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Drought assessment in the Dongliao River basin: traditional approaches vs. generalized drought assessment index based on water resources systems

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Abstract. Drought is firstly a resource issue, and with its development it evolves into a disaster issue. Drought events usually occur in a determinate but a random manner. Drought has become one of the major factors to affect sustainable socioeconomic development. In this paper, we propose the generalized drought assessment index (GDAI) based on water resources systems 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 in northeastern China. The results simulated by the GDAI are compared to observed drought disaster records in the Dongliao River basin. In addition, the temporal distribution of drought events and the spatial distribution of drought frequency from the GDAI are compared with the traditional approaches in general (i.e., standard precipitation index, Palmer drought severity index and rate of water deficit index). Then, generalized drought times, generalized drought duration, and generalized drought severity were calculated by theory of runs. Application of said runs at various drought levels (i.e., mild drought, moderate drought, severe drought, and extreme drought) during the period 1960–2010 shows that the centers of gravity of them all distribute in the middle reaches of Dongliao River basin, and change with time. The proposed methodology may help water managers in water-stressed regions to quantify the impact of drought, and consequently, to make decisions for coping with drought.

1 Introduction

With the increasing impact of climate change and anthropogenic activities, droughts happen in more areas with higher frequency. Since the 1990s, drought disasters have caused more than 11 million deaths and affected more than 2 billion people on the global level (United Nations International Strategy for Disaster Reduction Secretariat, 2009). Since the 1970s, the areas where droughts happened (PDSI < -3) have increased by 1.5 times in the world (Dai et al., 2004). The probability of drought events that 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 Quesna et al., 2009). The average annual economic losses that resulted from drought disasters in the US range from 6 to 8 billion dollars. That amount 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, which is mainly characterized by global warming, the stability of the climate system is declining, and the impacts of drought and other extreme climate events are increasing (Dai, 2011). The *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; the United States, southern Europe, southeastern Asia, Brazil, Chile, Australia, and Africa as well as other countries and regions would be affected by persistent drought severely (Intergovernmental Panel on Climate Change, 2012).

The drought occurrence and intensity in China demonstrate an increasing tendency which is similar to the global trend. The drought problem has become more and more prominent (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, as shown by historical records. Drought disasters which happened from 1500 to 1730 and from 1900 until the present day have a very wide spatial distribution (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 where crop yields decreased by over 10 % more than normal annual yields) and damaged areas (the areas where 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 northern China, where water resources are short, but also in southern China, where water resources are relatively abundant. In recent years, several extreme drought events happened frequently in China (Qin, 2009), such as the droughts that occurred in Sichuan and Chongqing in 2006 (Qin, 2009), the drought that occurred in the winter wheat region in northern China in 2008 (Qin, 2009), the drought that occurred in southern China in 2009 (Weng and Yan, 2010) and the drought that occurred in the middle and lower reaches of the Yangtze River in 2011.

The drought has become one of the major factors affecting sustainable socioeconomic development. Government departments, the public and researchers have paid more attention to the evolutionary rules and driving mechanism of drought in the changing environment, as well as corresponding strategies to cope with it. In addition, it is one of the emerging issues and hot topics in the field of hydrology and water resources (State Flood Control and Drought Relief Headquarters, 2010).

Drought is firstly a resource issue for its shortage of water resources, but as it develops it evolves into a disaster issue. Drought is one of the extreme events in water cycle. Its evolution is affected by the characteristics of water cycle in a particular region or basin. It is characterized by the shortage of water resources resulting from the subnormal precipitation continuously. It should follow the principle of taking both natural water cycle and artificial water cycle into account in order to cope with droughts (Yan et al., 2014).

Since 1900, a number of indices have been developed to quantify a drought, and they could be classified into three stages.

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

2. During the second stage (1965–1992), drought indices could also be divided into four types. Firstly, they were also proposed based on the precipitation records, such as the precipitation anomaly percentage index (National Meteorological Center of CMA, 1972), the drought area index (Bhalme and Mooley, 1980) as well as the positive and negative anomaly index (Liu and Wei, 1989). Secondly, they were produced based on the runoff records, such as the hydrological drought severity index (Dracup et al., 1980a, b) and the 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 put forward based on the soil water balance principle, such as the Palmer drought severity index (Palmer, 1965, 1967) and the Palmer revised surface-water supply index (Garen, 1993). Drought indices in this stage were established based on multiple factors. Drought indices in this stage considered water cycle elements and processes with some physical mechanism to some degree.

3. During the third stage (1993 till now), with the development of computers and hydrological models, drought indices not only contained multiple factors of the 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 (Serinaldi 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 the comprehensive drought index (GB/T 20481-2006, 2006) and the meteorological drought index (Yan et al., 2009). Secondly, they were proposed based on a distributed hydrological model (Xu et al., 2008), such

