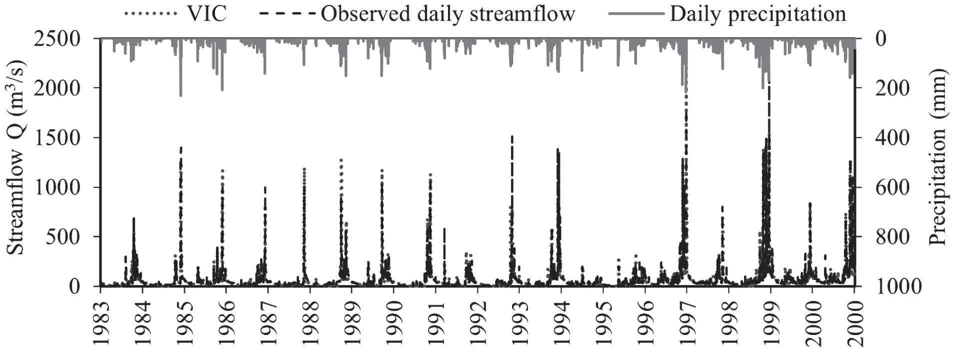

Fig. 2. Streamflow simulated and observed at Dongtrang Station (1983–2000).

The results of drought events in the research area based on SPI, SPEI, SSI, and SIDI are illustrated in Figs. 4, 5, 6, and 7 and in Table 4.

Assessing drought events in the Cai River basin, Vietnam

These results indicate that the possibility of drought in the research area is relatively high. Moreover, the

Table 2. Variable Infiltration Capacity (VIC) user–calibrated hydrological parameters

Parameter	Unit	Parameter values	Physical interpretation
B		0.25	Exponent of variable infiltration curve
Dm	mm/d	6.0	Maximum daily baseflow (mm)
Ds		1.0	Fraction of Dm in which non–linear base flow occurs
Ws		1.0	Fraction of maximum soil moisture in the lower soil layer for which nonlinear baseflow occurs
d1	m	0.1	Thickness of first soil layer
d2	m	0.5	Thickness of second soil layer
d3	m	1.0	Thickness of third soil layer

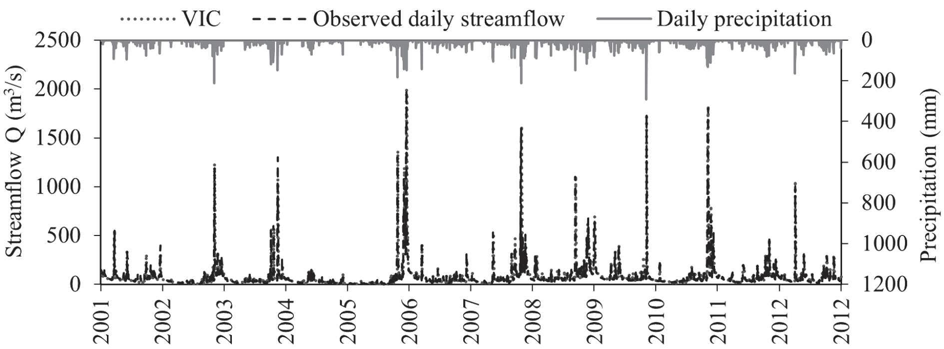

Fig. 3. Streamflow simulated and observed at Dongtrang Station (2001–2012).

Table 3. Values of parameters used in determining the Integrated Drought Index

Parameters	a	b	c	d	e	f	g	h
IDI1	0.8205	0.1165	0.6783	0.4438	0.5856	–0.7321	0.3397	0.5905
IDI3	0.8698	0.1022	0.7552	0.2711	0.5969	–0.6405	0.4990	0.5838
IDI6	0.8877	0.0974	0.7505	0.2817	0.5978	–0.7056	0.2806	0.6507
IDI12	0.9032	0.0881	0.7459	0.2977	0.5959	–0.6572	0.4745	0.5856

