Drought Monitoring and Early Warning Using Variable-Scale Standardized Precipitation Index

Teng-Wei Lin, Ke-Sheng Cheng

Department of Bioenvironmental Systems Engineering, National Taiwan University

Abstract

Because of the high population density, small area of reservoirs, and uneven precipitation, drought remains a serious issue in Taiwan. To ensure uninterrupted water supply, the drought situation should be monitored all year round, and adjustments should be made to water management measures. The Standardized Precipitation Index (SPI) has been commonly applied to monitor and describe the process of drought events. However, the SPI may delay detecting or prematurely end a drought event owing to its constant memory. Therefore, based on the original SPI structure, a variable-scale SPI is proposed in this study to capture drought events that corresponds to reality. These methods were examined using several past drought events, and suggestions about drought monitoring are provided. The government or policymakers can apply these results to water management procedures.
Keywords: Meteorological Drought, Standardized Precipitation Index, Variable-scale SPI

1. Introduction

Drought is a climate hazard resulting from long-term water shortage, and its impacts are multifaceted. It can be categorized into four types, namely meteorological, hydrological, agricultural, and socioeconomic drought (Richard et al., 2002). Meteorological drought usually appears earlier than the other types of drought (Richard et al., 2002). In the other types of drought, several causal factors, such as soil, hydraulic infrastructure, and industry structure, are too complex to define or observe. Therefore, this study focused on meteorological drought.

However, the evolution of drought features slow accumulation and high uncertainty. Predicting the onset and termination points of drought remains difficult (Mishra et al., 2011). To understand and grasp drought events, several drought indices have been proposed to evaluate the severity of drought. The Palmer Drought Severity Index (Palmer, 1965) combines precipitation, temperature, and soil moisture to evaluate drought. The Standardized Precipitation Index (SPI; McKee et al., 1993) only includes precipitation to represent the level of drought. The Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2009), which is based on the SPI, includes the potential evapotranspiration term to evaluate water balance. Other drought indices have unique advantages and disadvantages. Nevertheless, SPI was proposed to be the most suitable and convenient meteorological drought index by World Meteorological Organization and has been widely applied in many countries (Svoboda et al., 2012). Thus, based on the considerations of convenience and extensive use, SPI was selected to define and monitor a drought event in the present study.

Using the standard normal distribution in conjunction with SPI facilitates comparison of current precipitation data with historical records. When SPI is lower than zero in a certain period, the precipitation in that period is lower than the median (McKee et al., 1993). In the calculation of SPI, deciding a fixed timescale as a moving window is necessary, and the fixed timescale can be set depending on different water management applications (Svoboda et al., 2012). In this research, SPI using the fixed-scale moving window is called fixed-scale SPI. Usually, fixed-scale SPI with shorter timescales such as 1, 2, or 3 months is applied to detect the occurrence of drought, and longer timescales such as 6 or 12 months can help to assess the effects on groundwater, reservoirs, and other hydraulic devices (Svoboda et al., 2012). However, for water management, a drought event cannot be portrayed adequately by applying only one type of fixed-scale SPI. For instance, if precipitation is insufficient in the wet season and returns to normal in the dry season, a short fixed-scale SPI can be used to detect the occurrence of drought, but it would relieve the drought event too early in dry season because of its short memory. By contrast, a long fixed-scale SPI will initially detect the drought late, but it will record the drought event from the wet season to the dry season. Therefore, fixed-scale SPI does not facilitate illustration of the entire process of a drought event.

This study aims to develop a variable-scale SPI to describe drought events realistically. Variable-scale SPI combines short and long fixed-scale SPI. It first detects the start of a drought event by using a basic and short timescale and then extends the timescale with the development of the drought event to observe whether the previous precipitation shortage can be compensated for. The calculation ends when the SPI returns to normalcy or at the end of the hydrological year. This method not only provides early warning at the start of a drought event but also maps the development of such an event.

In the following chapters, information about the study area and data sources are first introduced. Second, the calculation of SPI is demonstrated. Thereafter, variable-scale SPI and fixed-scale SPI are demonstrated separately and compared. The process of drought monitoring and early warning is examined by past drought events. The results can provide information to the government or policymakers to implement effective measures as early as possible and make decisions related to water management.

