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Generalized drought assessment in Dongliao river basin based on water resources system

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Abstract

Drought is firstly a resource issue, and with its development it transforms into a disaster issue. The occurrences of drought events usually feature determinacy and randomness. Drought issue has become one of the major factors to affect sustainable economic and social development. In this paper, we propose the generalized drought assessment index (GDAI) based on water resources system for assessing drought events. The GDAI considers water supply and water demand using a distributed hydrological model. We demonstrate the use of the proposed index in the Dongliao river basin (DRB) in the northeast China. The results simulated by the GDAI are then compared to observed drought disaster records in DRB. As second, the temporal distribution of drought events and the spatial distribution of drought frequency from the GDAI are compared with the traditional approach (i.e. the SPI, the PDSI, and the RWD). Then, generalized drought times (GDT), generalized drought duration (GDD), and generalized drought severity (GDS) were calculated by theory of runs. Application of the GDT, the GDD, and the GDS of various drought levels (i.e. mild drought, moderate drought, severe drought, and extreme drought) to the period 1960–2010 shows that the centers of gravity of them are all distributed in the middle reached of DRB, and change with time. The proposed methodology helps water managers in water-stressed regions to quantify the impact of drought, consequently, to make decisions regarding coping with drought issue.

1 Introduction

With the increasing impact of climate change and anthropogenic activities, drought happens in more areas with higher frequency. Since 1990, drought disasters have caused more than 11 million deaths, and affected more than 2 billion people on a global level (United Nations International Strategy for Disaster Reduction Secretariat, 2009). Since the 1970s, the areas where droughts happened ($\mathrm{PDSI} < -3$) have increased by

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1.5 times in the world (Dai et al., 2004). The probability of drought events occurred in the southern US in the late 19th century and 20th century has increased, indicated by the analysis of the reconstructed precipitation series (Le Quesne et al., 2009). The average annual economic losses that resulted from drought disasters in US range from 6 to 8 billion dollars. It reached up to 40 billion in 1988 (Federal Emergency Management Agency, 1995). The drought-related disasters caused more than 500 thousand deaths in Africa in the 1980s (Kallis, 2008). Given the growing influence of climate change mainly characterized with global warming, the stability of climate system was reducing, and the impacts of drought and other extreme climate events were increasing (Dai, 2011). Special Report on Managing the Risks of Extreme Events Disasters to Advance Climate Change Adaptation showed that drought would be persistent in many regions of the world in the future owing to evaporation increase and soil moisture decrease, and the United States, Southern Europe, Southeast Asia, Brazil, Chile, Australia and Africa and other countries and regions would be affected by persistent drought severely (Intergovernmental Panel on Climate Change, 2012).

The drought areas and drought intensity in China are showing an increasing trend. It has the same trend as the global. Drought issue has become more and more obvious (Qin, 2009). Severe drought has happened every 2 to 3 years on average (Weng and Yan, 2010). Over the past 500 years, several large-scale drought disasters occurred in eastern China showed by historical records. Drought disasters happened from 1500 to 1730 and from 1900 till now have a wide range of distribution specifically (Dai, 2011). The areas where drought events and drought disasters occurred have increased since the middle 21st century. The annual average affected areas (the areas that crop yields decreased by over 10 % than normal annual yields) and damaged areas (the areas that crop yields decreased by over 30 % than normal annual yields) of drought disasters were nearly $0.21 \times 10^8\,\mathrm{km}^2$ and $0.10 \times 10^8\,\mathrm{km}^2$ from 1950 to 2010, which were 2.19 times and 1.77 times of the impacts of flood disasters respectively (State Flood Control and Drought Relief Headquarters, 2010). Drought occurs frequently not only in the northern China with shortage of water resources, but also in the southern China with relatively abundant water resources. In recent years, several extreme drought events happened frequently in China (Qin, 2009), such as the drought occurred in Sichuan and Chongqing in 2006 (Qin, 2009), the metrological drought occurred in the winter wheat region in northern China in 2008 (Qin, 2009), the extreme drought occurred in southern China in 2009 (Weng and Yan, 2010) and the severe drought occurred in the middle and lower Yangtze River in 2011.

The drought issue has become one of the major factors affecting sustainable economic and social development. Government departments, the public and researchers have taken more attention to the evolution law and driving mechanism of drought in the changing environment, and to coping with it. In addition, it is one of the front issues and hot topics in the field of hydrology and water resources.

Drought is firstly a resource issue which is shortage of water resources, and with its development it transforms into a disaster issue. Drought is one of the extreme events in water cycle. Its evolution is affected by the characteristics of water cycle of region or basin. It is characterized by the shortage of water resources resulted from the below-normal precipitation continuously. Coping with drought should obviously follow the principle of the natural-artificial water cycle.

Since 1900, a number of indices have been developed to quantify a drought, which could be classified into three stages: germination, growth and development.

During the germination stage (1900 ~ 1964), drought indices could be divided into four types. Firstly, they were created based on the precipitation records, such as Munger index (Munger, 1916), Kincer index (Kincer, 1919), Blumenstock index (Blumenstock, 1942), standard deviation index (Xu, 1950), antecedent precipitation index (McQuigg, 1954). Secondly, they were created based on the evaporation records, such as moisture adequacy index (McGuire and Palmer, 1957). Thirdly, they were created based on the precipitation and temperature records, such as Marcovitch index (Marcovitch, 1930), and Demartonne index (De Martonne, 1926). Fourthly, they were created based on the precipitation and evaporation records, such as aridity index (Ma et al., 2003). Drought indices in this stage were established based on a single factor or two-factors, in accordance with the particular region. They were simple to calculate. But the universality and the mechanism of water cycle were lacked.

During the growth stage (1965 ~ 1992), drought indices could also be divided into four types. Firstly, they were also created based on the precipitation records, such as precipitation anomaly percentage index (National Meteorological Center of CMA, 1972), drought area index (Bhalme and Mooley, 1980), positive and negative anomaly index (Liu and Wei, 1989). Secondly, they were created based on the runoff records, such as hydrological drought severity index (Dracup et al., 1980a), surface water supply index (Shafer and Dezman, 1982). Thirdly, they took surface conditions into consideration, such as Keetch-Byram drought index (Keetch and Byram, 1968), soil thermal inertia index (Wang and Guo, 2003). Fourthly, they were created based on the soil water balance principle, such as Palmer drought severity index (Palmer, 1965, 1967), Palmer revised surface-water supply index (Garen, 1993). Drought indices in this stage were established based on multi-factors, and considered water cycle elements and processes with some physical mechanism to some degree.

During the development stage (1993 till now), with the development of computers and hydrological models, drought indices not only contained multi-factors of water cycle, but also integrated multiple indices (GB/T 20481-2006, 2006). Furthermore, different drought parameters which included intensity, duration, severity and spatial extent were assessed (Francesco et al., 2009; Shiau and Modarres, 2009). Some drought indices can compute on various time scales, like standard precipitations index (SPI) (McKee et al., 1993). They could be divided into three types. Firstly, they integrated multiple indices, such as comprehensive drought index (GB/T 20481-2006, 2006), meteorological drought index (Yan et al., 2009). Secondly, they were created based on the distributed hydrological model, such as Palmer drought severity index based on geomorphology based hydrological model (Xu et al., 2008). Thirdly, they were created based on remote sensing, such as vegetation-temperature condition index (Wang et al., 2001), temperature–vegetation dryness index (Sandholt et al., 2002), vegetation supply water index (Mo et al., 2006), perpendicular drought index (Ghulam et al., 2007a, b), standard vegetation index (Peters et al., 2002), shortwave infrared perpendicular water stress index (Ghulam et al., 2007c).