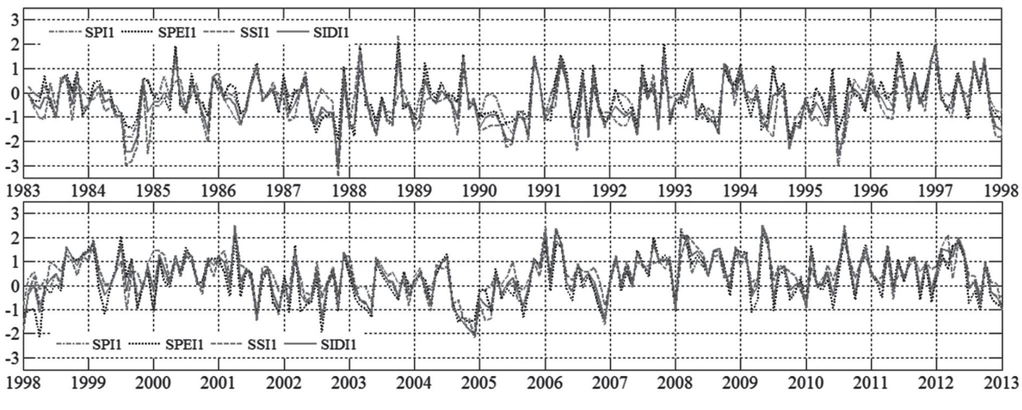

Fig. 4. The four drought indices events during one–month periods from 1983 to 2012. Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI.

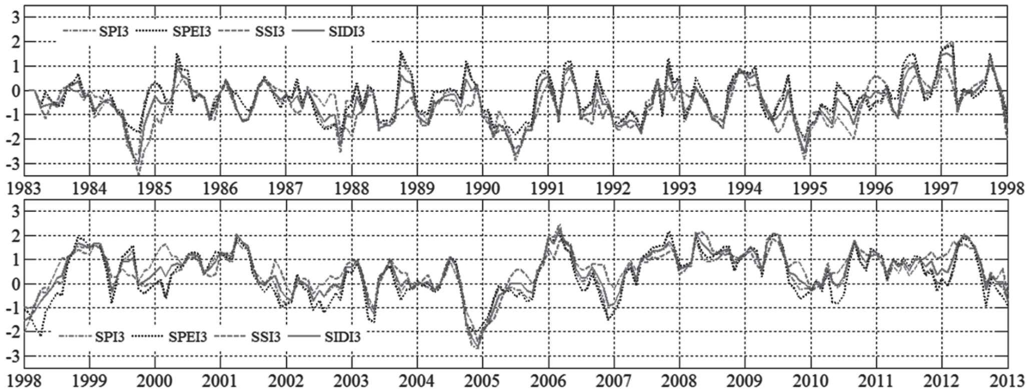

Fig. 5. The four drought indices events during three–month periods from 1983 to 2012. Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI.

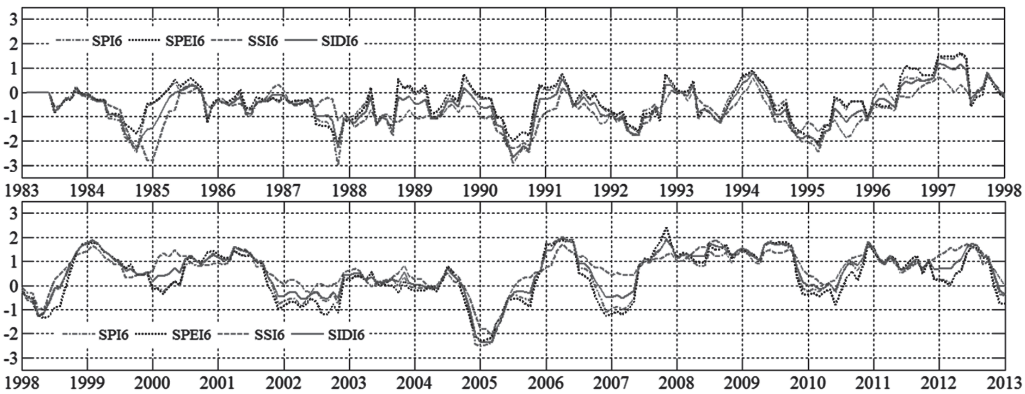

Fig. 6. The four drought indices events during six–month periods from 1983 to 2012. Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI.