2. Precipitation Data

The Taiwan Central Weather Bureau has installed hundreds of rainfall stations covering all of Taiwan. Considering the length and completeness of the data, 295 stations were selected in this study. The observation duration of each selected station was from May 1992 to April 2019 (27 years). The hydrological year in Taiwan can be considered from May to the following April with the mei-yu (stationary frontal rain) being an obvious boundary, and a new hydrological year can be considered a new realization in statistic.

In addition, drought should be evaluated based on a regional overview instead of considering a single rainfall station. Therefore, the 295 stations should be classified into several regions. In this study, two area-division methods were used to provide different views for policymakers. As shown in Fig. 1, first, these stations were divided into four water-resource regions (Northern, Central, Southern and Eastern Taiwan) according to the Taiwan Water Resources Agency. Second, these stations were assigned to eight climatic regions (1 to 8) based on their climatic similarities through k-means clustering analysis covering seven factors, namely longitude, latitude, altitude, mean and standard deviation of annual precipitation, and mean of rainy days in wet and dry seasons.

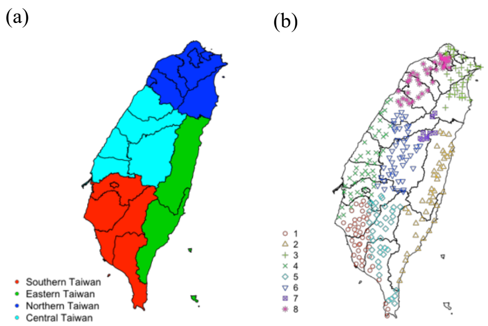

Fig. 1. (a) water-resource region. (b) climatic regions

3. Methods

3.1. Standardized Precipitation Index

In Taiwan, the population density is extremely high, but the reservoirs are smaller than those in most countries. These reservoirs must be refilled a few times each year to fulfill the water demand. If a period of rainfall shortage continues for several weeks, water supply and water management are affected. Therefore, unlike the regional studies of most countries, even 1-month SPI is too long for the purpose of this study. To increase the sensitivity of the SPI, 1 year is divided into 36 10-day periods (TDPs), as shown in Table 1. Therefore, for example, SPI1 and SPI3 denote 1-TDP SPI and 1-month SPI, respectively.

Table 1. 36 TDPs.

	January	February	…	December
1st–10th	1st	4th	…	34th
11th–20th	2nd	5th	…	35th
21st–end	3rd	6th	…	36th

According to the method proposed by McKee (McKee et al., 1993), to calculate the n-TDP SPI (SPIn) of the *i*th TDP, a moving window with a length of the consecutive n-TDP should be set up. Next, the precipitation within the moving window should be summed as x_{ijk}, which indicates the consecutive n-TDP precipitation of the *j*th TDP in the *k*th year at the *i*th station (Eq. (1)). The moving window moves forward to the following TDPs, and the calculation is repeated (Table 2).

$$x_{ijk};\ i = 1,2,\dots,295\ ;\ j = 1,2,\dots,36\ ;k = 1,2,\dots,27 \qquad (1)$$

Table 2 Consecutive n-TDP precipitation of different TDPs.

	j-n+1	j-n+2	j-n+3	…	j	j+1	j+2
j TDP	■	■	■	■	■		
j+1 TDP		■	■	■	■	■	
j+2 TDP			■	■	■	■	■

Precipitation of the same TDP across different years follows a gamma distribution; thus, 36 different gamma distributions corresponding to the 36 TDPs should be constructed for each station. Eq. (2) shows the probability density function of the *j*th TDP at the *i*th station.

$$f_{ij}(x_{ijk}) = \frac{1}{\Gamma(\alpha_{ij})\beta_{ij}^{\alpha_{ij}}} x_{ijk}^{\alpha_{ij}-1} \mathrm{e}^{-\frac{x_{ijk}}{\beta_{ij}}} \qquad (2)$$

