

# Using integrated meteorological and hydrological indices to assess drought characteristics in southern Taiwan

Hsin-Fu Yeh

## ABSTRACT

Numerous drought index assessment methods have been developed to investigate droughts. This study proposes a more comprehensive assessment method integrating two drought indices. The Standardized Precipitation Index (SPI) and the Streamflow Drought Index (SDI) are employed to establish an integrated drought assessment method to study the trends and characteristics of droughts in southern Taiwan. The overall SPI and SDI values and the spatial and temporal distributions of droughts within a given year (November to October) revealed consistent general trends. Major droughts occurred in the periods of 1979–1980, 1992–1993, 1994–1995, and 2001–2003. According to the results of the Mann–Kendall trend test and the Theil–Sen estimator analysis, the streamflow data from the Sandimen gauging station in the Ailiao River Basin showed a 30% decrease, suggesting increasing aridity between 1964 and 2003. Hence, in terms of water resources management, special attention should be given to the Ailiao River Basin. The integrated analysis showed different types of droughts occurring in different seasons, and the results are in good agreement with the climatic characteristics of southern Taiwan. This study suggests that droughts cannot be explained fully by the application of a single drought index. Integrated analysis using multiple indices is required.

**Key words** | drought assessment, integrated drought indices, southern Taiwan, trend test

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## INTRODUCTION

Climate change is one of the greatest environmental threats of the 21st century. According to the Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2013), global average surface temperature has been increasing over the past 157 years, and increases in temperature exhibit significant regional differences. These changes accelerate the global water cycle (Milly *et al.* 2002) and result in more extreme hydrological events. Numerous studies have shown that changes in precipitation patterns due to global warming may exacerbate extreme events, such as droughts and floods (Emam *et al.* 2015; Yan *et al.* 2016; Huang *et al.* 2017; Zhang *et al.* 2018). Such changes may also negatively impact water resources and result in more frequent droughts

(Shahid & Behrawan 2010; Dai 2011). The effects of droughts on the environment, society, and the economy are exacerbated by climate change (Bates *et al.* 2008; Romm 2011; Van Huijgevoort *et al.* 2013).

The world is facing a serious challenge related to climate change and global warming. According to the Global Risks Report 2017 by the World Economic Forum (WEF), ‘failure of climate-change mitigation and adaptation’ and ‘water crises’ were ranked among the top three global risks (World Economic Forum 2017). In recent years, some regions (e.g., California) have experienced extreme drought events with increasing frequency (Wang *et al.* 2017). Droughts in Morocco have led to desertification, and

extreme droughts have sharply reduced crop yields in North America, Europe, Australia, and Southeast Asia, resulting in food shortages (Lesk *et al.* 2016; Seif-Ennasr *et al.* 2016). In addition to making the lives of citizens difficult and inhibiting crop growth, water crises due to droughts significantly reduce industrial water and power generation, which eventually affect national economic development and public health security (Sheffield & Wood 2008; Mussá *et al.* 2015).

To carry out drought risk assessments and develop mitigation strategies, drought severity must be determined through the use of some form of index. Many drought indices have been developed to describe drought types. Table 1 compares the most commonly used drought indices.

Most indices for meteorological and hydrological droughts require consideration of a variety of data and complex calculations. In contrast, the Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) are effective indices that can be computed easily. The SPI, proposed by McKee *et al.* (1993), is widely applied in meteorological drought studies. It only requires precipitation data and is able to describe drought severity effectively under various climatic conditions. Hence, it has been used to evaluate the characteristics of meteorological drought events in many countries and regions (Ji & Peters 2003; Ntale & Gan 2003; Quiring & Papakryiakou 2003; Dash *et al.* 2012; Tabari *et al.* 2012; Ruiz-Sinoga & León-Gross 2013).

The SDI, developed by Nalbantis (2008), describes the severity and characteristics of hydrological droughts. It can be applied at any timescale and can easily fulfill regional and application requirements. Therefore, the SDI has been widely employed in hydrological drought research in recent years (Tigkas *et al.* 2012; Tabari *et al.* 2013; Hong *et al.* 2015) to analyze drought characteristics in many

countries (Tigkas *et al.* 2012; Manikandan & Tamilmani 2015; Zamani *et al.* 2015).

Despite the large number of studies on meteorological, hydrological, and agricultural droughts, only a few studies have combined the individual indices, particularly those developed to measure meteorological and hydrological droughts, to acquire more comprehensive integrated assessment results. Drought development is subject to the influence of several factors such as precipitation, temperature, topography, soil type, and water resources exploitation. If only one factor (e.g., precipitation, streamflow, or soil water content) is used as the criterion for drought assessment, it is difficult to represent the regional similarities or complex differences in drought development objectively (Huang *et al.* 2015). Indices for meteorological droughts can express the characteristics of large-scale and long-term regional droughts, but they cannot entirely describe the status of the water supply; a hydrological drought index is needed for that purpose. Hence, meteorological drought indices cannot completely reflect the actual drought situation and have limitations when applied in practical drought management.

Taiwan is located in the tropical and subtropical climate zones. Despite its relatively small area, Taiwan displays distinct seasonal climatic characteristics because of its complex topography and monsoon climate. Total precipitation decreases gradually from northeast to southwest, resulting in distinct wet and dry regions. The average annual precipitation in Taiwan between 1949 and 2015 was 2,491 mm, and a significant proportion of the precipitation falls between May and October (Water Resources Agency 2015). Despite the high rainfall, water resources management is challenging because of high population density and an uneven

**Table 1** | Commonly used drought indices of three types

Type	Index name	References
Meteorological drought	Standardized Precipitation Index (SPI)	McKee <i>et al.</i> (1993)
	Reconnaissance Drought Index (RDI)	Tsakiris & Vangelis (2005)
Hydrological drought	Palmer Drought Severity Index (PDSI)	Palmer (1965)
	Surface Water Supply Index (SWSI)	Shafer & Dezman (1982)
	Streamflow Drought Index (SDI)	Nalbantis (2008)
	Standardized Hydrological Index (SHI)	Sharma & Panu (2010, 2012)
Agricultural drought	Soil Moisture Deficit Index (SMDI)	Narasimhan & Srinivasan (2005)
	Agricultural Reference Index for Drought (ARID)	Woli <i>et al.</i> (2012)

temporal and spatial distribution of precipitation. Extreme weather events increase the severity of water shortages. In particular, southern Taiwan receives high precipitation in summer due to the southwest monsoon, but it is arid in winter due to mountain barriers. Compared to other areas in Taiwan, southern Taiwan displays a remarkable contrast between the wet and dry seasons and experiences serious droughts.