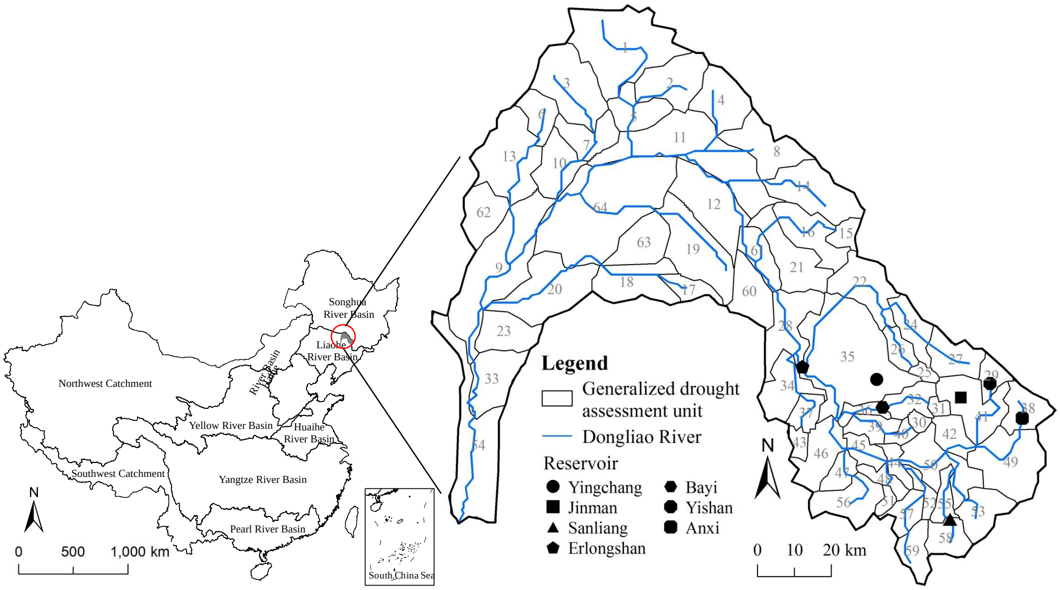

Figure 1. Location of study area. Note: the numbers (1–64) present the assessment units. We divide the Dongliao River basin into 64 assessment units. The methods are as the following. Firstly, it is divided by the location of reservoirs in main stream (i.e., the Erlongshan Reservoir) and the layout of the upper, middle and lower reaches of the basin (i.e., the three segments of the Dongliao River basin). Secondly, it is divided by the location of reservoirs (i.e., the Bayi Reservoir, the Jinman Reservoir et al.) or other main hydraulic engineering in tributary streams. Lastly, it is divided by the irrigation areas with considering the various crop planting structures.

as the Palmer drought severity index, which is based on a geomorphology-based hydrological model. Thirdly, they were created based on remote sensing, such as the vegetation–temperature condition index (Wang et al., 2001), the temperature–vegetation dryness index (Sandholt et al., 2002), the vegetation supply water index (Mo et al., 2006), the perpendicular drought index (Ghulam et al., 2007a, b), the standard vegetation index (Peters et al., 2002), the short-wave infrared perpendicular water stress index (Ghulam et al., 2007c).

In light of the advantages and disadvantages of the above indicators (Table 1), we propose the generalized drought assessment index (GDAI) based on water resources systems for assessing drought events.

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

2 Methodology

2.1 Case study

The Dongliao River basin (DRB) is located in northeastern China. It covers an area of 11 306 km^2 (Fig. 1). It is roughly divided into three segments. The upper reaches are the segment above Erlongshan Reservoir, which is a low-mountain and hilly area with an altitude from 200 to 600 m, primarily consisting of dark brown soil and planosol; the middle reaches are the segment from Erlongshan Reservoir downwards to Chengzishang Hydrological Station, which is a hilly area with an altitude from 100 to 300 m, mainly including black soil and meadow soil; the lower reaches are the segment from Chengzishang Hydrological Station downwards to the Sanjiangkou iron bridge on the Siping–Qiqihar railway line, which is a plain area with an altitude from 0m to 200 m, primarily consisting of meadow soil, salinized chernozem soil and steppe aeolian sandy soil.

The DRB is controlled by the Pacific low pressure and Siberian high pressure with four distinctive seasons. The precipitation decreases from the upper to lower reaches. The multi-year average precipitation is reduced from 710 to 450 mm from 1960 to 2011. It is distributed unevenly within the year. It accounts for 75 % of annual precipitation from June to September. It accounts for 50 % in July and August. Inter-annual precipitation change decreases from west to east. The temperature decreases from southwest to northwest. The multi-year average temperature decreases from

Table 1. Advantages and disadvantages of the common drought indices.

Name	Main parameters	Advantages	Disadvantages	Reference
Munger	Precipitation	Higher sensitivity and suitable for short-term drought	Mainly used for forest fire warning, but seldom used in agriculture and others	Munger (1916)
Kincer	Precipitation	Emphasizing seasonal distribution of precipitation and considering the climate of annual precipitation	Only considering precipitation, but not the universality	Kincer (1919)
Marcovitch	Precipitation temperature	Considering total days and precipitation at the same time and higher than 32.2 °C in summer	Not being universal	Marcovitch (1930)
Blumenstock	Precipitation	Higher sensitivity and suitable for short-term drought	Not being universal	Blumenstock (1942)
Antecedent Precipitation Index	Precipitation	Wide application	Subjective parameter determination	McQuigg (1954)
Moisture Adequacy Index	Evapotranspiration	Considering the water balance, soil characteristics and crop growths	Much data needed; complex computation	McGuire and Palmer (1957)
Palmer Drought Severity Index	Precipitation Evapotranspiration Runoff et al.	Considering rainfall, latent evaporation, antecedent soil moisture and runoff; quickly reflecting the change of soil moisture	Complex computation	Palmer (1965)
Keetch–Byram Index	Precipitation Temperature Land use	Considering precipitation, temperature and land use at the same time; effectively determining the onset of drought; reflecting the cumulative effects of drought by recurrence method	No distinguishing between soil texture and climate conditions	Keetch and Byram (1968)
Drought Area Index	Precipitation	Simple calculation; eliminating differences caused by different climate types; effectively reflecting regional and seasonal scales of the water status	Considering the precipitation as normal distribution without considering the evaporation and land use	Bhalme and Mooley (1980)
Hydrological Drought Severity Index	Runoff	Analyzing the time integral flow of concrete section of the river	Low resolution	Dracup et al. (1980a, b)
Surface Water Supply Index	Runoff Water supply	Representing water supply conditions for different hydrological zones	Complex analysis due to necessary consideration of the probability distribution change and the weight of each factor	Shafer and Dezman (1982)
Standard Precipitation Index	Precipitation	Quantifying the impacts of different precipitation shortages to different water resources on different time scales	Assuming that droughts in all sites occurred with the same frequency, so spatial distribution features cannot be identified	McKee et al. (1993)
Temperature and Vegetation Index	Surface temperature Normalized differential vegetation index	Directly obtaining the parameters from the image data; simple and convenient calculation	Only representing the relative values of the same image moisture state but not comparable in time	Sandholt et al. (2002)
Meteorological Drought Index	Precipitation Temperature	Combing the advantages of SPI and PDSI	Neither reflecting the relationship between drought disaster area and runoff nor considering ecosystem and economic environment	Yan et al. (2009)
Palmer wetland drought index	Precipitation Surface inflow Evapotranspiration Outflow The amount of water stored in the wetlands	Being suitable to evaluate wetland drought caused by the integrated effects of precipitation, surface inflow, and water volume, especially that influenced strongly by human activities	Complex computation; being not of universality; much data needed	Yuan et al. (2014)