$i = 1,2,\dots,295;\ j = 1,2,\dots,36;\ k = 1,2,\dots,27$

$\alpha: shape\ parameter, \beta: scale\ parameter$

Gamma Function $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1}e^{-t}dt$

The parameters (α, β) can be estimated using the method of maximum likelihood estimation (Rao et al., 2000):

$$\hat{\alpha} = \begin{cases} \frac{1}{U}(0.500876 + 0.1648852U - 0.054427U^2), 0 \le U < 0.5772 \\ \frac{8.898919 + 9.05995U + 0.9775373U^2}{U(17.7928 + 11.968477U + U^2)}, \quad 0.5772 \le U \le 17 \end{cases}$$
$$\hat{\beta} = \frac{\bar{x}_n}{\hat{\alpha}}$$
$$U = \ln \bar{x}_n - \ln G, G = (x_1 x_2 \dots x_n)^{\frac{1}{n}}$$

After fitting consecutive n-TDP precipitation to a gamma distribution, the precipitation can be transformed into standard normal distribution through probability integral transformation (Eq. (3)) to obtain SPIn.

$$(SPI_n)_{ijk} = \Phi^{-1}\left(F_{ij}(x_{ijk})\right) \quad (3)$$
$$\Phi^{-1}(p) = \sqrt{2}\,\mathrm{erf}^{-1}(2p-1)$$
$$F_{ij}(x_{ijk}) = \int_0^{x_{ijk}} \frac{1}{\Gamma(\alpha_{ij})\beta_{ij}^{\alpha_{ij}}} t^{\alpha_{ij}-1} e^{-\frac{t}{\beta_{ij}}}\, dt$$
$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{t^2}{2}}\, dt$$
$$i = 1, 2, \dots, 295;\ j = 1, 2, \dots, 36;\ k = 1, 2, \dots, 27$$

F_{ij} is the cumulative distribution function of gamma distribution, and Φ is the cumulative distribution function of standard normal distribution.

However, if n is low, the consecutive n-TDP precipitation of some TDPs may be zero. However, the probability of zero precipitation in a gamma distribution is zero. Therefore, a mixed distribution that combines the Bernoulli distribution with gamma distribution is introduced. This allows for the probability of zero precipitation existing in the distribution. Thus, $F_{ij}(x_{ijk})$ can be expressed as follows:

$$F_{ij}(x_{ijk}) = p_{ij} + (1 - p_{ij}) \int_0^{x_{ijk}} \frac{1}{\Gamma(\alpha_{ij})\beta_{ij}^{\alpha_{ij}}} t^{\alpha_{ij}-1} e^{-\frac{t}{\beta_{ij}}}\, dt \quad (4)$$

where p_{ij} is the probability of zero precipitation for the consecutive n-TDP of the *j*th TDP at the *i*th station. If p_{ij} is zero, $F_{ij}(x_{ijk})$ is a pure gamma distribution. However, in the case of zero precipitation, SPIn should have a lower bound:

$$min\{SPI_n\}_{ij} = \Phi^{-1}(p_{ij}) \quad (5)$$

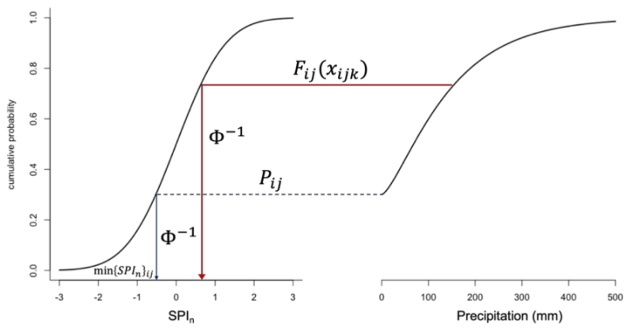

Fig. 2. Transformation from precipitation to SPIn.

Because SPI follows the standard normal distribution, the amount of precipitation can easily be compared with past records. A positive (negative) SPI means the precipitation is higher (lower) than the median. When focusing on dry situations, negative SPI can be classified into several levels (Table 3) to describe the severity of drought.

Table 3 Levels of drought with the corresponding SPI values.