This study is organized as follows. Section 2 describes the methodology, including the water and energy transfer process model in Dongliao river basin (Sect. 2.2), the method of generalized drought assessment index (GDAI) (Sect. 2.3), the theory of runs (Sect. 2.4), and the assessment method of standard precipitation index (SPI), Palmer drought severity index (PDSI) and rate of water deficit (RWD) (Sect. 2.5). Section 3 presents the results, including the generalized drought times (Sect. 3.1), the generalized drought duration (Sect. 3.2), the generalized drought severity (Sect. 3.3) of Dongliao River Basin. Section 4 assesses the difference between the GDAI, the SPI, the PDSI and the RWD. The study concludes in Sect. 5.

2 Methodology

2.1 Case study

Dongliao River Basin (DRB) is located in northeastern China. Its area is 11 306 km^2 (Fig. 1). It is roughly divided into three segments. The upper reaches are the segment above Erlongshan Reservoir as a low-mountain and hilly area with altitude from 200 to 600 m, where soil primarily consists of dark brown soil and planosol; the middle reaches are the segment from Erlongshan Reservoir downwards to Chengzishang hydrological station as a hilly area with altitude from 100 to 300 m, where soil primarily consists of black soil and meadow soil; the lower reaches are the segment from Chengzishang hydrological station downwards to Sanjiangkou Iron Bridge in Siping-Qiqihar Railway Line as a plain area with altitude from zero to 200 m, where soil primarily consists of meadow soil, salinized chernozem soil and steppe aeolian sandy soil.

DRB is controlled by the Pacific low and Siberian high with obvious four seasons. The precipitation is decreasing from upper to lower reaches, and multi-year average precipitation is reduced from 710 to 450 mm from 1960 to 2011. It is distributed unevenly

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within the year, of which, that from June to September accounts for 75 % of annual precipitation, and that of July and August accounts for 50 %. Inter-annual precipitation change is decreasing from west to east. The temperature is decreasing from southwest to northwest, and multi-year average values reduce from 6.7 to 5.6 °C. The evaporation is increasing from upper to lower reaches, and multi-year average values change from 850 to 1200 mm. The runoff is decreasing from upper to lower reaches, and multi-year average runoff reduces from 150 to 25 mm, that from June to September accounts for 80 % of annual runoff.

2.2 Water and energy transfer process model in DRB

Water and energy transfer process model in DRB (WEP-DRB) is chosen to simulate the elements of natural and artificial water cycle, and then to calculate the water supply and water demand of the assessment units based on water resources system. More details of WEP-DRB can be found in the studies by Jia et al. (2001).

2.2.1 Model input

WEP-DRB model input data consists of six types, i.e. digital elevation data, soil data, land use data, meteorological and hydrological data, hydraulic engineering data, and socio-economic data (Table 1). They are treated by spatial interpolation and formatting before inputting the model.

2.2.2 Model verification and validation

DRB is divided into eleven catchments and sixty-four assessment units. The simulated time step of WEP-DRB is one day. Firstly, WEP-DRB model is verified by using observed and restoring monthly runoff records of Erlongshan reservoir, Wangben, Quantai hydrological station from 1956 to 2000. The warm-up period is from 1956 to 1959, and the verified period is from 1960 to 2000. Secondly, WEP-DRB model is validated by using observed daily runoff records of Wangben, Quantai, Liaoyuan hydrological station from 2001 to 2010. The warm-up period is from 2001 to 2005, and the verified period is from 2006 to 2010.

Comparing the simulated and observed restoring monthly runoff from 1960 to 2000 (Table 2), the result shows that the maximum deviation is −4.89 % in Quantai hydrological station and the minimum one is 2.90 % in Wangben hydrological station. Nash–Sutcliffe model efficiency coefficients are all over 0.70, and it is up to 0.812 in Erlongshan reservoir hydrological station. Comparing the simulated and observed monthly runoff from 1960 to 2000 (Table 3), the result shows that the maximum deviation is −6.32 % in Quantai hydrological station and the minimum one is 0.47 % in Erlongshan reservoir hydrological station. Nash–Sutcliffe model efficiency coefficients are all over 0.70, and it is up to 0.830 in Quantai hydrological station. Comparing the simulated and observed daily runoff from 2006 to 2010 (Table 4), the result shows that the maximum deviation is −7.91 % in Liaoyuan hydrological station and the minimum one is 2.90 % in Wangben hydrological station. Nash–Sutcliffe model efficiency coefficients are also all over 0.70, and it is up to 0.763 in Wangben hydrological station.

Overall, the simulation accuracy of WEP-DRB has reached the requirement to obtain good simulation results. The model can be used to simulate water supply and water demand of water resources system to calculate the generalized drought assessment index (Yan et al., 2014).

2.3 Generalized drought assessment index

DRB is an important production base of commodity grain. The areas of cultivated land and forest land account for 88.03 %. Therefore, agricultural system and ecosystem in DRB are chosen to be evaluated. Then water demand (DW) per assessment unit is the sum of them. Water supply (SW) represents sum of surface effective evapotranspiration and special water resources per assessment unit in DRB. The water resources shortage D is:

$$D = \mathrm{SW} - \mathrm{DW} \quad (1)$$

In order to let Eq. (1) be used to compare water resources shortage in different assessment units and different assessment periods, the correct index K is considered here by referencing for the PDSI. That is:

$$K' = 1.6\log_{10}((\overline{\mathrm{DW}}/\overline{\mathrm{SW}} + 2.8)/\overline{|D|}) + 0.5$$

$$K = 329.37 \times K' / \sum_{1}^{36} (\overline{|D|} \times K') \tag{2}$$

Where, $\overline{\mathrm{DW}}$ is the ten days average water demand; $\overline{\mathrm{SW}}$ is the ten days average water supply; $\overline{|D|}$ is the average absolute D.

The water resources shortage index Z is:

$$Z = K \cdot D \tag{3}$$

Then, the generalized drought assessment index (GDAI) DI is:

$$\mathrm{DI}(i) = 0.91\mathrm{DI}(i-1) + Z(i)/25.0 \tag{4}$$

Where, $\mathrm{DI}(i)$, $Z(i)$ is the DI, Z for the ith ten days, respectively; $\mathrm{DI}(i-1)$ is the DI for the $(i-1)$th ten days. The classification of drought-wet still follows the standard of Palmer drought severity index (Palmer, 1965), as shown in Table 5.

To verify the reasonability and representativeness of the GDAI, the results simulated by GDAI using Eq. (4) were compared with the observed drought disaster records from 1960 to 2010 in Gongzhuling city and Lishu county in DRB.