6.7 to 5.6° (1960–2011). The evaporation increases from upper to lower reaches. The multi-year average evaporation changes from 850 to 1200 mm (1960–2011). The runoff decreases from upper to lower reaches. The multi-year average runoff decreases from 150 to 25 mm (1960–2011), with that from June to September taking up 80 % of annual runoff.

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 reduced by 10 % during 11 May to 12 June 1996. They were 1133 km^2 which accounted for 63 % from 21 April to 16 May 1997. They accounted for 88 % until 30 July 1997. They were 2440 km^2 from 1 to 28 June 2000. The yields were reduced by 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 and 30 July 1997. They were 667 km^2 which accounted for 70 % during 2 and 20 July 2000.

2.2 The water and energy transfer process model in the DRB

The water and energy transfer process (WEP) model (Jia et al., 2001) is chosen to simulate the elements of natural and artificial water cycle in the DRB, and then to calculate the water supply and water demand of the assessment units based on water resources systems. The WEP model has been successfully applied in several watersheds in Japan, Korea, and China with different climate and geographic conditions (Jia and Tamai, 1998; Jia et al., 2001, 2002, 2004, 2005; Kim et al., 2005; Qiu et al., 2006).

2.2.1 Model input

The WEP model has the following main characteristics: (1) combining modeling of hydrological processes and energy transfer processes; (2) considering the land use heterogeneity inside a computation unit by adopting the mosaic method; and (3) incorporating the runoff generation theory of various source areas into the model through a numerical simulation in groundwater flows to directly reflect the topography's effects in runoff generation, thus capable of modeling infiltration excess, saturation excess and mixed runoff generation mechanism (Jia et al., 2006).

The WEP model consists of the vertical structure within a grid cell and the horizontal structure within a watershed. Each grid cell in the vertical direction, from top to bottom, includes nine layers, namely an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer and two confined aquifers. Land use is divided into five groups, namely the soil vegetation (SV) group, the non-irrigated farmland (NF) group, the irrigated farmland (IF) group, the water body (WB) group, and the impervious area (IA) group. The SV group is further classified into bare soil land, tall vegetation (forest or urban trees) and short vegetation (grassland). The IA group consists of impervious urban cover, urban canopy and rocky mountain (Jia et al., 2006).

The simulated hydrological processes include snow melting, evapotranspiration, infiltration, surface runoff, subsurface runoff, groundwater flow, overland flow, river flow and water use. The simulated energy transfer processes include short-wave radiation, long-wave radiation, latent heat flux, sensible heat flux, and soil heat flux. Adopted modeling approaches for hydrological and energy processes are referenced in Jia et al. (2001); snow-melting processes and water-use processes are not.

WEP-DRB model input data consists of six types: digital elevation data, soil data, land use data, meteorological and hydrological data, hydraulic engineering data, and socioeconomic data (Table 2). They are treated by spatial interpolation and formatting before applying the model.

2.2.2 Model verification and validation

The DRB is divided into 11 catchments and 64 assessment units. The simulated time step of the WEP–DRB model is 1 day. Firstly, the WEP–DRB model is verified by using observed and restored monthly runoff records from the Erlongshan Reservoir and the Wangben and Quantai hydrological stations from 1956 to 2000. The warm-up period is from 1956 to 1959, and the verified period is from 1960 to 2000. Secondly, the WEP–DRB model is validated by using observed daily runoff records from the Wangben, Quantai, and Liaoyuan hydrological stations 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 restored monthly runoff from 1960 to 2000 (Table 3), the result shows that the maximum deviation is −4.89 % at the Quantai Hydrological Station and the minimum is 2.90 % at the Wangben Hydrological Station. Nash–Sutcliffe model efficiency coefficients are all over 0.70, and they range up to 0.812 at the Erlongshan Reservoir Hydrological Station. Comparing the simulated and observed monthly runoff from 1960 to 2000 (Table 4), the result shows that the maximum deviation is −6.32 % in Quantai Hydrological Station and the minimum is 0.47 % at the Erlongshan Reservoir Hydrological Station. Nash–Sutcliffe model efficiency coefficients are all over 0.70, and they range up to 0.830 at the Quantai Hydrological Station. Comparing the simulated and observed daily runoff from 2006 to 2010 (Table 5), the result shows that the maximum deviation is −7.91 % in Liaoyuan Hydrological Station and the minimum is 2.90 % at the Wangben Hydrological Station. Nash–Sutcliffe model efficiency coef-

Table 2. Model input data and their source.