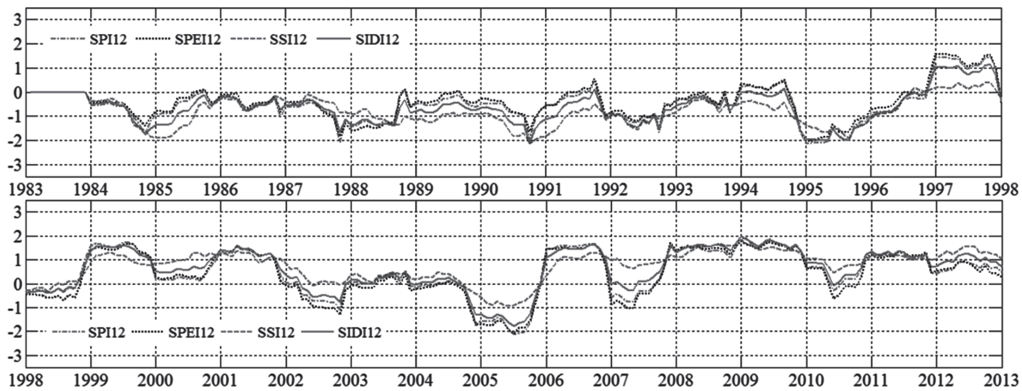

Fig. 7. The four drought indices events during 12-month periods from 1983 to 2012. Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI.

drought events exhibited major differences in indices and over time. Drought severity from 1984 to 1995 was more serious than that from 1996 to 2012. Severe drought occurred over the course of many years including 1984, 1990, 1995, and 2005 and through numerous months of the year. These data are in agreement with historical drought data in the research area.

Figs. 4, 5, 6, and 7 shows that drought events based on SPI and SPEI have similar differences that are evident only in several periods, or time steps. The frequency of occurrence and the occurrence number of severe drought events following SPEI were higher than those following SPI (Table 4).

Drought events following SSI differed significantly

Table 4. Frequency (%) of drought levels of the four drought indices: Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI

Average (1-, 3-, 6-, and 12-month periods)	Normal	Mild drought	Moderate drought	Severe drought	Extreme drought
SPI	71.8	14.3	6.6	4.8	2.5
SPEI	68.1	16.3	10.2	4.6	0.8
SSI	67.6	14.4	10.7	4.9	2.4
SIDI	68.4	15.3	9.9	4.2	2.2

from those following SPI/SPEI. In a few time steps, even the wet (positive) and dry (negative) signals were different. In 1984, for example, the three–month SPI/SPEI show recovery from drought, whereas SSI indicated that the drought continued for a few more months (Fig. 5, top panel). Such discrepancies could be attributed to abnormally high rainfall over a very short period of time, whereas most of the month remained dry with SPI/SPEI > 0 and SSI < 0. Alternatively, a below–average rainfall distribution throughout the month, such that creating soil that remained wet (SPI/SPEI < 0 and SSI > 0), could lead to opposite signs of SPI/SPEI and SSI.

It is emphasized that as the drought duration increased from 1– to 12–month periods, the differences between SPI/SPEI and SSI tended to decrease (Figs. 4, 5, 6, and 7). For example, the 6– and 12–month SPI/SPEI and SSI were more consistent than those of the one–month or three–month drought durations. However, SPI/SPEI and SSI show different levels of severity (Table 4), which indicates that the risk assessment and return–period estimation using these indices lead to different results. Furthermore, the results demonstrate that the estimated drought duration from SPI/SPEI and SSI often varied considerably (e.g., 1987–1988 in Fig. 4, 1999–2000 in Fig. 5, 1987–1989 in Fig. 6, and 1988–1991 in Fig. 7). These variations may have lead to different definitions for drought onset and termination.

We hypothesize that SIDI can provide a new perspective based on the joint probability distribution of SPI/SPEI and SSI (Figs. 4, 5, 6, and 7). During 1989–1991, for example, the three–month SPI/SPEI and SSI both show deficits in precipitation, soil moisture, and evapotranspiration with different durations (Fig. 5). The SPI/SPEI captured the drought earlier than the SSI and showed more variability. Conversely, SSI indicated a longer drought that by SPI/SPEI, which indicates a more reliable demonstration of drought persistence. The SIDI exhibited drought onset similar to that by SPI/SPEI and drought persistence similar to that by SSI. The drought duration based on SIDI was similar to that of SSI and was longer than the duration of the same event based on SPI/SPEI. During this two–year drought period, precipitation showed signals of drought recovery in late 1989, as evidenced by the high values of SPI/SPEI. However, the drought termination signals based on precipitation and evapotranspiration were temporary, primarily because of the high variability of precipitation. Conversely, SSI did not show significant variability. Therefore, a description of droughts based solely on the state of precipitation and evapotranspiration may be misleading at certain time steps. Here, SIDI captured the drought as early as SPI/SPEI and described drought development and termination based on the states of precipitation and soil moisture.