The observed drought disaster records in Lishu County were listed below. Maize growth was affected by drought disaster starting from 18 April 1994. The affected areas account for 30 % in 25 June 1994. The damaged areas of the maize were 1487 km^2, and the yields were decreased by 10 % during 11 May to 12 June 1996. They were 1133 km^2 which accounted for 63 % during 21 April to 16 May 1997. They accounted for 88 % until 30 July 1997. They were 2440 km^2 during 1 to 28 June 2000. The yields were reduced 70 % until 9 August 2000.

The observed drought disaster records in Gongzhuling city were listed below. The damaged areas of the maize were 1200 km^2 and the disaster areas (the areas that crop yields decreased by over 80 % than normal annual yields) were 300 km^2 during 8 June to 30 July 1997. They were 667 km^2 which accounted for 70 % during 2 July to 20 July 2000.

Comparing the results evaluated by GDAI and the observed drought disaster records in Lishu county (Fig. 2a) and Gongzhuling city (Fig. 2b), we could see that the GDAI is able to assess the characteristics of droughts in DRB.

2.4 Theory of runs

Generalized drought times (GDT), generalized drought duration (GDD), and generalized drought severity (GDS) are calculated by theory of runs (Dracup et al., 1980b; Feng and Zhu, 1997). The generalized drought duration D is expressed in ten days during which a drought parameter is continuously below the critical level. In other words, it is the time period between the initiation and termination of a drought event. That is the positive run-length. The generalized drought severity S indicates a cumulative deficiency of a drought parameter below the critical level. −DI is defined by taking logarithm of the GDAI. X_0, X_1, and X_2 are thresholds of the GDAI. For mild drought, they are 0, 1.0, 2.0; for moderate drought, they are 1.0, 2.0, 3.0; for severe drought, they are 2.0, 3.0, 4.0; for extreme drought, they are 3.0, 4.0, 5.0, respectively.

Figure 3 shows that “g” is a drought event because −DI is more than X_1. “h” is not a drought event because the GDD is only one unit and −DI is less than X_2, though it is more than X_1. “p” is a drought event because −DI is more than X_1, though there is one unit of GDD below X_1 between D_1 and D_2, say $D = D_1 + D_2 + 1$, $S = S_1 + S_2$. More details can be found in the studies by Lu et al. (2010).

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2.5 SPI, PDSI and RWD

The GDAI is constructed based on the elements of water resources system and “natural-artificial” dualistic water cycle process. It is evaluated by comparing with the standard precipitation index (SPI), the Palmer drought severity index (PDSI) and the rate of water deficit (RWD).

The SPI for 1 and 12 month time scales, the PDSI for 1 month, and the RWD for 1–ten days of sixty-four assessment units from 1960 to 2010 are calculated. The inter-annual difference between the results assessed by the GDAI, the SPI, the PDSI and the RWD is compared. Moreover, the annual difference is also compared from 1999 to 2001 because DRB has occurred continuously drought disasters in this period.

The method of the SPI can be found on Zhang and Gao (2004) and Yuan and Zhou (2004a). The method of the PDSI can be found on Palmer (1965), Yuan and Zhou (2004b) and GB/T 20481-2006 (2006). The evaporation is estimated by Thornthwaite’s method (GB/T 20481-2006, 2006). The available moisture stored in surface layer ($0 \sim 20$ cm) at the beginning of the month is 40 mm, and the available moisture stored in underlying levels ($20 \sim 100$ cm) at the beginning of the month is 150 mm (Liu et al., 2004). The method of the RWD is similar to the GDAI. The differences are that the RWD is defined as the ratio of the water resources shortage and the water demand, and the water supply here did not consider surface effective evapotranspiration, it equals to special water resources.

3 Results

According to the results simulated by the GDAI and theory of runs, the spatial distribution of the GDT, the GDD, and the GDS of different drought levels (i.e. mild drought, moderate drought, severe drought, extreme drought) in different periods (i.e. 1960s, 1970s, 1980s, 1990s, 2000s) were compared with each other. For the GDT of various drought levels, assessment units were chosen when their GDT were greater than or

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equal to the minimum of average GDT of sixty-four assessment units in five decades. For the GDD or GDS of various drought levels, the maximum GDD (MGDD) or GDS (MGDS) of each unit was calculated firstly. Assessment units were chosen when their GDD or GDS was greater than or equal to the minimum of average MGDD or MGDS of sixty-four assessment units in five decades. Then, their centers of gravity were calculated.

3.1 Distribution of the generalized drought times

The centers of gravity of the GDT of various drought levels in various periods are all distributed in the middle reached of DRB (near Erlongshan reservoir) (Fig. 4). For mild drought, the center of gravity moved toward southeast from the 1960s to the 1970s. The reason may be that the GDT in upper reaches are increasing while decreasing in lower reaches. It moved toward southwest, east, and west from the 1970s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively. For moderate drought, the center of gravity moved toward southeast from the 1960s to the 1990s, though it moved toward northwest from the 1990s to the 2000s. For severe drought, it moved toward southeast from the 1960s to the 1970s, then toward northwest from the 1970s to the 2000s. For extreme drought, it moved toward southwest, northwest, and southeast from the 1960s to the 1970s, the 1970s to the 1990s, and the 1990s to the 2000s, respectively.

3.2 Distribution of the generalized drought duration

The centers of gravity of the MGDD of various drought levels in various periods are also all distributed in the middle reached of DRB (Fig. 5). For mild drought, the center of gravity moved toward southeast, northwest, southeast, and northwest from the 1960s to the 1970s, the 1970s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively. For moderate drought, it moved toward southeast, northwest, east, and southeast from the 1960s to the 1970s, the 1970s to the 1980s, the 1980s to the

1990s, and the 1990s to the 2000s, respectively. For severe drought, the movement direction of the center of gravity is similar to mild drought, but the movement distance is short from the 1960s to the 1970s. For extreme drought, it moved toward southwest and southeast from the 1960s to the 1970s and the 1970s to the 1980s respectively, but the movement distance is short. It moved toward northwest and southeast from the 1980s to the 1990s and the 1990s to the 2000s respectively.

3.3 Distribution of the generalized drought severity

The centers of gravity of the MGDS of various drought levels in various periods are also all distributed in the middle reached of DRB (Fig. 6). For mild drought, the center of gravity moved toward southeast, northwest, southeast, and northwest from the 1960s to the 1970s, the 1970s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively. For moderate drought, it moved toward southeast, northwest, and southeast from the 1960s to the 1970s, the 1970s to the 1980s, and the 1980s to the 2000s, respectively. For severe drought, it moved toward southwest, northwest, southeast, and northwest from the 1960s to the 1970s, the 1970s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively. For extreme drought, it moved toward northwest, northeast, and southeast from the 1960s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively.

4 Discussion

Temporal distribution of drought events and spatial distribution of drought frequency (Fig. 7) simulated by the GDAI was compared with the SPI, the PDSI, and the RWD. The drought frequency was the ratio of the months or ten days of drought events occurrence and the total number of months or ten days. The month or ten days was chosen when a drought event was equal to or greater than mild drought.