Integrated meteorological and hydrological drought indices have the potential to describe the characteristics of large-scale droughts and the water supply, allowing for the development of more comprehensive drought identification and early drought warning systems. Using a meteorological drought index (SPI) and a hydrological drought index (SDI), this study establishes an integrated drought assessment method to evaluate drought events accurately and investigates the distribution of droughts in southern Taiwan at various timescales. The characteristics of drought trends and the probability of drought occurrence are analyzed using trend tests and probability analysis.

## METHODOLOGY

### Standardized Precipitation Index

The SPI, proposed by [McKee et al. \(1993\)](#), is widely used to evaluate the intensity of meteorological drought events. It uses cumulative precipitation at various timescales to assess the distribution of drought intensity. Given that the average monthly precipitation ( $P_{i,j}$ ) is continuous,  $P_{i,j}$  is added sequentially according to the timescale under investigation,  $k$ . The cumulative precipitation,  $R_{i,k}$ , of the  $i$ th year at timescale  $k$  can be obtained as follows:

$$R_{i,k} = \sum_{j=1}^{3k} P_{i,j}, i = 1, 2, 3, \dots, j = 1, 2, 3, \dots, 12, k = 1, 2, 3, 4 \quad (1)$$

where  $i$  is the year under analysis and  $j$  is the month  $k$ . The values of  $k = 1, k = 2, k = 3$ , and  $k = 4$  denote the periods of November to January, November to April, November to July, and November to October, respectively. The SPI of

the  $i$ th year at timescale  $k$  defined by cumulative precipitation  $R_{i,k}$  is as follows:

$$\text{SPI}_{i,k} = \frac{R_{i,k} - \bar{R}_k}{s_{R,k}}, i = 1, 2, 3, \dots, k = 1, 2, 3, 4 \quad (2)$$

where  $\bar{R}_k$  and  $s_{R,k}$  are the average cumulative precipitation and standard deviation at timescale  $k$ , respectively.

Only normally or log-normally distributed data can be used in the SPI computation. Because the precipitation data distribution resembles the gamma distribution, the data must be transformed before they can be analyzed by SPI. The two-parameter log-normal distribution function is employed to transform the distributions and take the natural logarithm of the precipitation data. The SPI is defined as follows:

$$\text{SPI}_{i,k} = \frac{w_{i,k} - \bar{w}_k}{s_{w,k}}, i = 1, 2, 3, \dots, k = 1, 2, 3, 4 \quad (3)$$

$$w_{i,k} = \ln(R_{i,k}), i = 1, 2, 3, \dots, k = 1, 2, 3, 4 \quad (4)$$

where  $\text{SPI}_{i,k}$  is the SPI value at the cumulative precipitation timescale  $k$ ,  $w_{i,k}$  is the natural logarithm of the cumulative precipitation,  $\bar{w}_k$  is the average value, and  $s_{w,k}$  is the standard deviation.

The annual SPI values were calculated and categorized based on the classification scheme based on the SPI suggested by [McKee et al. \(1993\)](#) (Table 2).

### Streamflow Drought Index

The SDI, proposed by [Nalbantis \(2008\)](#), is computed based on the cumulative stream discharge data at various timescales to study the distribution of and variations in drought severity. The SDI is a calculated approach similar to the SPI.

**Table 2** | Definition of different states of the SPI and SDI

Condition	Criterion
Non-drought	$-1.0 < \text{SPI}, \text{SDI} \leq 1.0$
Moderate drought	$-1.5 < \text{SPI}, \text{SDI} \leq -1.0$
Severe drought	$-2.0 < \text{SPI}, \text{SDI} \leq -1.5$
Extreme drought	$\text{SPI}, \text{SDI} < -2.0$

The annual SDI values were calculated and then categorized to define the SDI range for various drought intensities. The drought intensity classification scheme based on the SDI suggested by Al-Faraj *et al.* (2014) was employed in this study (Table 2).

### Mann–Kendall trend test

The Mann–Kendall trend test was devised by Mann (1945) and Kendall (1975). It is a non-parametric method commonly used in the analysis of trends in meteorological and hydrological droughts (Hamed 2008; Gocic & Trajkovic 2013). The test determines whether significant trends exist using the differences in consecutive data. The results are not affected by extreme values or missing values in data sequences. Given a time series  $t_1, t_2, \dots, t_n$  and its corresponding data sequences  $x_1, x_2, \dots, x_n$ , where  $n$  is the number of data points, the Mann–Kendall statistic,  $S$ , is defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Sign}(X_j - X_i), \text{Sign}(X_j - X_i) = \begin{cases} +1, X_j - X_i > 0 \\ 0, X_j - X_i = 0 \\ -1, X_j - X_i < 0 \end{cases} \quad (5)$$

For  $n \geq 10$ , the probability distribution of  $S$  approximately fits a normal distribution with an average of 0. The variance is defined as follows:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

Whether significant trends exist in the time series data is determined by the  $Z$ -value defined as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, S < 0 \end{cases} \quad (7)$$

Positive and negative  $Z$ -values represent increasing and decreasing trends, respectively. The  $Z$ -values are then

subjected to further significance tests. This study set the level of significance at  $\alpha = 0.05$ . If  $|Z| \geq 1.96$ , the time series data show a significant trend; if  $|Z| < 1.96$ , there is no significant trend.