No.	Type	Name	Description	Center
1	Digital elevation data	Elevation, slope, aspect, flow direction, digital river, catchment, etc.	1 : 250 000 national fundamental geographic information system	National Geomatics Center of China
2	Soil data	Soil depth, soil texture, etc.	1 : 1 000 000 soil database in China Observed soil data	National Second Soil Survey China Soil Scientific Database (http://www.soil.csdb.cn/)
3	Land use data	Land use data in 1954, 1986, 2000, 2005	MODIS, TM images from 1980 to 2010	Institute of Geographic Sciences and Natural Resources Research
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 stations	China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn)
		Monthly runoff	Observed and restored monthly runoff records from the Erlongshan Reservoir and the Wangben and Quantai hydrological stations from 1956 to 2000	Dongliao Water Resources Commission, Ministry of Water Resources
		Daily runoff	Observed daily runoff records from the Wangben, Quantai and Liaoyuan hydrological stations from 2006 to 2010	
5	Hydraulic engineering data	Distribution of reservoir and irrigation	Erlongshan reservoir operation manual in 1986 Hydrological yearbook in the DRB	Dongliao Water Resources Commission, Ministry of Water Resources
6	Socioeconomic data	Water supply, water use, water consumption, irrigation schedule, etc.	Water resources integrated planning in China in 2006 Water resources bulletin in the Dongliao Basin from 1990 to 2010	Dongliao Water Resources Commission, Ministry of Water Resources

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

Hydrological station	Observed restored 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

Note: The Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. It is defined as

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})^2},$$

where Q_o is the mean of observed discharges, and Q_m is modeled discharge. Q_o^t is observed discharge at time t. Its definition is identical to the coefficient of determination R^2 used in linear regression.

ficients are also all over 0.70, and they range up to 0.763 at the Wangben Hydrological Station.

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

2.3 Generalized drought assessment index

The DRB is an important production base of commodity grain. The cultivated land and forest land account for 88.03 % of its total watershed area. Therefore, agricultural system and ecosystem in the 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 the DRB. The water resources shortage D is

$$D = \mathrm{SW} - \mathrm{DW}. \tag{1}$$

In order to let Eq. (1) be used to compare water resources shortage in different assessment units and different assessment periods, the climatic characteristic coefficient K is considered here by referring to 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 average water demand of 10 days; $\overline{\mathrm{SW}}$ is the average water supply of 10 days; $\overline{|D|}$ 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 (generalized drought assessment index) is

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

where DI(i), $Z(i)$ is the DI , Z for the ith 10 days, respectively; DI($i-1$) is the DI for the ($i-1$)th 10 days. The classification of drought (wet) still follows the standard of Palmer drought severity index (Palmer, 1965), as shown in Table 6.

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 the DRB.

Comparing the results evaluated by the 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 the DRB.

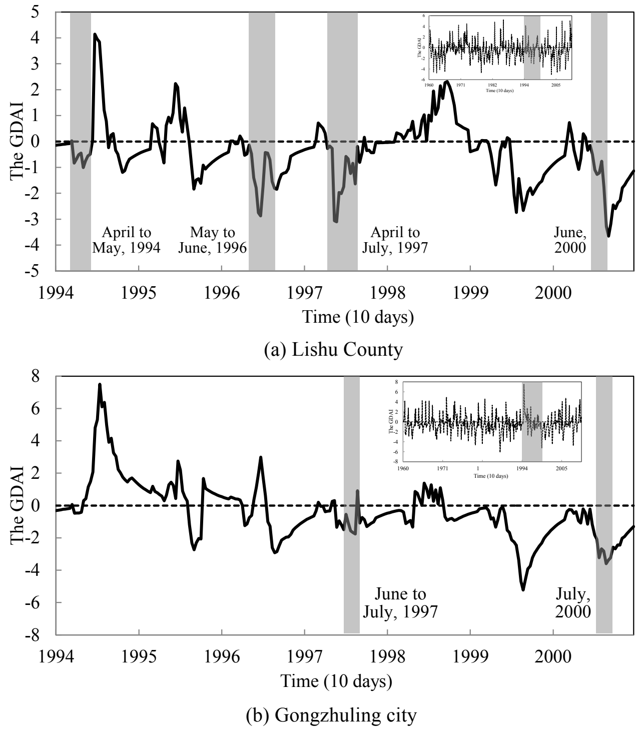

Figure 2. Compared the results evaluated by the GDAI and the observed drought disaster records (1960–2010). Note: parts in gray were the periods of the observed drought disaster records.

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., 1980a; Feng and Zhu, 1997). The generalized drought duration DD is expressed in 10 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 using the 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 DD_1 and DD_2, say $\mathrm{DD} = \mathrm{DD}_1 + \mathrm{DD}_2 + 1$, $S = S_1 + S_2$. More details can be found in the studies by Lu et al. (2010).

Table 4. 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 5. 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

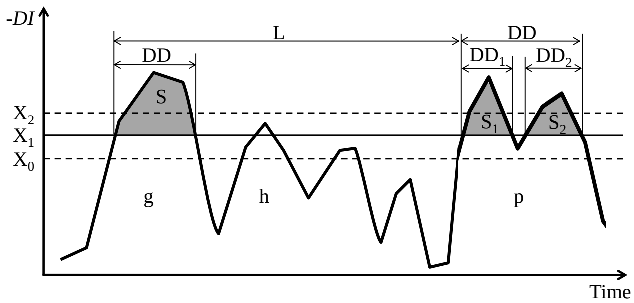

Figure 3. Recognition methods of GDD and GDS. Note: L is drought inter-arrival time between $(n+1)$th drought and nth drought.