4.1 The GDAI vs. the SPI

4.1.1 Temporal distribution

Figures 8 and 9 show that the results simulated by the SPI for 1 and 12 month are generally greater than the GDAI during drought periods. Though the former are changed steady and the latter are changed greatly. Figure 10 shows that the SPI for 1 month expresses wet spell in winter. The results calculated by the SPI for 1 month are greater than the GDAI during crop growth periods. The results calculated by the SPI for 12 month are also greater than the GDAI, however, their change is stable. It is difficult to evaluate the annual distribution of drought events. The GDAI and the SPI both can express the characteristic of two drought disasters happened in Lishu country in June and in Gongzhuling city in July 2000. But the results simulated by the GDAI are better than the SPI.

The differences between the GDAI and the SPI are listed as follows (Table 6). Firstly, for driving forces, the GDAI considered the influence of natural climate variability (NCV), anthropogenic climate change (ACC), underlying conditions change (UCC), and hydraulic engineering regulation (HER), though the SPI just considered the influence of NCV and ACC. Secondly, for water cycle processes and elements, the GDAI is constructed based on "natural-artificial" water cycle processes. And it considered the elements of water cycle (i.e. precipitation, evaporation, soil water, and water supply of hydraulic engineering). Though the SPI is constructed based on natural water cycle and it considered the precipitation. Thirdly, for water resources system, the GDAI considered water supply (i.e. surface water resources, groundwater resources, and soil water resources) and water demand (i.e. agricultural system and ecosystem). Though, the SPI did not consider water resources system.

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4.1.2 Spatial distribution

The drought levels of the SPI are defined according to the probability density distribution of precipitation (Huang et al., 2010). It is assumed that the drought frequency in different locations is the same. So it is difficult to express the spatial distribution of drought events (Yuan and Zhou, 2004). Figure 11 shows that the differences of drought frequency of sixty-four assessment units are little; they changed from 28 % to 34 %.

The GDAI is defined by considering water supply and water demand, as well as the characteristics of topography, soil and vegetation per assessment unit. And it also considered the irrigation water supply of hydraulic engineering. So it can express the spatial distribution of drought frequency. The drought frequency of assessment units changed from zero to 90 % (Fig. 7). The drought frequency of the upper reaches is higher. It is lower in Lishu irrigation district of the lower reaches because of the regulation of Erlongshan reservoir. Though it is higher in Shuangshan and Nanwaizi irrigation districts. Because their irrigation water supply of Erlongshan reservoir is less.

4.2 The GDAI vs. the PDSI

4.2.1 Temporal distribution

Figures 12 and 13 show that the results simulated by the PDSI are generally greater than the GDAI during drought period, especially in summer, that is, the intensity of drought of the PDSI is more serious than the GDAI. The GDAI and the PDSI both can express two drought disasters in June and July 2000. However, the results simulated by the GDAI are close to the observed drought disaster records.

The differences between the GDAI and the PDSI are listed as follows (Table 6). Firstly, for driving forces, the PDSI just considered the influence of NCV and ACC. It did not consider the influence of UCC and HER, especially the irrigation water supply. Secondly, for water cycle processes and elements, the PDSI is constructed based on natural water cycle and it considered the precipitation, evaporation, soil water, and runoff. The evaporation is estimated by Thornthwaite's method which only considered temperature and assumed that evaporation equals to zero when temperature is lower than zero. This assumption is unsuitable for DRB which temperature is low in the winter. The available moisture stored of the PDSI for the entire DRB took the same value. It did not consider the impact of different soil types. Thirdly, for water resources system, the PDSI did not consider water resources system, but the climatically appropriate for existing conditions.

The water resources shortage of the GDAI is expressed by water supply and water demand of water resources system. The GDAI considered the characteristic of natural and artificial water cycle, though the methods of drought levels and the correct index of the GDAI are similar to the PDSI. Therefore, it is more appropriate to evaluate drought events affected by human activities, especially hydraulic engineering regulation.

4.2.2 Spatial distribution

In order to compare different things at different places and at different times, Palmer assumed the climatic characteristic coefficient (K), and chose weather data of western Kansas, central Iowa, and northwestern North Dakota to correct. However, the PDSI did not consider the impact of different soil types and different underlying conditions, and the influence of human activities, especially irrigation water supply. Therefore, the differences of drought frequency of sixty-four assessment units are little; they changed from 24 to 31 %. Figure 14 shows that the results simulated by the PDSI are greater than the GDAI in Qintun irrigation area because the PDSI did not consider the regulation of Erlongshan reservoir.

4.3 The GDAI vs. the RWD

Figures 15 and 16 show that the results simulated by the RWD are generally less than the GDAI no matter inter-annual or annual. The RWD can express two drought disasters at Lishu country in June and at Gongzhuling city in July 2000, but the simulated results are more severe than the observed drought disaster records. Because the water supply of the RWD considered surface water resources and groundwater resources, and did not consider soil water resources (Table 6), however, soil water resources are important to agricultural system and ecosystem. Therefore, the results simulated by the RWD show that DRB is affected by drought for a long time, and drought frequency of sixty-four assessment units is greater. The drought frequency of the entire DRB is over 80 % (Fig. 17).

5 Conclusion

Drought is firstly a resource issue which is shortage of water resources, and with its development it transforms into a disaster issue which affects natural and socio-economic systems. The occurrences of drought events usually feature determinacy and randomness. The basic principle of natural-artificial water cycle should be followed. This study has proposed the generalized drought assessment index (GDAI) from the perspective of water resources system for assessing drought events.

To demonstrate this new drought assessment approach, a case study site on the northeast China, the Dongliao river basin which has high frequency of drought occurrences, was studied. Temporal distribution of drought events and spatial distribution of drought frequency from the GDAI were compared with the traditional approach (i.e. the SPI, the PDSI, and the RWD). The differences of them were analyzed from driving forces (i.e. NCV, ACC, UCC, and HER), water cycle elements (i.e. precipitation, evaporation, and soil water), water cycle processes (i.e. natural water cycle and artificial water cycle), water supply (i.e. surface water resources, groundwater resources, and soil water resources), and water demand (i.e. agricultural system and ecosystem).

Generalized drought times (GDT), generalized drought duration (GDD), and generalized drought severity (GDS) were calculated by theory of runs. The distribution of the centers of gravity of the GDT, the maximum GDD (MGDD), and the maximum GDS (MGDS) of various drought levels in various periods was analyzed. They were

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all distributed in the middle reached of DRB, and changed in various drought levels in various periods.

The proposed drought assessment methodology gives a water manager a tool to distinguish between natural and human effects and adapt his/her management accordingly. This would imply adapting to drought and reducing its affects.

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Table 1. Model input data and their source.