The aforementioned example highlights an attractive property of SIDI, in which drought onset and persistence is based on the states of multiple variables. When either SPI/SPEI or SSI indicates a drought event, SIDI also shows a drought event. According to drought severity, SIDI is higher than SPI/SPEI and lower than SSI (Table 4). The results show that SIDI can combine the information from three indices and provide one measure of drought based on the states of precipitation, soil moisture, and evapotranspiration. SIDI has common characteristics of SPI/SPEI and SSI; SIDI captures the drought onset as early as SPI/SPEI and describes similar drought persistence as that by SSI.

The research area experiences a large rainfall variation during the months of the wet season. Conversely,

Table 5. Frequency (%) of drought levels of the four drought indices in season. Standardized Precipitation Index, SPI; Standardized Precipitation Evapotranspiration Index, SPEI; Standardized Soil Moisture Index, SSI; Standardized Integrated Drought Index, SIDI

Average (1-, 3-, 6-, and 12-month periods)	Normal		Mild drought		Moderate drought		Severe drought		Extreme droughtl	
	dry season	wet season	dry season	wet season	dry season	wet season	dry season	wet season	dry season	wet season
SPI	72.6	70.8	18.0	13.5	6.0	9.1	1.7	3.7	1.7	2.9
SPEI	70.0	67.1	16.4	16.3	8.9	10.9	3.4	5.2	1.3	0.5
SSI	65.1	68.9	15.5	13.7	14.4	8.8	4.5	5.2	0.4	3.4
SIDI	68.9	68.1	16.8	14.6	10.6	9.6	2.8	4.7	0.9	2.9

there was less rainfall and less change during the dry season, which led to more frequent seasonal drought occurrences and major differences among indices (Table 5). The results shown in Table 5 indicate that, based on SPI and SPEI, the frequency of drought occurrence during the wet season was higher than that during the dry season; based on SSI, the opposite occurred. SIDI had general characteristics of SPI, SPEI, and SSI. The occurrence frequency of drought was the same in dry and wet seasons, which shows that using drought index based on only a single variable such as precipitation, soil moisture or evapotranspiration did not reflect drought characteristics fully. Therefore, establishing SIDI on the basis of multiple variables has important meaning in drought assessment. Each drought index reflects a characteristics component of drought. SPI and SPEI showed a lack of precipitation in the wet season; therefore, these indices have important significance in building plans of water use in the wet season. In the dry season, SPI and SPEI did not reflect drought status, whereas SSI indicated a lack of soil moisture indicating the importance in agriculture production plans. SIDI reflected precipitation, evapotranspiration, and soil moisture. Thus, drought events based on SIDI agree strongly with historical drought data in both dry and wet seasons. Therefore, SIDI has very important indications for building both water use and agriculture production plans.

CONCLUSIONS

Drought severity in the research area is relatively high. Our model showed that severe drought occurred through several months in many years; these results agree well with historical drought data from the research area. Large differences in drought were shown among the indices, particularly between SPI/SPEI and SSI. Although drought events are typically defined as periods with a sustained lack of water, the definition may vary according to the region, indicator variable, and user requirement and may be indicated by a lack of precipitation, soil moisture, or ground water. For this reason, providing reliable and relevant drought information based on multiple indicators or variables is important for overall characterization of drought.

In this study, a multivariate, multi–index drought–modeling approach was proposed using the concept of copulas. The proposed model, SIDI determined the drought onset and termination on the basis of combined SPI/SPEI and SSI, with onset time dominated by SPI/SPEI and the persistence of droughts showing high similarity to SSI behavior. SIDI had common characteristics of SPI/SPEI and SSI. Moreover, SIDI described the drought onset as early as that by SPI/SPEI and showed drought persistence similar to that given by SSI. Further, the drought severity of SIDI was higher than that shown by SPI/SPEI and lower than that given by SSI.

Each drought index reflects a characterized component of drought events and has important significance for assessing drought. SIDI reflects drought events on the basis of many factors such as precipitation, soil moisture, and evapotranspiration; therefore, it has special significance in assessing drought because other indices are not reflected. The proposed framework for creating multi–index drought models is rather general, and other indices can be integrated into SIDI. In the future, the authors will evaluate the integration of other indices, such as runoff or ground–water storage, to evaluate meteorological, agricultural, and hydrological droughts. The authors emphasize that drought information should be based on multiple sources of information. For this reason, SIDI is not meant to replace SPI/SPEI and SSI. Instead, we propose that SIDI be used as an additional source of information based on the joint probability of precipitation, soil moisture, and evapotranspiration.

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