### Theil–Sen estimator

The Theil–Sen estimator was proposed by Theil (1950) and Sen (1968) to calculate the trend slope,  $\beta$  (Amirataee & Montaseri 2017), which is defined as follows:

$$\beta = \text{Median} \left[ \frac{x_j - x_i}{j - i} \right], i < j \quad (8)$$

where  $\beta$  is the median of the slopes of all lines through pairs of points in the time series data, and  $x_j$  and  $x_i$  are the corresponding data at times  $j$  and  $i$  ( $j > i$ ), respectively. The regression line was calculated after the trend slope was determined:

$$\begin{aligned} X(t) &= \beta t + C \\ X(t) &= X_1 \sim X_n, t = 1 \sim n \end{aligned} \quad (9)$$

Substituting the median of precipitation and stream discharge data  $\{X_1, X_2, X_3, \dots, X_T\}$  and time  $t$  into Equation (9) gives the constant term  $C$ . The slope  $\beta$  computed using this method differs from that obtained using simple linear regression because of the former the median is not affected by extreme values in data sequences. Positive and negative  $\beta$  values represent increasing and decreasing trends, respectively.

### Mann–Whitney–Pettit test

The Mann–Whitney–Pettit test was suggested by Pettit (1979) to evaluate whether significant change points are present in data sequences. If there is a change point  $X_i$  in the sequence  $\{X_1, X_2, X_3, \dots, X_n\}$ , then  $\{X_1, X_2, X_3, \dots, X_t\}$  and  $\{X_{t+1}, X_{t+2}, X_{t+3}, \dots, X_n\}$  follow  $F_1(X)$  and  $F_2(X)$ , respectively, where  $F_1(X) \neq F_2(X)$ .

The change point  $U_{t,n}$  is defined as follows:

$$U_{t,n} = \sum_{i=1}^t \sum_{j=t+1}^n \text{Sign}(X_j - X_i), \text{Sign}(X_j - X_i) \\ = \begin{cases} +1, X_j - X_i > 0 \\ 0, X_j - X_i = 0 \\ -1, X_j - X_i < 0 \end{cases} \quad (10)$$

If there are no change points in the sequence, the  $|U_{t,n}|$  function with respect to time  $t$  shows a continuous increase without any turning points. In contrast, if there is a change point, the  $|U_{t,n}|$  function with respect to time  $t$  decreases following an increase, resulting in a turning point. For a single sequence, there may be several turning points, indicating multiple change points for that sequence. Equation (11) shows the computation of  $K_n$ , which verifies the existence of change points (or turning points) by calculating the maximum value of  $|U_{t,n}|$ .

$$K_n = \text{Max}|U_{t,n}|, 1 \leq t < n \quad (11)$$

Equation (12) is then used to calculate the probability  $P$  at the change point (turning point). This study applied  $P = 0.95$  as the detection standard. If  $P > 0.95$ , the change point is considered significant at that time point.

$$P = 1 - \exp\left(\frac{-6K_n^2}{n^2 + n^3}\right) \quad (12)$$

In some sequences, there may be multiple change points; thus, Equation (13) can be employed to calculate the annual  $P(t)$  values. This allows for the identification of multiple points and intervals satisfying the detection standard.

$$P(t) = 1 - \exp\left(\frac{-6|U_{t,n}|^2}{n^2 + n^3}\right) \quad (13)$$

## STUDY AREA

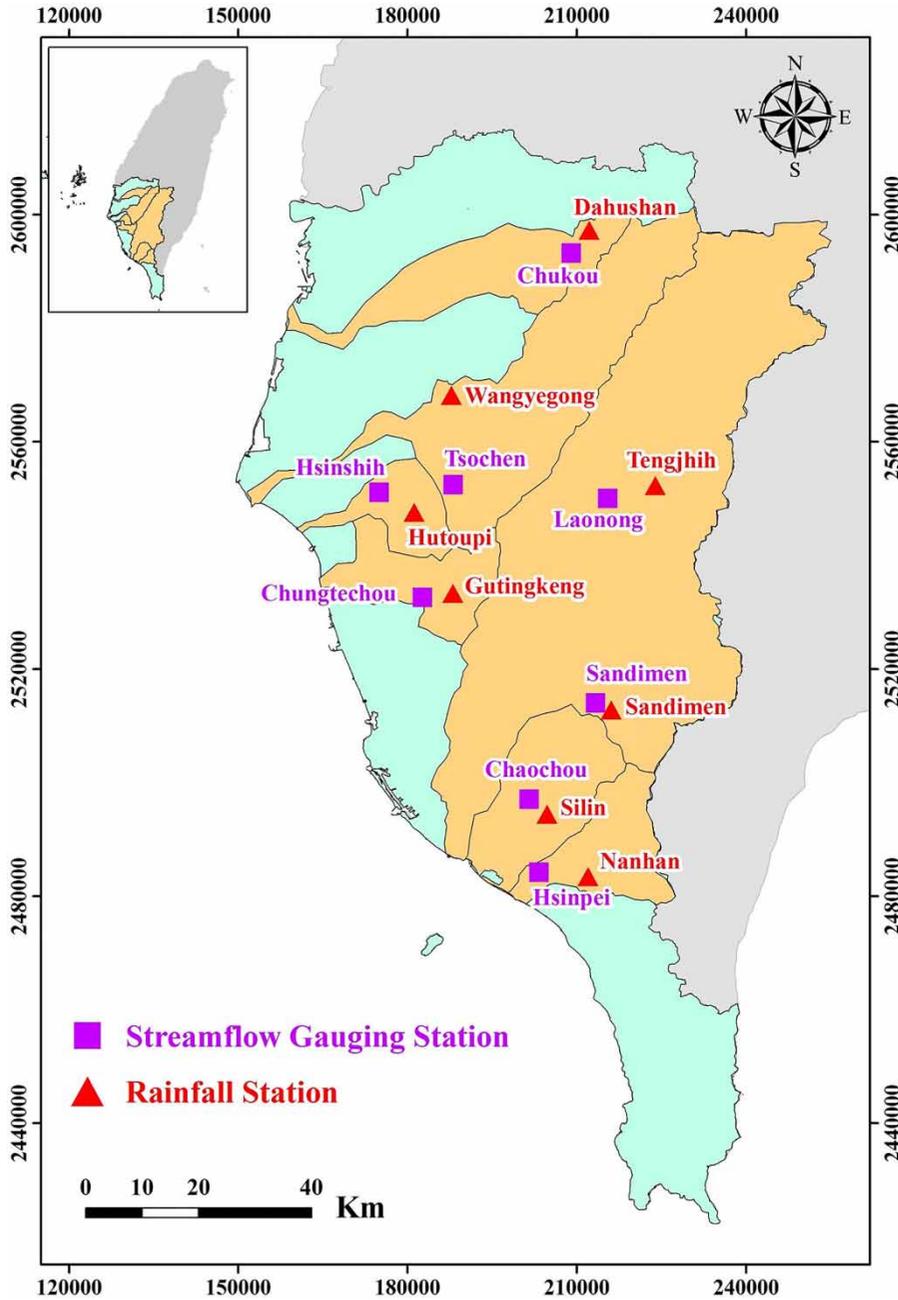
The administrative districts of southern Taiwan are Chiayi County, Chiayi City, Tainan City, Kaohsiung City, and Pingtung County, with a total area of 9,883 km<sup>2</sup>. Owing to its