2.5 SPI, PDSI and RWD

The GDAI is constructed based on the elements of water resources systems and the "natural–artificial" dualistic water cycle which includes natural water cycle and artificial water cycle. It is evaluated by comparing with the standard precipitation index (SPI), the Palmer drought severity index (PDSI) and the rate of water deficit index (RWD).

The SPI for 1- and 12-month time scales, the PDSI for 1-month, and the RWD for 1–10 days of 64 assessment units from 1960 to 2010 are calculated. The inter-annual differences between the results assessed by the GDAI, the SPI, the PDSI, and the RWD are compared. Moreover, the annual difference is also compared from 1999 to 2001 because drought disasters have occurred continuously in the DRB during 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 (0–20 cm) at the beginning of the month is 40 mm, and the available moisture stored in underlying levels (20–100 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.

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 equal to the minimum of average GDT of 64 assessment units in 5 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 were greater than or equal to the minimum of average MGDD or MGDS of 64 assessment units in 5 decades. Then, their centers of gravity were calculated.

Table 6. Classification of the GDAI, SPI, PDSI, and RWD.

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

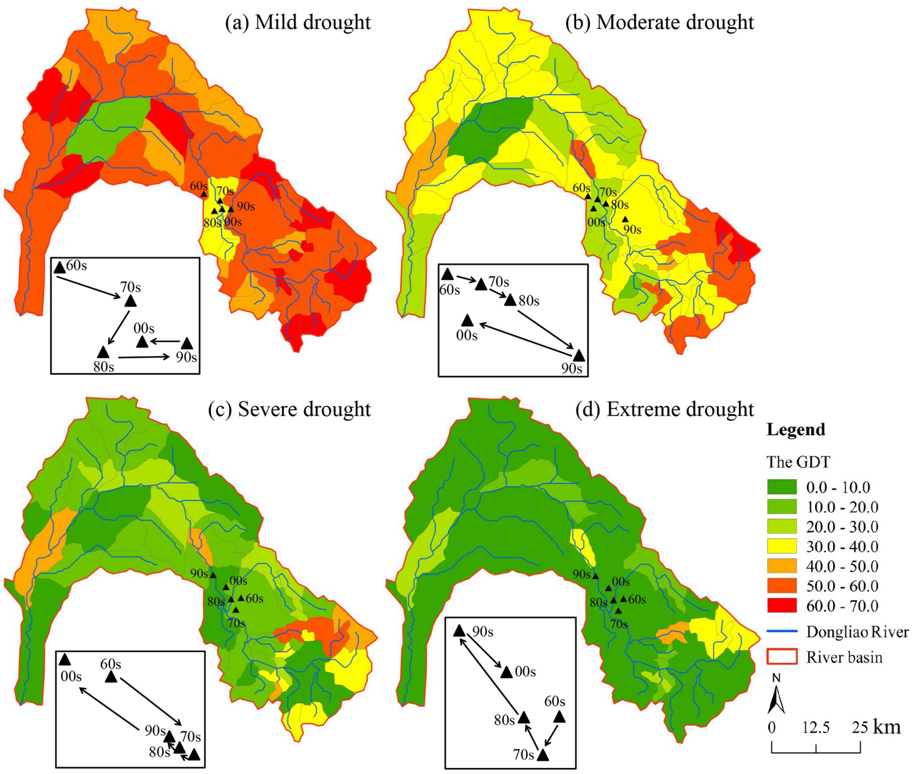

Figure 4. Spatial distribution of the GDT of different drought levels in various periods.

3 Results

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 reaches of the DRB (near Erlongshan Reservoir) (Fig. 4). For mild drought, the center of gravity moved toward the 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 the southwest, east, and west from the 1970s to the 1980s, the 1980s to the 1990s, and the 1990s to the 2000s, respectively. For a 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 a severe drought, it moved toward southeast from the 1960s to the 1970s, then toward northwest from the 1970s to the 2000s. For an 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 the 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 a 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 a severe drought,