No.	Type	Name	Description
1	Digital elevation data	Elevation, slope, aspect, flow direction, digital river, catchment, etc.	1 : 250 000 national fundamental geographic information system
2	Soil data	Soil depth, soil texture, etc.	National second soil survey data 1 : 1 000 000 soil database in China Observed soil data
3	Land use data	Land use data in 1954, 1986, 2000, 2005	MODIS, TM images from 1980 to 2010
4	Meteorological and hydrological data	Precipitation, wind speed, temperature, sunshine hours, relative humidity	Observed daily meteorological data of Kaiyuan, Changling, Shuangliao, Siping, Changchun, Panshi, Qingyuan, Meihekou station
		Monthly runoff	observed and restoring monthly runoff records of Erlongshan reservoir, Wangben, Quantai hydrological station from 1956 to 2000
		Daily runoff	Observed daily runoff records of Wangben, Quantai, Liaoyuan hydrological station from 2006 to 2010
5	Hydraulic engineering data	Distribution of reservoir and irrigation	Erlongshan reservoir operation manual in 1986 Hydrological yearbook in DRB
6	Socio-economic data	Water supply, water use, water consumption, irrigation schedule, etc.	Water resources integrated planning in China in 2006 Water resources bulletin in Songliao basin from 1990 to 2010

Table 2. Comparing the simulated and observed restoring monthly runoff from 1960 to 2000.

Hydrological station	Observed restoring annual average runoff ($m^3 s^{-1}$)	simulated annual average runoff ($m^3 s^{-1}$)	Deviation (%)	Nash–Sutcliffe model efficiency coefficient	Correlation coefficient
Erlongshan reservoir	166.16	171.98	3.50	0.812	0.932
Wangben	282.99	291.20	2.90	0.775	0.900
Quantai	91.56	87.08	−4.89	0.805	0.937

Table 3. Comparing the simulated and observed monthly runoff from 1960 to 2000.

Hydrological station	Observed annual average runoff ($m^3\,s^{-1}$)	simulated annual average runoff ($m^3\,s^{-1}$)	Deviation (%)	Nash–Sutcliffe model efficiency coefficient	Correlation coefficient
Erlongshan reservoir	157.21	157.95	0.47	0.720	0.899
Wangben	226.19	238.22	5.32	0.800	0.913
Quantai	84.52	79.18	−6.32	0.830	0.937

Table 4. Comparing the simulated and observed daily runoff from 2006 to 2010.

Hydrological station	Observed annual average runoff ($m^3 s^{-1}$)	simulated annual average runoff ($m^3 s^{-1}$)	Deviation (%)	Nash–Sutcliffe model efficiency coefficient	Correlation coefficient
Wangben	181.54	186.81	2.90	0.763	0.916
Quantai	111.62	105.37	−5.60	0.754	0.923
Liaoyuan	69.23	63.76	−7.91	0.732	0.908

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Table 5. Classification of the GDAI, SPI, PDSI, and RWD.

Index	Normal or wet spell	Mild drought	Moderate drought	Severe drought	Extreme drought
GDAI	$-1.0 < \text{GDAI}$	$-2.0 < \text{GDAI} \le -1.0$	$-3.0 < \text{GDAI} \le -2.0$	$-4.0 < \text{GDAI} \le -3.0$	$\text{GDAI} \le -4.0$
SPI	$-0.5 < \text{SPI}$	$-1.0 < \text{SPI} \le -0.5$	$-1.5 < \text{SPI} \le -1.0$	$-2.0 < \text{SPI} \le -1.5$	$\text{SPI} \le -2.0$
PDSI	$-1.0 < \text{PDSI}$	$-2.0 < \text{PDSI} \le -1.0$	$-3.0 < \text{PDSI} \le -2.0$	$-4.0 < \text{PDSI} \le -3.0$	$\text{PDSI} \le -4.0$
RWD	$-1.0 < \text{RWD}$	$-2.0 < \text{RWD} \le -1.0$	$-3.0 < \text{RWD} \le -2.0$	$-4.0 < \text{RWD} \le -3.0$	$\text{RWD} \le -4.0$

Table 6. Comparing the GDAI with the SPI, the PDSI, and the RWD.

Indices		The GDAI	The SPI	The PDSI	The RWD
Driving forces		NCV, ACC, UCC, and HER	NCV and ACC	NCV and ACC	NCV, ACC, UCC, and HER
Water cycle	Processes	“Natural-artificial” water cycle	Natural water cycle	Natural water cycle	“Natural-artificial” water cycle
	Elements	Precipitation, evaporation, soil water, and water supply of hydraulic engineering	Precipitation	Precipitation, evaporation, soil water, and runoff	Precipitation, evaporation, soil water, and water supply of hydraulic engineering
Water resources	Water supply	Surface water resources, groundwater resources, and soil water resources	–	–	Surface water resources and groundwater resources
	Water demand	Agricultural system and ecosystem	–	–	Agricultural system and ecosystem

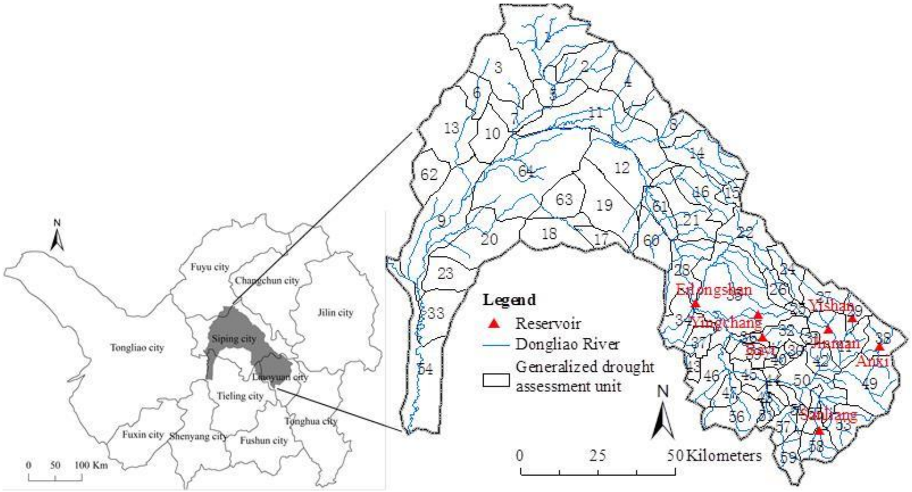

Figure 1. Location of study area.

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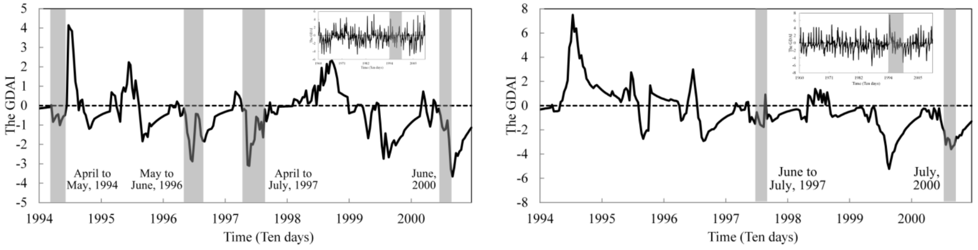

(a) Lishu county

(b) Gongzhuling city

Figure 2. Compared the results evaluated by the GDAI and the observed drought disaster records (1960∼ 2010). Note: parts in gray were the periods of the observed drought disaster records.