sub-tropical monsoon climate, topography, and geographical location, southern Taiwan receives abundant rainfall, especially during the East Asian rainy season from May to June and the typhoon season from July to September. Little precipitation occurs in winter. There is a remarkable contrast between the wet and dry seasons. The average annual precipitation in southern Taiwan is 2,535 mm. The average during the wet season (May to October) is approximately 2,256 mm, accounting for 89.01% of the annual total. During the dry season (November to April), the average precipitation is approximately 279 mm, accounting for 10.99% of the annual total. Therefore, the wet-to-dry ratio is approximately 9:1 (Water Resources Agency 2015). The main rivers in southern Taiwan are the Bazhang, Zengwun, Yanshui, Erren, Gaoping, Donggang, and Linbian, with river basin areas of 475, 1,177, 340, 339, 3,257, 472, and 344 km<sup>2</sup>, respectively. The average annual stream discharge is 17.4 billion m<sup>3</sup>. Southern Taiwan has the greatest streamflow discharge in Taiwan. The streamflow discharge during the wet season is 15.59 billion m<sup>3</sup> and that during the dry season is 1.85 billion m<sup>3</sup> (Water Resources Agency 2015). This study selected eight pairs of precipitation and gauging stations in the upstream sections of the rivers that are relatively less prone to external influences (water intake facilities). Precipitation and streamflow data for more than 10 consecutive years were used. The geographic distribution and related information for the precipitation and gauging stations are presented in Figure 1.

## RESULTS AND DISCUSSION

### Meteorological drought analysis results

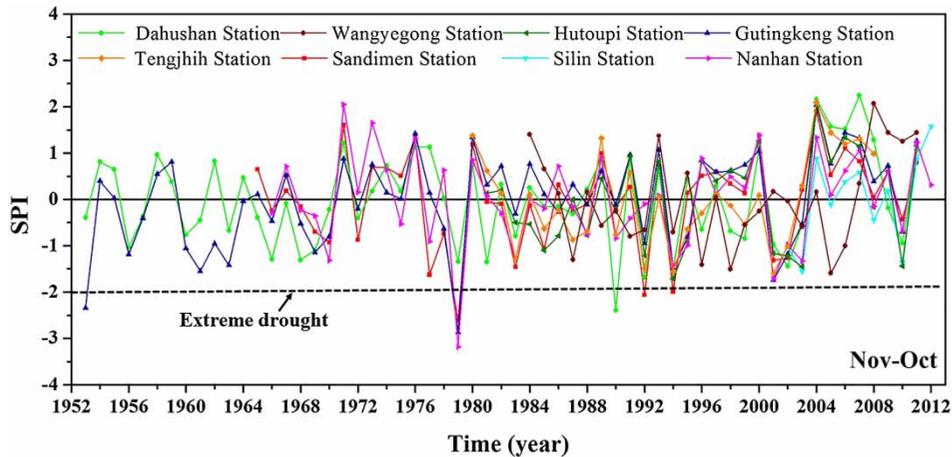
This study summarizes the annual SPI results from precipitation stations in each river basin in southern Taiwan. The overall SPI trend and the temporal and spatial distributions of drought events were investigated (Figure 2). In general, the trends in SPI are consistent for all precipitation stations. There was a moderate drought incident in the period of 1969–1970, and there were no significant drought incidents in 1970–1979. Only one severe drought event occurred in 1977–1978, namely that at the Sandimen station in the Ailiao River Basin, with an SPI of  $-1.63$ . An extreme



**Figure 1** | Locations of rainfall stations and streamflow gauging stations in the study area.

drought event took place in 1979–1980 at the Nanhan station in the Linpien River Basin, with an SPI of  $-3.18$ . Droughts were generally rare in 1980–1992. There was only one extreme drought in 1990–1991, namely at the Dahushan station in the Bazhang River Basin, with an SPI of  $-2.39$ . In 1992–1993, there were drought events of various intensities. An extreme drought was noted at the

Sandimen station in the Ailiao River Basin, with an SPI of  $-2.06$ . There were mostly moderate to severe droughts in 1994–1995; the SPI at the Sandimen station in the Ailiao River Basin was  $-1.99$ , indicating an extreme drought event. There were no droughts in 1995–2001, but moderate to severe drought incidents were noted in 2001–2004.