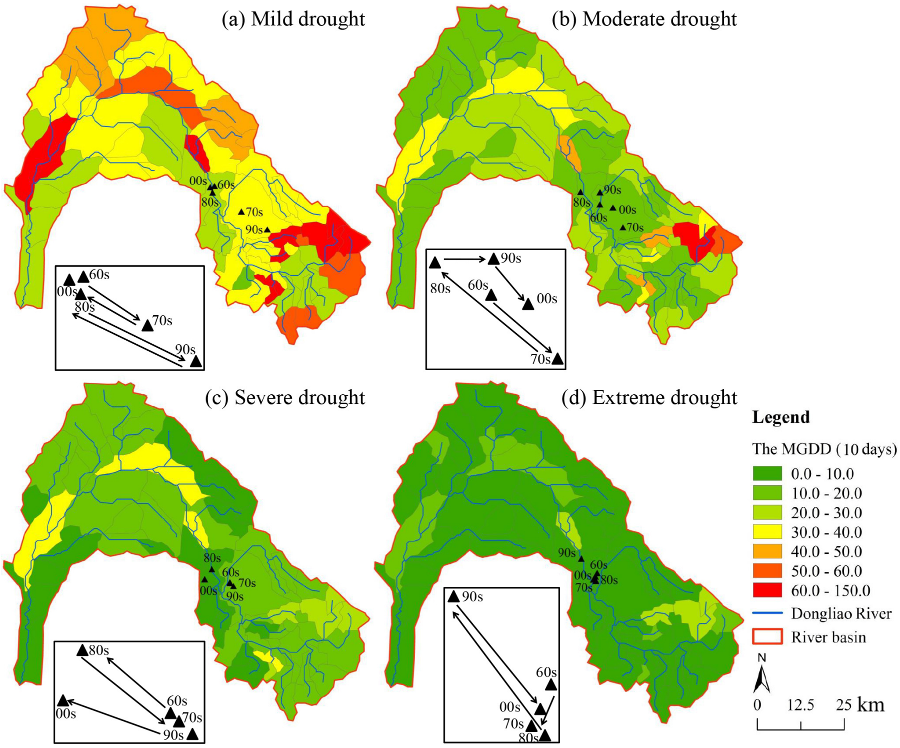

Figure 5. Spatial distribution of the MGDD of different drought levels in various periods.

the movement direction of the center of gravity is similar to a mild drought, but the movement distance is short from the 1960s to the 1970s. For an 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 reaches of the DRB (Fig. 6). For a 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 a 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 a 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 an 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 were compared with the SPI, the PDSI, and the RWD. The drought frequency was the ratio of the months or 10 days of drought event occurrence and the total number of months or 10 days. The month or 10 days was chosen when a drought event was equal to or greater than a mild drought.

4.1 The GDAI versus the SPI

4.1.1 Temporal distribution

Figures 8 and 9 shows that the results simulated by the SPI for 1- and 12-month are generally greater than the GDAI during drought periods. Though the former change steadily and the latter change greatly. Figure 10 shows that the SPI for 1 month expresses wet spells 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 months 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 characteristics of two drought disasters which happened in Lishu County in June and in Gongzhuling City in July 2000. But the results simulated by the GDAI are better than the SPI.

Table 7. 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 elements	"Natural–artificial" water cycle Precipitation, evaporation, soil water, and water supply of hydraulic engineering	Natural water cycle Precipitation	Natural water cycle Precipitation, evaporation, soil water, and runoff	"Natural-artificial" water cycle 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

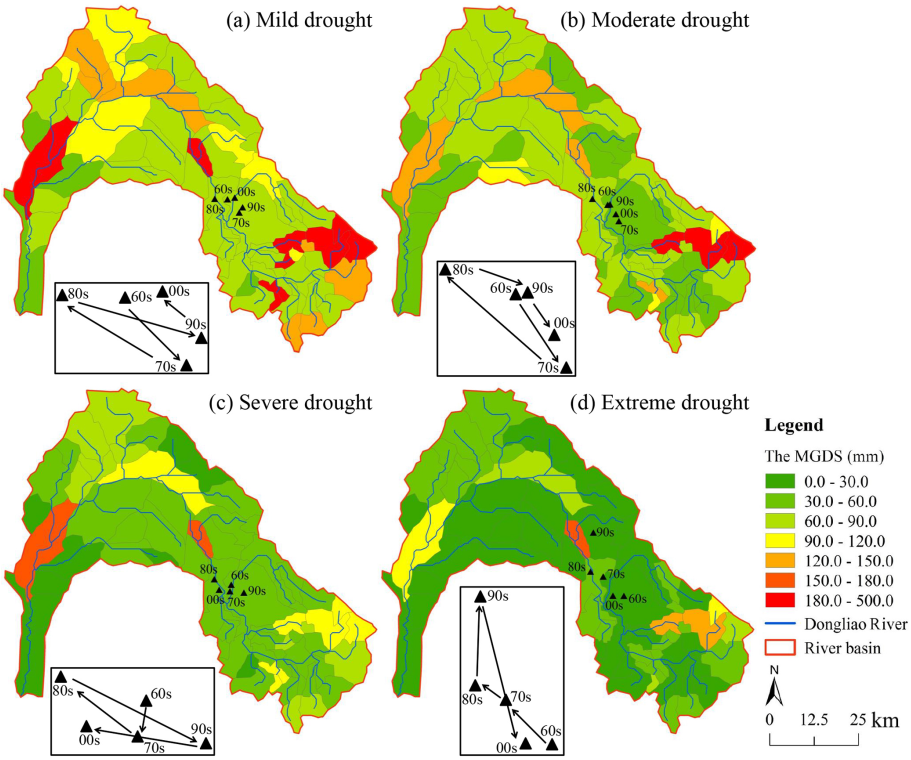

Figure 6. Spatial distribution of the MGDS of different drought levels in various periods.

The differences between the GDAI and the SPI are listed as follows (Table 7). 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), while 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 the natural water cycle and it considered the precipitation. Thirdly, for water resources systems, 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 systems.

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, 2004a). Fig-

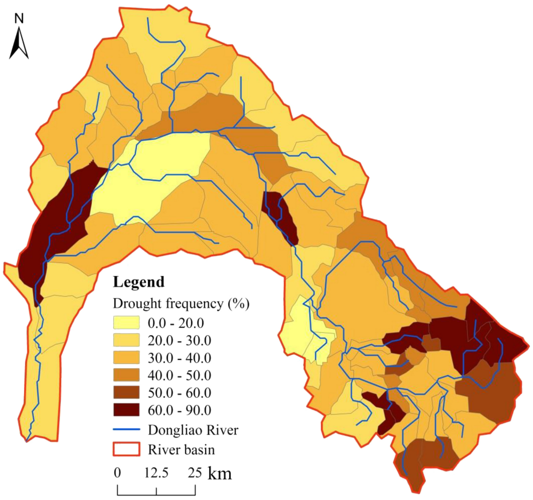

Figure 7. Spatial distribution of drought frequency simulated by the GDAI in the DRB.