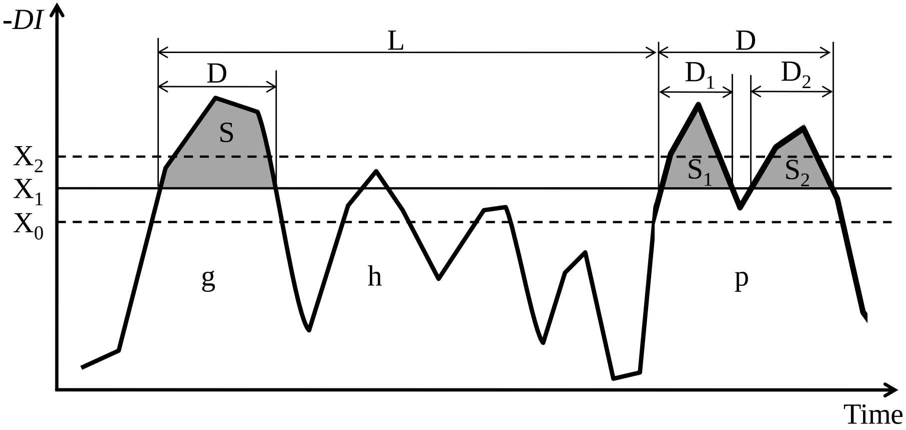

Figure 3. Recognition methods of GDD and GDS. Note: L is drought inter-arrival time between $(n+1)$th drought and nth drought.

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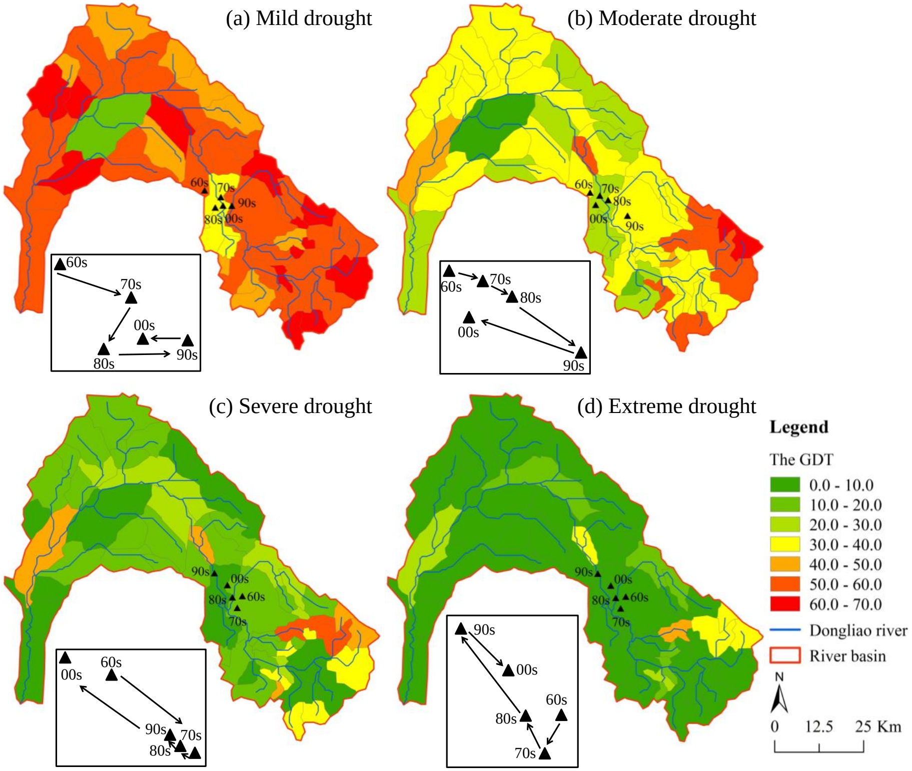

Figure 4. Spatial distribution of the GDT of different drought levels in various periods.

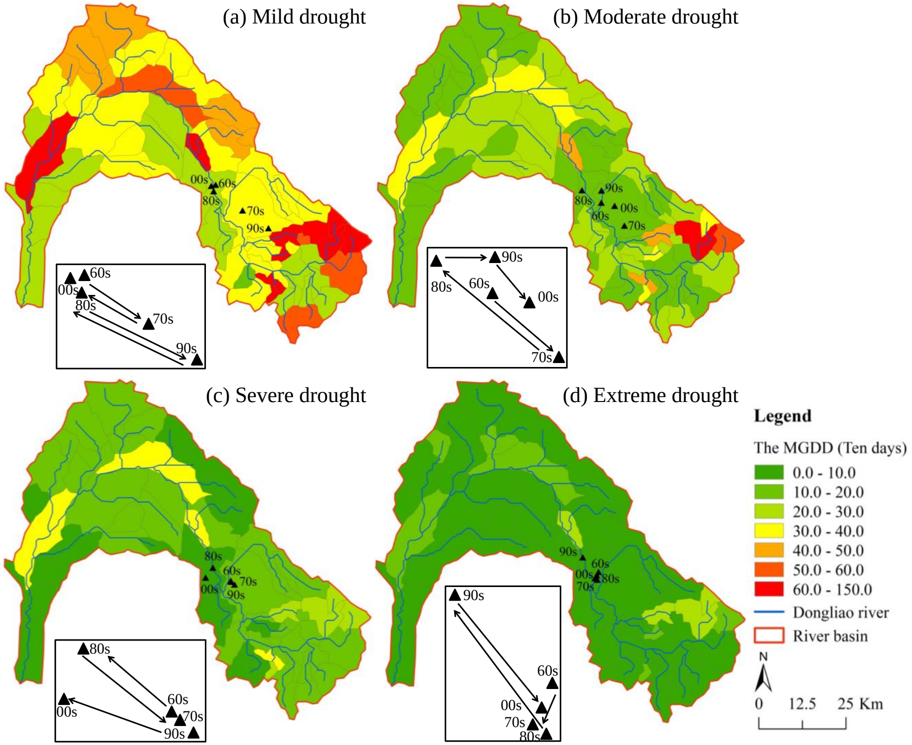

Figure 5. Spatial distribution of the MGDD of different drought levels in various periods.