**Figure 2** | SPI series for the reference periods of November–October in all rainfall.

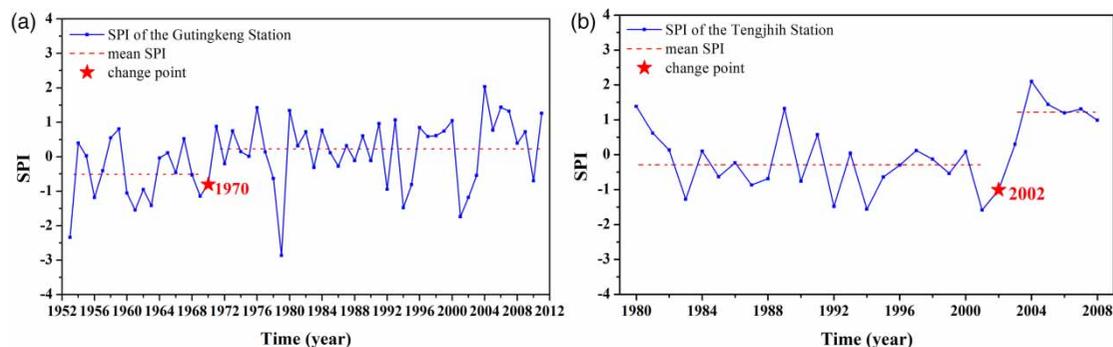
The Mann–Kendall trend test was employed to test the significance of the long-term SPI trends at the precipitation stations in each river basin in southern Taiwan. Trend slopes were evaluated using the Theil–Sen estimator. Change points of the trends were detected using the Mann–Whitney–Pettit test. The percentage changes in the average annual precipitation before and after the change points were calculated. The trend test produced positive values for the SPI long-term trends at all precipitation stations in the eight river basins, suggesting increasing trends. The Gutingkeng station in the Erren River Basin had a Mann–Kendall statistic value of 2.77, indicating a significant increasing trend. According to the Theil–Sen estimator results, drought trend slopes were positive at all data intervals for all precipitation stations in the eight river basins.

This result suggests that there has been no tendency for increasing droughts in recent years, but rather an increasing trend for precipitation (Table 3). Using the Mann–Whitney–Pettit test, change points were detected at the Gutingkeng station in the Erren River Basin and the Tengjihih station in the Laonong River Basin (Figure 3). The average SPI values before and after the change point at the Gutingkeng station in the Erren River Basin in 1970 were  $-0.51$  and  $0.23$ , respectively. The corresponding average annual precipitation values were  $1,731$  and  $2,167$  mm, respectively, resulting in a 25% increase. The average SPI value increased from  $-0.29$  to  $1.22$  at the change point at the Tengjihih station in the Laonong River Basin in 2002. The average annual precipitation increased by 47%, from  $3,019$  to  $4,425$  mm (Table 4).

**Table 3** | Results of SPI of Mann–Kendall test and slope estimators

Basin	Rainfall station	Record length	Mann–Kendall test result	Slope estimator
Bazhang River	Dahushan	1953–2012	0.77	0.01
Zengwen River	Wangyegong	1984–2012	0.81	0.03
Yanshui River	Hutoupi	1981–2012	1.36	0.03
Erren River	Gutinheng	1953–2012	2.77*	0.02
Laonong River	Tengjihih	1980–2009	0.88	0.03
Ailiao River	Sandimen	1965–2012	1.25	0.01
Donggang River	Silin	2002–2013	1.25	0.2
Linpian River	Nanhan	1966–2013	0.37	0.005

\*Significant trends. The positive values represent increasing trends, and the negative ones represent decreasing trends.



**Figure 3** | Change points of SDI at the Gutingkeng Station in the Erren River Basin and at the Tengjih Station in the Laonong River Basin.

**Table 4** | Results of SPI of Mann–Whitney–Pettit methods and change points

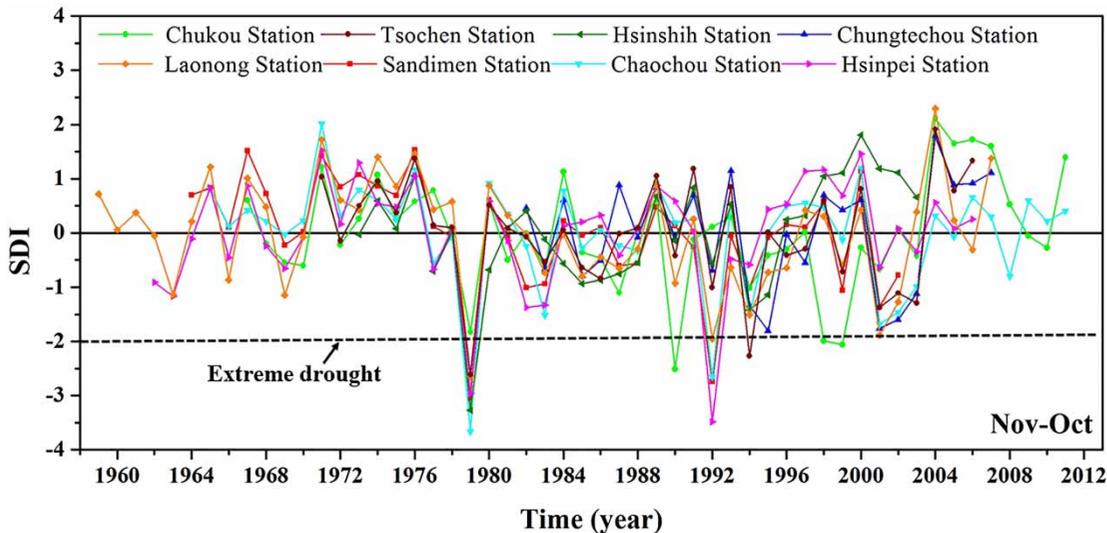
Basin	Rainfall station	Mann–Whitney–Pettit	Mean SPI			Annual mean rainfall (mm)		
			Before change point	After change point	Change point (year)	Before change point	After change point	Relative change at the change point (%)
Bazhang River	Dahushan	0.68	–	–	–	–	–	–
Zengwen River	Wangyegong	0.92	–	–	–	–	–	–
Yanshui River	Hutoupi	0.87	–	–	–	–	–	–
Erren River	Gutingkeng	0.97	$0.51 \pm 0.88$	$0.23 \pm 0.98$	1970	$1,731 \pm 478.1$	$2,167 \pm 619.8$	25
Laonong River	Tengjih	0.96	$0.29 \pm 0.83$	$1.22 \pm 0.59$	2002	$3,019 \pm 844.4$	$4,425 \pm 1203.0$	47
Ailiao River	Sandimen	0.81	–	–	–	–	–	–
Donggang River	Silin	0.65	–	–	–	–	–	–
Linpien River	Nanhan	0.62	–	–	–	–	–	–