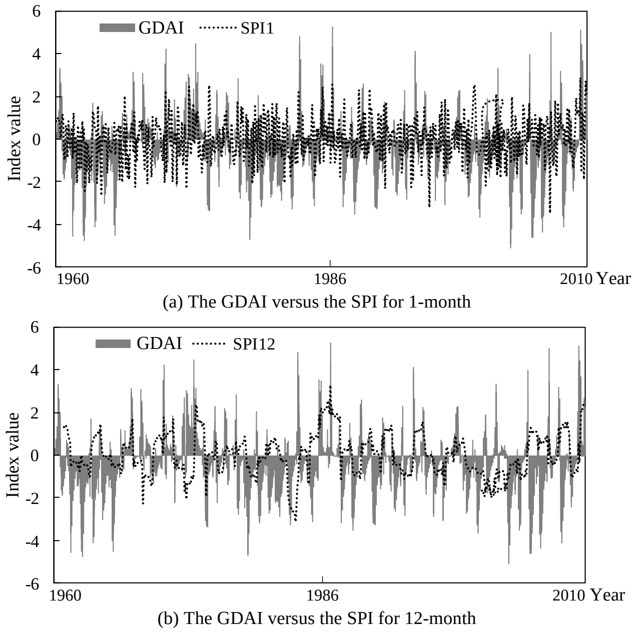

Figure 8. Compared the GDAI with the SPI in Lishu County from 1960 to 2010.

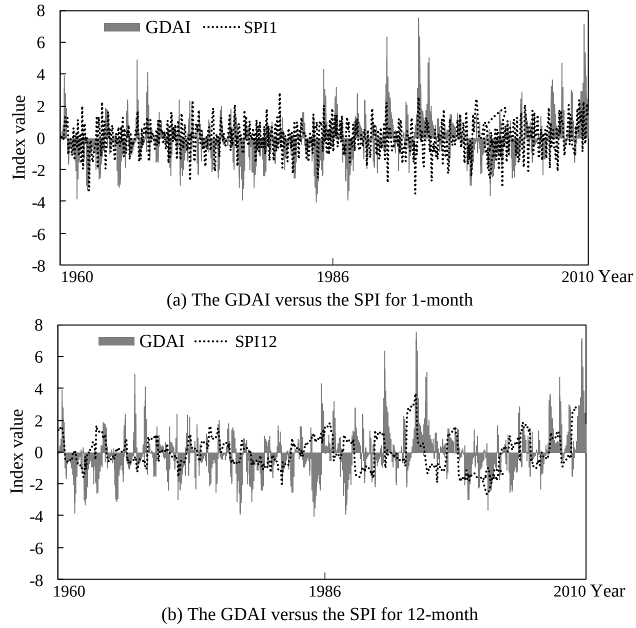

Figure 9. Compared the GDAI with the SPI in Gongzhuling city from 1960 to 2010.

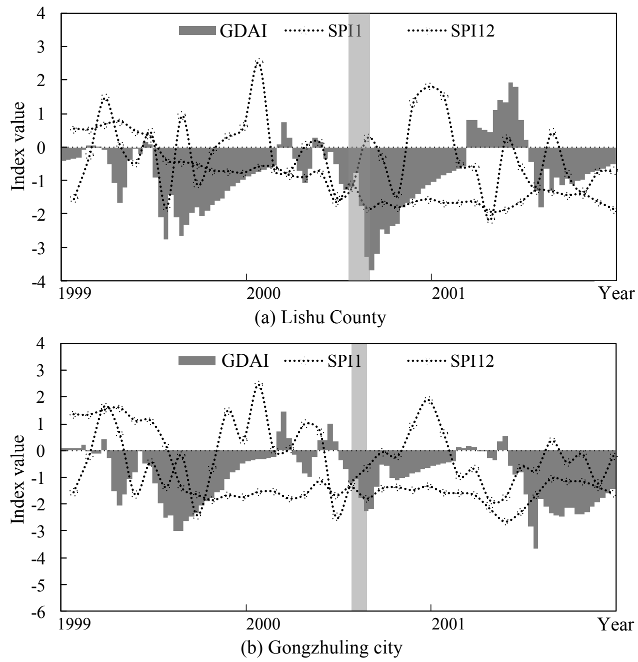

Figure 10. Compared the GDAI with the SPI from 1999 to 2001.

ure 11 shows that the differences of drought frequency of 64 assessment units are small, changing only 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 in the upper reaches of the Lishu irrigation district is higher, and lower in the lower reaches because of the regulation of the Erlongshan Reservoir. But it is higher in Shuangshan and Nanwaizi irrigation districts since the irrigation water supply of Erlongshan Reservoir is less.