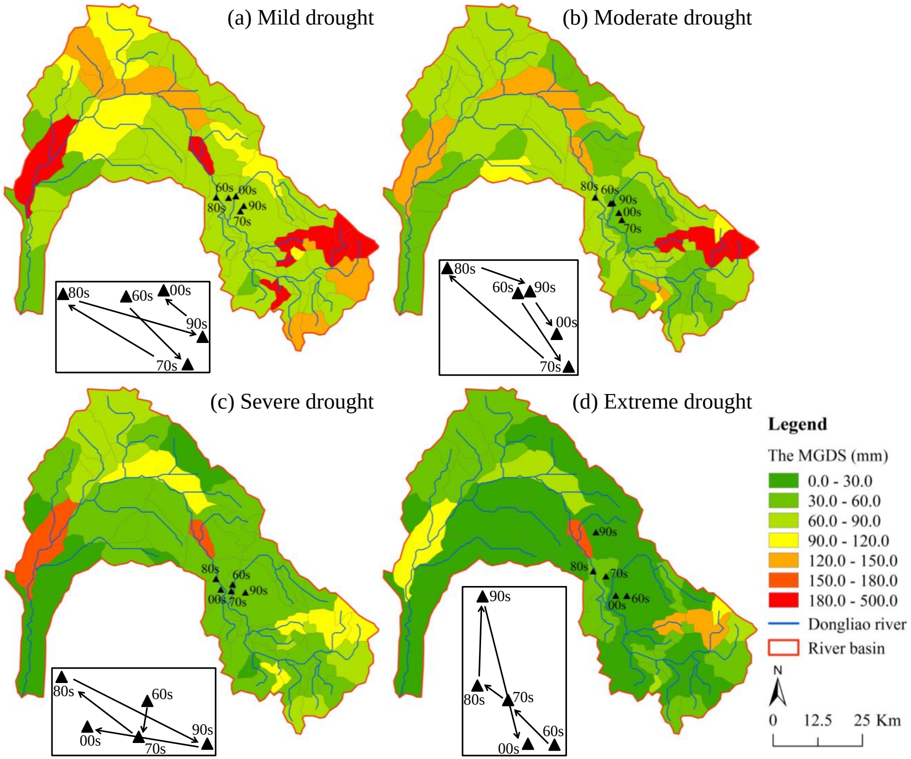

Figure 6. Spatial distribution of the MGDS of different drought levels in various periods.

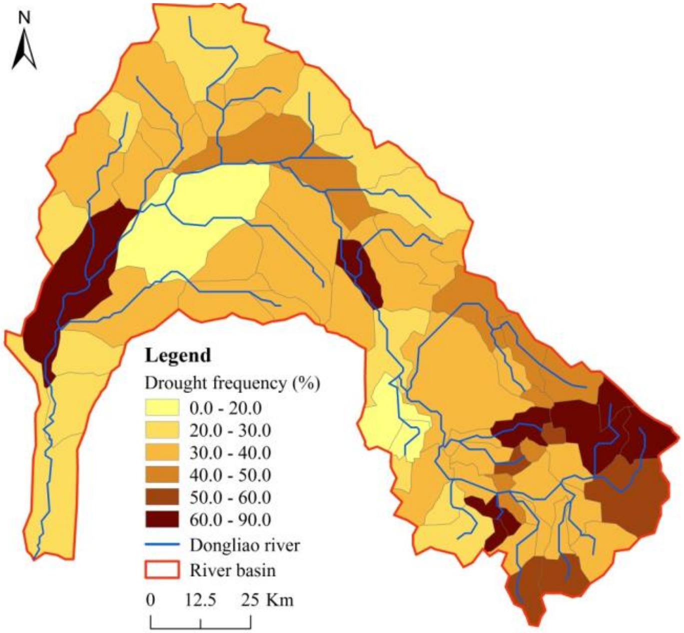

Figure 7. Spatial distribution of drought frequency simulated by the GDAI in DRB.

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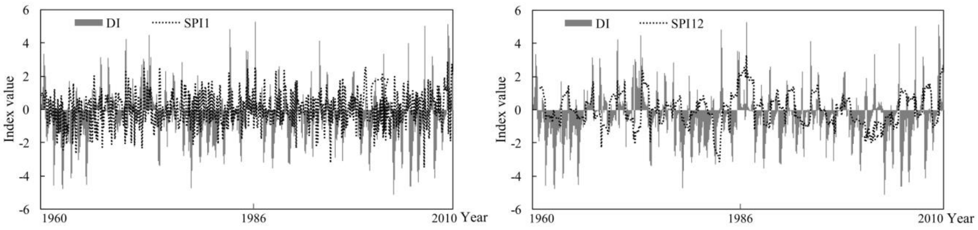

(a) The GDAI versus the SPI for 1-month

(b) The GDAI versus the SPI for 12-month

Figure 8. Compared the GDAI with the SPI in Lishu country from 1960 to 2010.

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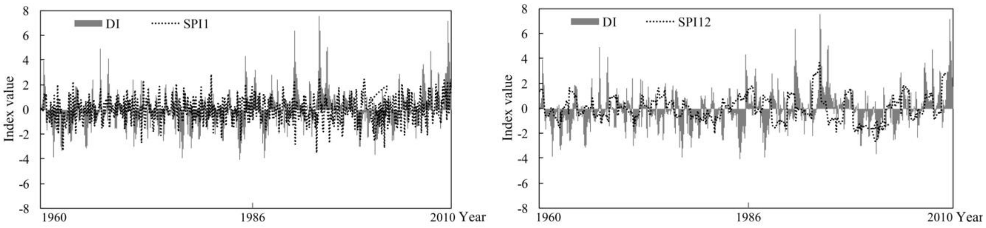
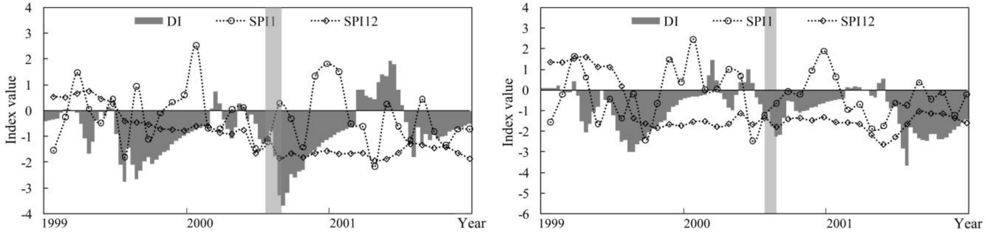


(a) The GDAI versus the SPI for 1-month

(b) The GDAI versus the SPI for 12-month

Figure 9. Compared the GDAI with the SPI in Gongzhuling city from 1960 to 2010.



(a) Lishu country

(b) Gongzhuling city

Figure 10. Compared the GDAI with the SPI from 1999 to 2001.

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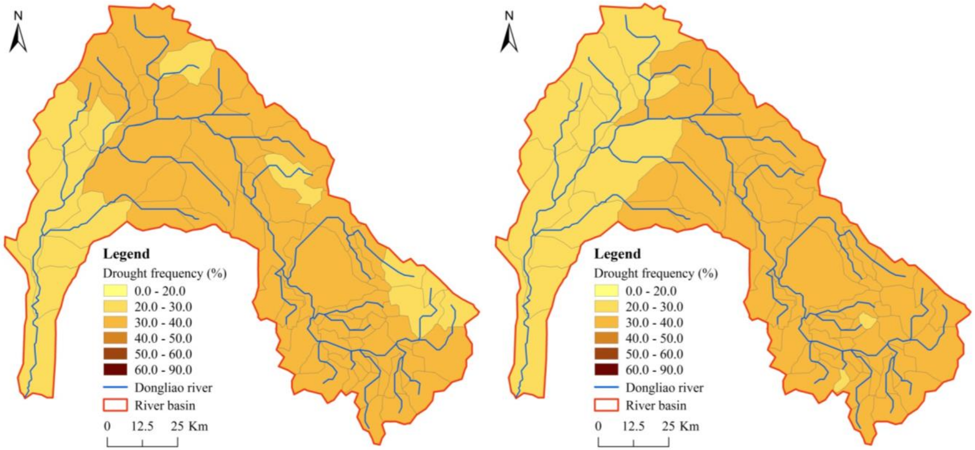
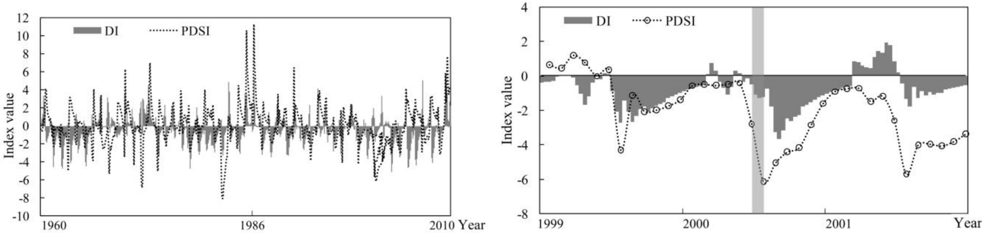