### Hydrological drought analysis results

In this section, the annual SDI results from each gauging station are summarized to study the general SDI trends and the correlations between drought severity and duration in each river basin in southern Taiwan (Figure 4). Two extreme droughts were clearly noted, one each in 1979–1980 and 1992–1993. There were relatively few drought events before 1979. An extreme drought incident occurred in 1979–1980, namely at the Chaochou station in the Donggang River Basin, with an SDI value of  $-3.66$ . Most droughts took place after 1990. A severe to extreme drought event occurred in 1992–1993, namely at the Hsinpei station in the Linpien River Basin, with an SDI of  $-3.49$ . Moderate to severe droughts were noted at most gauging stations in 1994–1995. An extreme drought was measured at the Tsochen station in the Zengwen River Basin, with an SDI

of  $-2.27$ . Severe droughts were reported at the Chungtechou station in the Erren River Basin, with SDI values of  $-1.76$  and  $-1.60$  in 2001–2002 and 2002–2003, respectively. At the Hsinpei and Chukou stations, no drought events were detected during the same period; in fact, some wet days were observed at the Hsinpei station. In general, the annual SDI results showed consistent drought trends before 1998 for all gauging stations in the river basins. After 1998, the drought intensities detected at the various station displayed differences, which warrant further investigation.

The trend test produced negative Mann–Kendall statistic values for the Tsochen station in the Zengwen River Basin, Laonong station in the Laonong River Basin, Sandimen station in the Ailiao River Basin, and Chaochou station in the Donggang River Basin. In particular, the value at the Sandimen station was  $-2.93$ , suggesting a decreasing trend



**Figure 4** | SDI series for the reference periods of November–October in all streamflow gauging stations.

**Table 5** | Results of SDI of Mann–Kendall test and slope estimators

Basin	Streamflow gauging station	Record length	Mann–Kendall test result	Slope estimator
Bazhang River	Chukou	1967–2012	0.28	0.01
Zengwen River	Tsochen	1971–2007	−1.10	−0.02
Yanshui River	Hsinshih	1973–2004	2.07*	0.04
Erren River	Chungtechou	1982–2008	0.93	0.02
Laonong River	Laonong	1959–2008	−1.37	−0.01
Ailiao River	Sandimen	1964–2003	−2.93*	−0.04
Donggang River	Chaochou	1965–2012	−0.95	−0.01
Linpian River	Hsinpei	1962–2007	1.03	0.01

\*Significant trends. The positive values represent increasing trends, and the negative ones represent decreasing trends.

(Table 5). Change points were found at the Hsinshih station in the Yanshui River Basin, Laonong station in the Laonong River Basin, and Sandimen station in the Ailiao River Basin (Table 6). The average SDI values before and after the change point at the Hsinshih station in the Yanshui River Basin in 1995 were  $-0.29$  and  $0.93$ , respectively. The corresponding average annual streamflows were  $5.45$  and  $6.5$  cm, respectively, an increase of  $19\%$ . At the change point at the Laonong station in the Laonong River Basin in 1978, the average SDI decreased from  $0.41$  to  $-0.29$  and the average annual stream discharge decreased by  $20\%$ , from  $77.69$  to  $62.49$  cm. Negative SDI values were noted after 1978. At the change point of the Sandimen station in the Ailiao River Basin in 1977, the average SDI decreased from  $0.78$

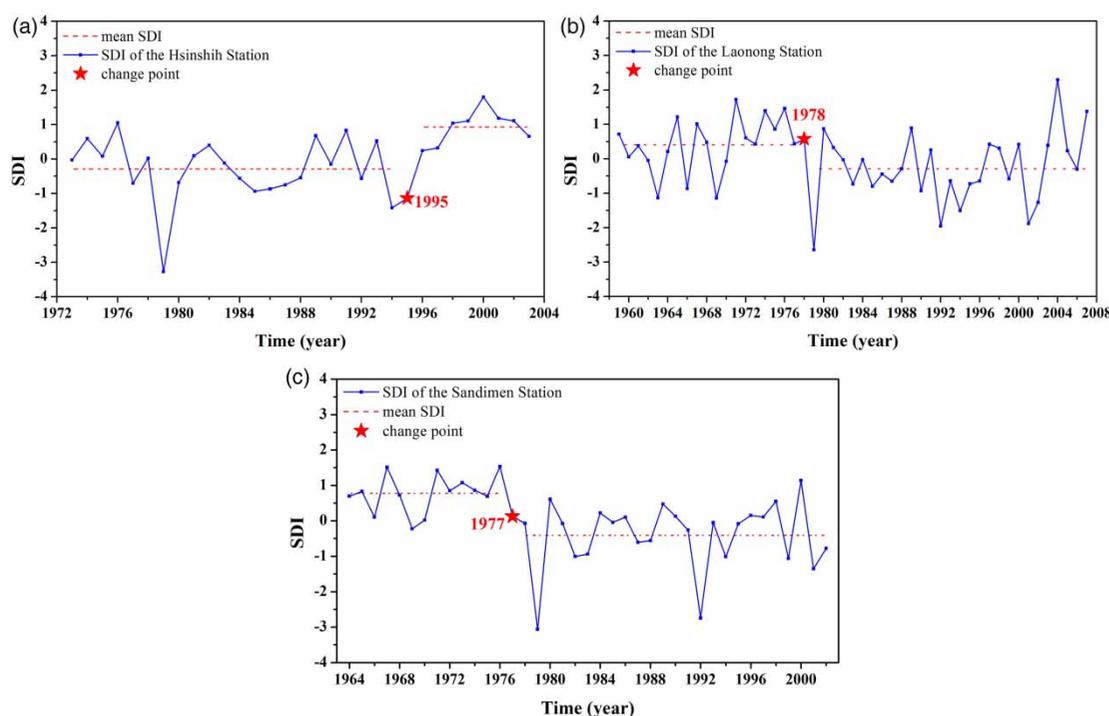
to  $-0.41$ . The average annual streamflow decreased by  $33\%$ , from  $43.36$  to  $28.96$  cm. The negative SDI values after 1977 showed a relatively large difference from the average value before 1977. This result suggests the occurrence of increasingly serious drought events at the Sandimen station in the Ailiao River Basin after 1977 (Figure 5).