Level	SPI
Wet to near normal	Inf to -0.49
Light drought	-0.5 to -0.99
Moderate drought	-1 to -1.49
Severe drought	-1.5 to -2
Extreme drought	-2 to -Inf

3.2. Regional Analysis

The 10-day precipitations of the same region can be added to obtain 10-day regional precipitation:

$$x_{gjk} = \Sigma_{i=1}^{p_g} x_{ijk};\ j = 1, 2, \dots, 36;\ k = 1, 2, \dots, 27 \quad (6)$$

where g is any of water resource regions or climatic regions, and p_g denotes the number of stations in the *g* region. The series of regional precipitation is similar to stations; thus, the SPI can be calculated using the same process as that described above. Based on the application, different stations can be arbitrarily summed together to calculate SPI; for example, the stations within the catchment of a reservoir can be used to evaluate the drought situation of the catchment.

3.3. Variable-scale Standardized Precipitation Index

To record the real evolution of meteorological drought, the variable-scale SPI was proposed in this study. The calculation of the variable-scale SPI should start from SPI1, and the starting point of drought should be verified. As mentioned before, a negative SPI1 indicates that the 10-day precipitation is lower than the median. Typically, the starting point of drought coincides with the time at which the SPI1 is lower than zero. However, in some situations, quasinormality should be tolerated because it is usually affordable in water management. Therefore, in this research, the starting point of drought is considered as the period in which SPI1 is lower than -0.5. Nevertheless, in some TDPs, the probability of zero precipitation is higher than 0.309. This implies that even though the SPI1 is greater than -0.5, the precipitation may not be adequate and may even be zero. Because the root cause of drought is inadequate precipitation, zero precipitation should be considered when determining the starting point of drought. Therefore, in the variable-scale SPI, drought is thought to start when (1) SPI1 is lower than -0.5 or (2) the 10-day precipitation is zero. By contrast, the drought is thought to end when the variable-scale SPI returns to a value higher than -0.5, and the consecutive precipitation is not zero. However, because a hydrological year is a new realization, the climatic mechanism can be considered to reset in a new hydrological year. Therefore, when the process of drought moves to the end of the hydrological year (the 12th TDP), the drought is relieved. Moreover, if the calculation is not ended at the end of the hydrological year, the memory of the variable-scale SPI may exceed 36 TDPs. In this case, the sample size would be reduced to half and will not be able support the calculation.

After defining the starting point and endpoint of drought, the variable-scale SPI can be calculated for each TDP. First, detect the starting point of drought (i.e., the SPI1 of the *j*th TDP is lower than -0.5 or the precipitation is zero in the *j*th TDP ($r_j = 0$)). Next, by holding the starting point, the step moves to the (j + 1)th TDP and accumulates the precipitation in the (j + 1)th TDP together with that in the *j*th TDP to obtain SPI2. If SPI2 is lower than -0.5, the process is repeated to obtain SPI3. This cycle is repeated until the variable-scale SPI is higher than -0.5 or is moving toward the end of the hydrological year. The point at which the variable-scale SPI calculation stops is considered the end of drought, and the calculation returns to SPI1 to detect the next drought event. By following this process, the real evolution of drought in a hydrological year can be recorded.

$if\ SPI1 < -0.5\ or\ r_j = 0$ in the j-th TDP

variable-scale SPI in the (j+n-1)th TDP :

$$\begin{cases} SPIn\ \ if\ SPIn \le -0.5 \\ SPI1\ \ if\ SPIn > -0.5 \end{cases} \tag{7}$$

$$SPIn = \Phi^{-1}\left(F\left(\Sigma_{l=j}^{j+n-1} r_l\right)\right)$$

$$SPI1 = \Phi^{-1}\left(F\left(r_{j+n-1}\right)\right)$$

Table 4 Calculation of variable-scale SPI.

TDP	j-th	(j+1)-th	…	(j+n-1)-th
precipitation	r_j	$r_j + r_{j+1}$	…	$r_j + r_{j+1} + \cdots + r_{j+n-1}$
Variable-scale SPI	SPI1	SPI2	…	SPIn