(a) The SPI for 1-month **(b) The SPI for 12-month**

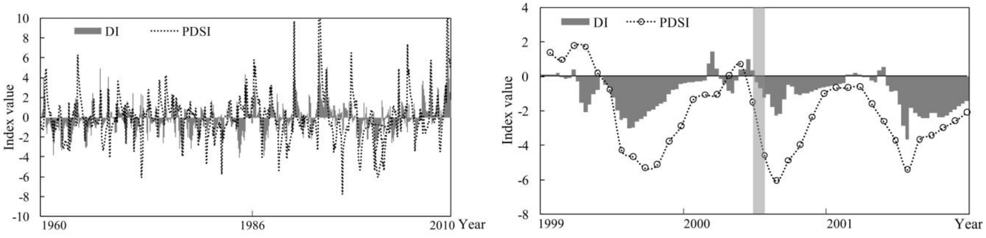
Figure 11. Spatial distribution of drought frequency simulated by the SPI in DRB.



(a) 1960 to 2010

(b) 1999 to 2001

Figure 12. Compared the GDAI with the PDSI in Lishu country.



(a) 1960 to 2010

(b) 1999 to 2001

Figure 13. Compared the GDAI with the PDSI in Gongzhuling city.

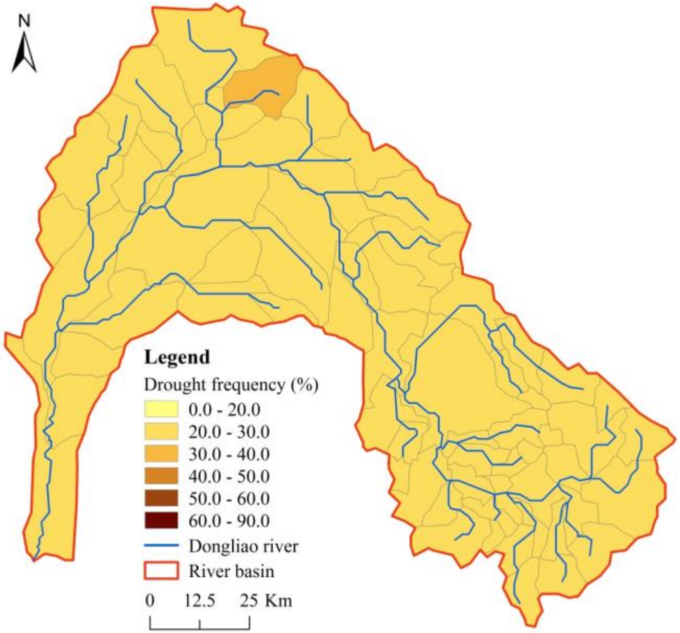
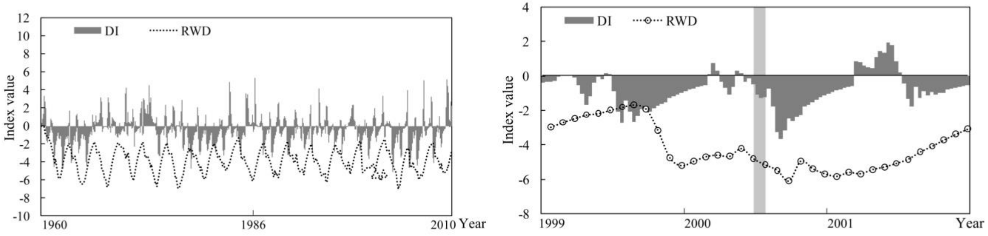


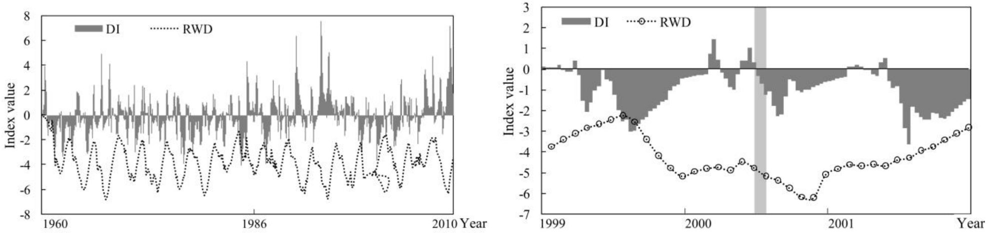
Figure 14. Spatial distribution of drought frequency simulated by the PDSI in DRB.



(a) 1960 to 2010

(b) 1999 to 2001

Figure 15. Compared the GDAI with the RWD in Lishu country.



(a) 1960 to 2010 **(b) 1999 to 2001**

Figure 16. Compared the GDAI with the RWD in Gongzhuling city.

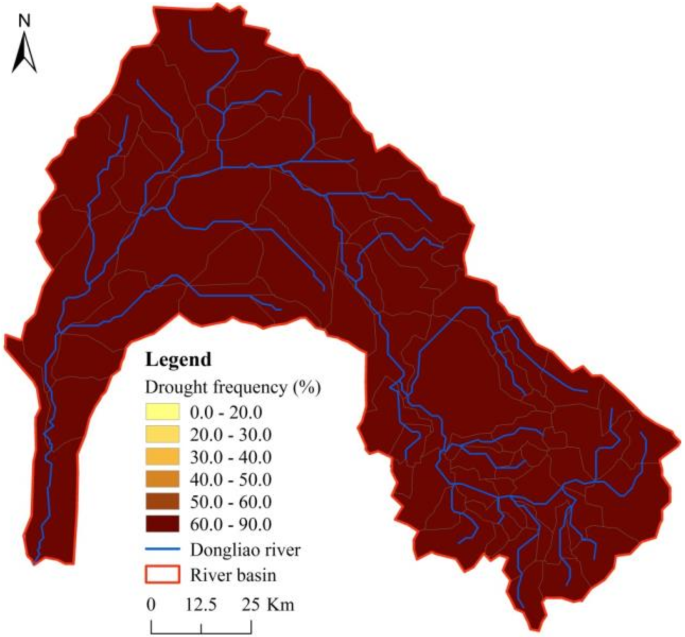


Figure 17. Spatial distribution of drought frequency simulated by the RWD in DRB.