### Integrated analysis results for meteorological and hydrological droughts

In this study, two drought types were studied for different seasons and the applicability of the SPI and SDI was discussed. Precipitation and streamflow data from eight river basins were computed at the same timescale to assess the

**Table 6** | Results of SDI of Mann–Whitney–Pettit methods and change points

Basin	Streamflow gauging station	Mann–Whitney–Pettit	Mean SDI		Change point (year)	Annual mean streamflow (cm)		Relative change at the change point
			Before change point	After change point		Before change point	After change point	
Bazhang River	Chukou	0.94	–	–	–	–	–	–
Zengwen River	Tsochen	0.74	–	–	–	–	–	–
Yanshui River	Hsinshih	0.99	$-0.29 \pm 0.93$	$0.93 \pm 0.51$	1995	$5.45 \pm 2.29$	$6.5 \pm 2.54$	19%
Erren River	Chungtechou	0.89	–	–	–	–	–	–
Laonong River	Laonong	0.96	$0.41 \pm 0.82$	$-0.29 \pm 1.03$	1978	$77.69 \pm 21.25$	$62.49 \pm 23.35$	–20%
Ailiao River	Sandimen	1.00	$0.78 \pm 0.55$	$-0.41 \pm 0.96$	1977	$43.36 \pm 10.73$	$28.96 \pm 9.37$	–33%
Donggang River	Chaochou	0.88	–	–	–	–	–	–
Linpian River	Hsinpei	0.75	–	–	–	–	–	–

**Figure 5** | Change points of SDI at the Hsinshih Station in the Yanshui River Basin, at the Laonong Station in the Laonong River Basin and at the Sandimen Station in the Ailiao River Basin.

impacts of meteorological and hydrological changes on droughts. Next, the SPI and SDI classifications are combined and four scenarios for integrated assessment are proposed.

The drought intensity classification schemes show that SPI and SDI values greater than  $-1$  imply no drought conditions. When SPI and SDI are assigned as the horizontal and vertical axes of a two-dimensional Cartesian system,

respectively, drought events are designated into four scenarios, represented by the four quadrants. The first quadrant represents Scenario 1, in which both meteorological and hydrological droughts are absent. The second quadrant represents Scenario 2, in which meteorological droughts but not hydrological droughts occur. The third quadrant represents Scenario 3, in which there are both meteorological and hydrological droughts. The fourth quadrant represents

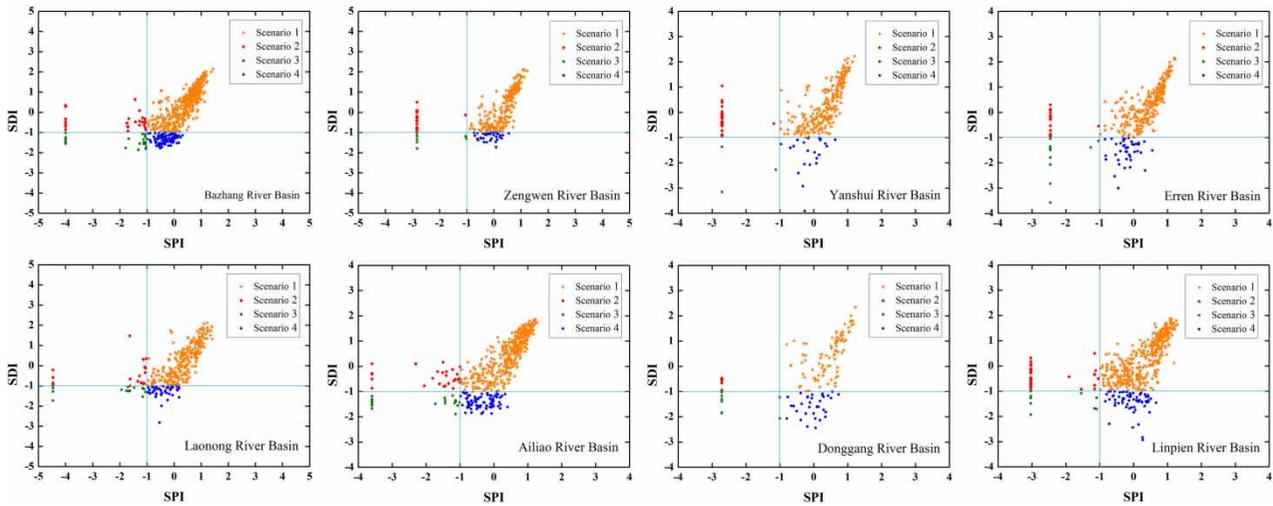


Figure 6 | Integrated assessment (SPI-SDI) for hydrometeorological drought in the all river basin.

Scenario 4, in which only hydrological drought events occur. The drought development usually begins with Scenario 2 (only meteorological droughts). As precipitation continues to decline, surface water shortages occur and Scenario 3 begins. When it rains again, meteorological droughts are easily alleviated and the region returns to normal conditions or even becomes relatively wet. However, hydrological droughts cannot be reversed immediately (Scenario 4). When the amount of precipitation is sufficient for the region to return to normal conditions or even reach a wet state, Scenario 4 evolves into Scenario 1.

The SPI-SDI four-quadrant integrated assessment results for the river basins in southern Taiwan are illustrated in Figure 6. The distribution of drought events categorized into the four scenarios reveals that most droughts belong to Scenario 1 or Scenario 4. The annual probability of droughts in each scenario was also calculated. The average probability of Scenario 1 (absence of both droughts) is 75%. Scenario 4, indicating the dominance of hydrological droughts, has the highest average probability. For Scenario 3 (presence of both droughts), the probability is highest for the Donggang River Basin (6%) (Table 7). Because the annual drought probability may conceal the seasonal drought characteristics in the study area, our analyses were performed on the seasonal drought probability under the four scenarios for the eight river basins.