The first image in Fig. 3 shows the time series of SPI1 (dark line) and 10-day precipitation (blue line) at Tainan station from the 13th TDP in 2014 to the 12th TDP in 2015. Based on the SPI1 and the 10-day precipitation, three drought events can be recognized in the second image. First, the SPI1 of the 17th TDP in 2014 was lower than -0.5, and it was a starting point of a drought event. By calculating the variable-scale SPI from the starting point for each TDP, this drought event was determined to continue for 6 TDPs and ended in the 23rd TDP in 2014; therefore, the SPI7 of the 23rd TDP was higher than -0.5. Next, the SPI1 of the 25th TDP was lower than -0.5, but the SPI2 of the 26th TDP was higher than -0.5. Therefore, the second drought lasted for only 1 TDP. The third drought event occurred in the 29th TDP. Even though the SPI1 of the 29th TDP was higher than -0.5, the 10-day precipitation in that TDP was zero. Therefore, the calculation of variable-scale SPI was still executed. The third drought event continued to the end of the hydrological year (the 12th TDP in 2015). At this point, the drought ended because the process approached the end of the hydrological year instead of the variable-scale SPI exceeding -0.5.

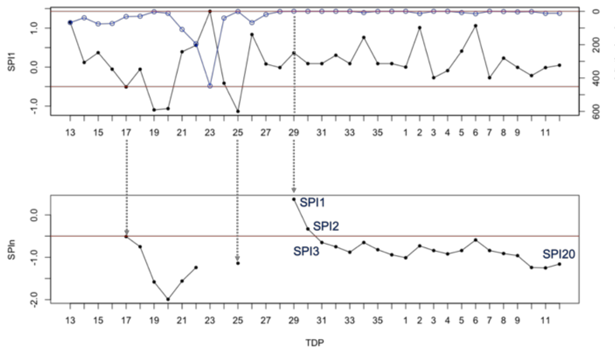

Fig. 3. Variable-scale SPI from the 13th TDP in 2014 to the 12th TDP in 2015.

3.4. Fixed-scale Standardized Precipitation Index

The calculation of the fixed-scale SPI is easier than that of the variable-scale SPI. The precipitation in summer and autumn should usually support the water supply in winter and even early spring, and the mechanism of precipitation usually changes each 3- or 4-month period in Taiwan. Therefore, in this study, 9-TDP SPI (SPI9) was used for the fixed-scale SPI, and a comparison was made with the variable-scale SPI.

The calculation of SPI9 is the same as that described in *3.1*, with nine consecutive 10-day precipitations. In SPI9, the criteria for determining the starting point of drought are the same as those for the variable-scale SPI (i.e., the point at which SPI9 is lower than -0.5). In the same way, drought is considered to end when SPI9 returns to a value higher than -0.5. In addition, 90-day zero precipitation is unlikely to happen in Taiwan. Therefore, it is not necessary to consider the likelihood of zero precipitation in the criteria. Moreover, unlike the variable-scale SPI, the calculation of SPI9 will not be reset at the end of the hydrological year because consecutive 90-day precipitation data are required as the base of the calculation.

As shown in Fig. 4, the first image represents the time series of SPI9 at Tainan station from the 13th TDP in 2014 to the 12th TDP in 2015, and the second image represents four drought events recognized from the time series. The first drought event started from the 17th TDP, when the SPI9 was lower than -0.5. This drought event continued for 6 TDPs and ended in the 23rd TDP. SPI9 returned to a value higher than -0.5 in the 23rd TDP. From the 32nd TDP in 2014 to the 12th TDP in 2015, another three drought events occurred, and they lasted for 2, 7, and 3 TDPs.

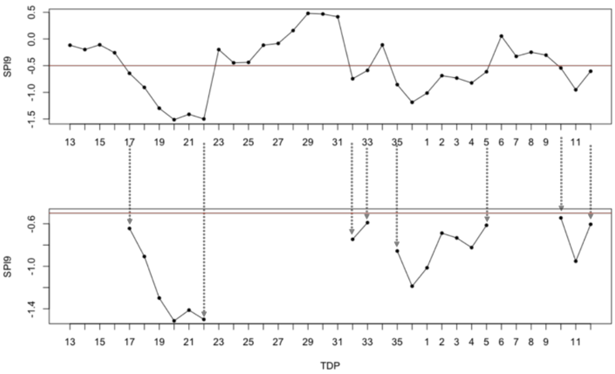

Fig. 4. Droughts according to SPI9 from the 13th TDP in 2014 to the 12th TDP in 2015.

4. Result and Discussion

The series in Fig. 3 and Fig. 4 represent the same hydrological year, and they are shown together in Fig. 5 First, both variable-scale SPI and SPI9 indicated the drought event from the 17th to the 22nd TDP in 2014. Second, only the variable-scale SPI recognized the short drought in the 25th TDP. Because the precipitation shortage in the 25th TDP can be compensated by the precipitation in the previous 8 TDPs, SPI9 did not identify the drought in the 25th TDP. Finally, the variable-scale SPI recognized a long and severe drought from the 29th TDP due to zero precipitation. However, SPI9 recognized this drought until the 32nd TDP because the precipitation shortage from the 29th to the 32nd TDP can be covered by the precipitation in the 27th and 28th TDPs. This implies that SPI9 may delay the identification of the starting point of drought because the previous precipitation is retained. Furthermore, SPI9 divided the long drought event into three small parts, whereas the variable-scale SPI held the drought until the end of the hydrological year. In the 6th TDP in 2015, SPI9 ignored the shortage of precipitation in the 29th–33nd TDPs. According to the variable-scale SPI, the drought event continued for a long period. That is, in most cases, the precipitation shortage in the wet season cannot be compensated in the dry season. Therefore, the memory of SPI9 was sometimes too long or too short for describing a drought event.

Based on the above situations, the fixed-scale SPI has two main drawbacks:

(1) Its memory may lead to a delay in recognizing the starting point of drought.

(2) Its memory may ignore the information of previous rainfall shortage and end the drought too early.

By contrast, variable-scale SPI immediately recognized a drought event without memory of previous precipitation, and it remembers the entire evolution of drought until the all shortages were recovered or the next realization was entered.

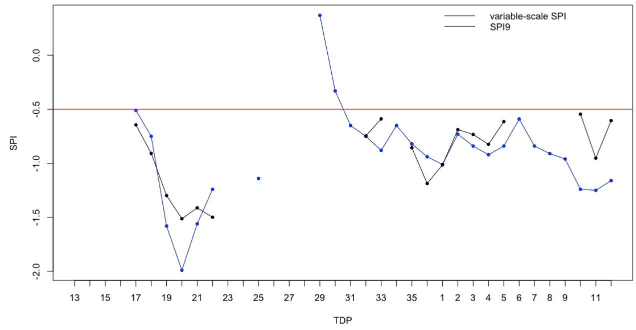

Fig. 5. Drought events identified using variable-scale SPI and SPI9 from the 13th TDP in 2014 to the 12th TDP in 2015

Moreover, to achieve more practical water management, the precipitation levels recorded at the stations within the catchment of the Zhengwen Reservoir were summed to obtain the variable-scale SPI and SPI9. The water level of the reservoir is also shown in Fig. 6, which represents the period from the 24th TDP in 2009 to the 12th TDP in 2010. The water level almost continuously decreased from the 24th TDP to the end of the hydrological year. The variable-scale SPI detected the drought in the 24th TDP and maintained the drought until the end of the hydrological year. By contrast, SPI9 detected the drought until the 31st TDP and divided it into four small parts. Because typhoon Morakot hit Taiwan in the 21st TDP of 2009 and caused large amounts of precipitation, SPI9 ignored the flood event until the 31st TDP. In the dry season, SPI9 ignored the rainfall shortage from the wet season, that is, the 24th to the 29th TDP, and did not record the entire evolution of the drought. Therefore, the variable-scale SPI may be more suitable for application to reservoir management than the fixed-scale SPI.

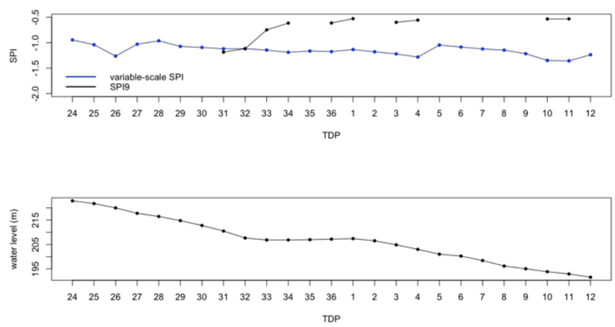

Fig. 6. Variable-scale SPI, SPI9, and the water level of Zhengwen Reservoir from the 24th TDP in 2009 to the 12th TDP in 2010