The seasonal drought probability results suggest that winter has the highest drought probability (49%), followed

Table 7 | Annual drought probabilities of four scenarios in the all river basin (unit: %)

Basin	Drought scenarios			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Bazhang River	73	6	5	17
Zengwen River	77	8	3	12
Yanshui River	81	10	1	8
Erren River	78	6	3	13
Laonong River	76	5	4	14
Ailiao River	74	6	4	16
Donggang River	64	5	6	25
Linpien River	78	7	2	13

Scenario 1 is no meteorological drought with no hydrological drought, Scenario 2 is meteorological drought with no hydrological drought, Scenario 3 is meteorological drought with hydrological drought, and Scenario 4 is no meteorological drought with hydrological drought.

by autumn, spring, and summer in descending order. Among the four scenarios, Scenario 3 represents relatively severe droughts because both drought types occur under this scenario. The probability of Scenario 3 is much higher in winter, with an average of 9%. Hence, the co-occurrence of both drought types is most likely in winter (Table 8).

The Donggang and Linpien River Basins are more prone to droughts as well as the occurrence of both drought types in spring. For droughts in summer, the eight river basins show consistent results. The Yanshui River Basin is prone to droughts in autumn, whereas droughts are more

**Table 8** | Drought probabilities of four scenarios in seasons of the southern Taiwan (unit: %)

Basin Seasons	Scenario	Bazhang River	Zengwen River	Yanshui River	Erren River	Laonong River	Ailiao River	Donggang River	Linpien River
Spring	Scenario1	70	75	82	84	79	72	27	52
	Scenario2	1	0	3	0	0	3	0	3
	Scenario3	4	4	1	4	2	3	6	6
	Scenario4	25	21	14	12	19	22	67	38
Summer	Scenario1	100	99	100	100	100	99	100	98
	Scenario2	0	0	0	0	0	0	0	0
	Scenario3	0	0	0	0	0	0	0	1
	Scenario4	0	1	0	0	0	1	0	1
Autumn	Scenario1	83	74	71	75	86	84	91	94
	Scenario2	15	21	29	16	14	7	6	6
	Scenario3	0	3	0	1	0	3	0	0
	Scenario4	1	3	0	7	0	6	3	0
Winter	Scenario1	38	61	71	54	42	39	39	67
	Scenario2	6	13	10	6	7	14	12	18
	Scenario3	14	4	3	9	14	10	18	1
	Scenario4	42	22	17	31	37	37	30	13

Scenario 1 is no meteorological drought with no hydrological drought, Scenario 2 is meteorological drought with no hydrological drought, Scenario 3 is meteorological drought with hydrological drought, and Scenario 4 is no meteorological drought with hydrological drought.

common in winter in the Bazhang, Zengwen, Erren, Laonong, and Ailiao River Basins. For winter droughts, the probability of Scenario 3 (co-occurrence of both droughts) is the highest in the Donggang River Basin (18%) (Table 8).

Based on the precipitation and stream discharge data, the annual and seasonal probabilities of droughts under the different scenarios were analyzed to investigate the results of the two drought indices. The annual probability of each scenario suggests that Scenario 4 is more likely than Scenarios 2 and 3. This reflects the considerable loss of surface water and the difficulties in water resources preservation in Taiwan attributable to its steep topography and hints at more frequent hydrological droughts in the future. The seasonal probabilities for each scenario indicate that droughts are more common in winter and spring. The co-occurrence of meteorological and hydrological droughts is more likely in winter. These results are in good agreement with the climate in southern Taiwan, which is characterized by abundant precipitation in summer and minimal rainfall in winter. In spring, the probability of hydrological droughts is highest (high probability of Scenario 4). In summer, almost no drought events are recorded (high probability of Scenario 1). In autumn, precipitation gradually decreases, so meteorological droughts become more likely (high

probability of Scenario 2). In winter, precipitation continues to decrease, so hydrological droughts occur with increased probability due to aridity (high probability of Scenario 4). Although winter is more prone to hydrological droughts, the probability of co-occurrence of both drought types (Scenario 3) is also highest in this season (10% on average). The results demonstrate that the four quadrants match the seasonal climatic characteristics of Taiwan and form a complete water cycle. The results also show that a single drought index cannot fully describe the drought situation. Different types of droughts occur in different seasons; therefore, more than one drought index should be used for a more comprehensive description of droughts.

## CONCLUSIONS

Precipitation and streamflow data were collected to compute SPI and SDI values and study the drought intensities for a full year (November to October) in eight river basins in southern Taiwan. The characteristics of the SPI and SDI drought trends were examined using trend tests and change-point analyses. Finally, using the SPI–SDI four-quadrant integrated assessment method, the meteorological and hydrological

drought events in the river basins were evaluated. The overall SPI and SDI trends and the spatiotemporal distribution of droughts show that major droughts took place in 1979–2003. Relatively serious droughts occurred in 1979–1980, 1992–1993, 1994–1995, and 2001–2003. Both trend tests and trend slope analyses on hydrological droughts suggested significant decreasing trends in streamflow in the Ailiao River Basin. A 30% decrease was observed, indicating an increase of aridity in 1964–2003. Hence, in water resource analysis, special attention should be given to this region.

According to the SPI–SDI four-quadrant integrated assessment for the eight river basins, the four quadrants corresponded to the seasonal climatic characteristics in Taiwan and formed a complete water cycle. Few drought events were noted in summer. The probability of meteorological droughts increased in autumn. In winter, the probability of co-occurrence of both drought types (meteorological and hydrological) increased. The probability of hydrological droughts became higher in spring. These results are consistent with the climate of southern Taiwan, which is characterized by abundant summer precipitation and little winter precipitation. The results demonstrate that a single drought index cannot fully describe drought situations and may even lead to false judgments; a composite drought index is thus needed. Because different types of drought occur in different seasons, using multiple drought indices allows for a more comprehensive description of regional drought characteristics and more accurate drought analyses. The results of this study provide insights for future research on drought characteristics in southern Taiwan.

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