Nevertheless, SPI9 would have some advantages if two consecutive hydrological years are considered. Fig. 7 shows the drought events in Northern Taiwan over two hydrological years (May 2002 to April 2004), as identified using the variable-scale SPI and SPI9. In these two hydrological years, four drought events were identified by the variable-scale SPI, and three drought events were identified by SPI9. As mentioned before, the variable-scale SPI can detect the beginning of a drought event earlier than SPI9, and it indeed recognized a drought event in the 20th TDP of 2002, which was 9 TDPs earlier than the point at which SPI9 recognized the same event. However, the variable-scale SPI renewed the calculation in the next realization, whereas SPI9 retained the precipitation data of the previous 8 TDPs and connected the two hydrological years. Therefore, for water management, SPI9 can provide information about how the drought from the previous hydrological year influences the situation at the start of the current hydrological year. However, SPI9 still prematurely ended the drought in the middle of the second hydrological year because of its short memory, whereas the variable-scale SPI recorded the drought until the end of hydrological year.

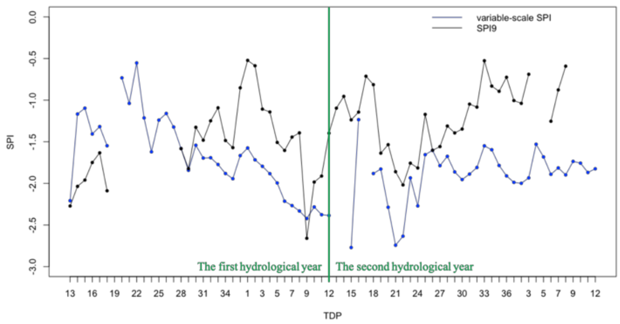

Fig. 7. Drought events in Northern Taiwan from May 2002 to April 2004.

5. Conclusion

In this study, time series of fixed-scale SPI (SPI9) and variable-scale SPI were established for 295 rainfall stations in Taiwan. These 295 stations were also divided into four water-resource regions and eight climatic regions for the purpose of regional overview. To correspond with the method of water management in Taiwan, 1 year was divided into 36 TDPs, with the 13th TDP representing the start of a hydrological year. With the fixed-scale SPI, a constant moving window should be applied to evaluate the precipitation within a constant period. Although the time-scale of the fixed-scale SPI depends on different water management strategies, the constant memory of the fixed-scale SPI may lead to the following drawbacks.

I. The constant memory may delay the recognition of a new drought event.

II. The constant memory may indicate the end of a drought too early, especially a drought event continuing from the wet season.

To overcome these drawbacks, the variable-scale SPI starts from SPI1. Upon detecting the traits of the beginning of a drought, it includes the precipitation of the next TDP and repeats this cycle until the lack of precipitation is compensated for or until the end of the hydrological year. Thus, it can not only precisely detect the beginning of a new drought but also does not relieve the drought too soon, meaning that a drought from wet season is remembered until the dry season. Nevertheless, for more practical water management, the variable-scale SPI cannot provide drought information across the hydrological year. Therefore, the fixed-scale SPI should still be applied at the start of the hydrological year to overcome the limitation of the variable-scale SPI until the observation time of the variable-scale SPI is no less than that of the fixed-scale SPI.

By combining monitoring and early warning, the process of drought management can be summarized as follows:

I. Calculate SPI9 and the variable-scale SPI in each TDP.

II. Determine whether either SPI9 or the variable-scale SPI reaches the level of drought.

III. From the 13th to 21st TDP, concentrate on SPI9 to evaluate the severity of drought.

IV. From the 22nd TDP to the following 12th TDP, concentrate on the variable-scale SPI to evaluate the severity of drought.

By using this strategy, a drought event can be detected early and end at an appropriate time point. In addition, based on an analysis of the previous drought, water shortage in the wet season is unlikely to be compensated for in the dry season. Therefore, the government should make accurate decisions pertaining to water management at the end of the wet season and keep tracing the variable-scale SPI and the fixed-scale SPI to appropriately adjust the drought management measures.

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