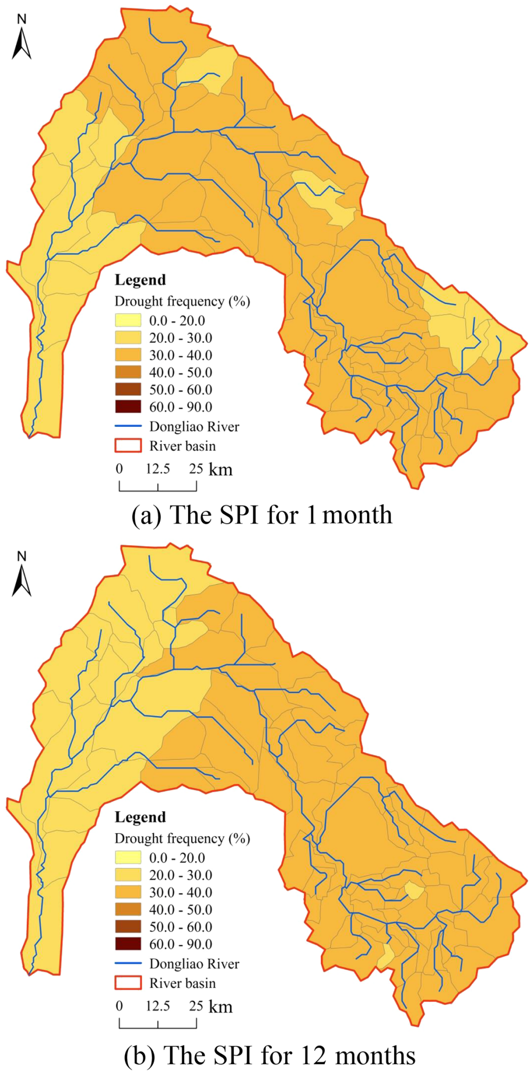

Figure 11. Spatial distribution of drought frequency simulated by the SPI in the DRB.

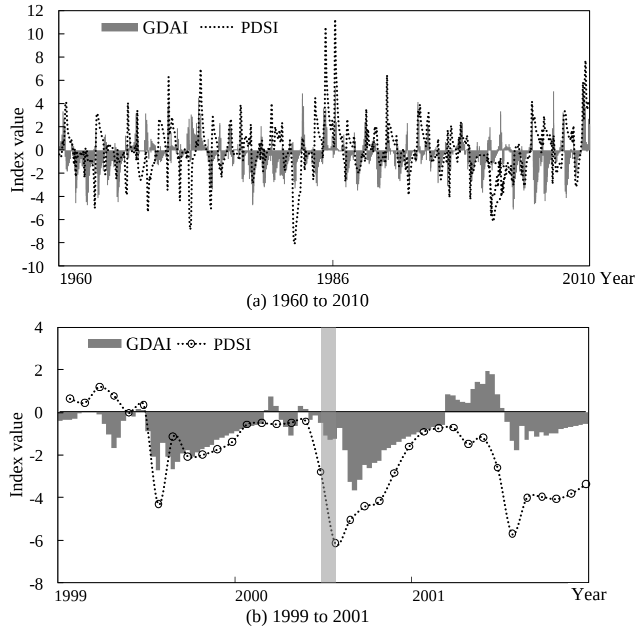

Figure 12. Compared the GDAI with the PDSI in Lishu County.

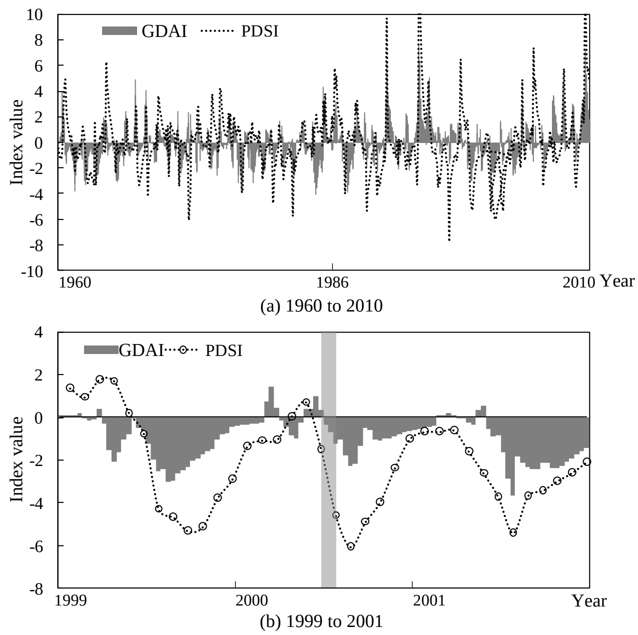

Figure 13. Compared the GDAI with the PDSI in Gongzhuling city.

4.2 The GDAI versus the PDSI

4.2.1 Temporal distribution

Figures 12 and 13 shows that the results simulated by the PDSI are generally greater than the GDAI during drought periods, 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 7). 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 considers the precipitation, evaporation, soil water and runoff. The evaporation is estimated by Thornthwaite's method which only considered temperature and assumed that evaporation equals zero when temperature is lower than zero. This assumption is unsuitable for the DRB since its temperature is low in the winter. The stored available moisture of the PDSI for the entire DRB took the same value. It did not consider the impact of different soil types. Thirdly, for wa-

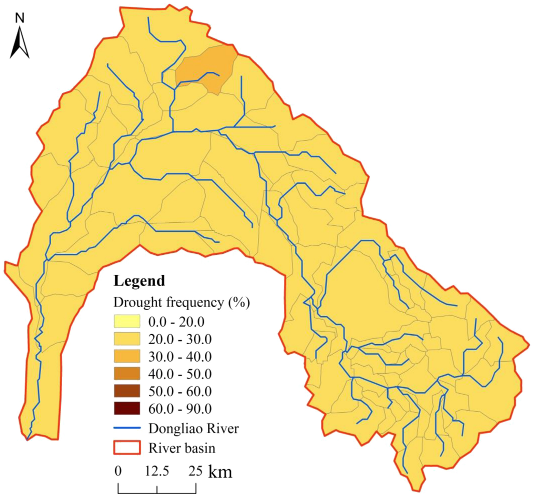

Figure 14. Spatial distribution of drought frequency simulated by the PDSI in the DRB.

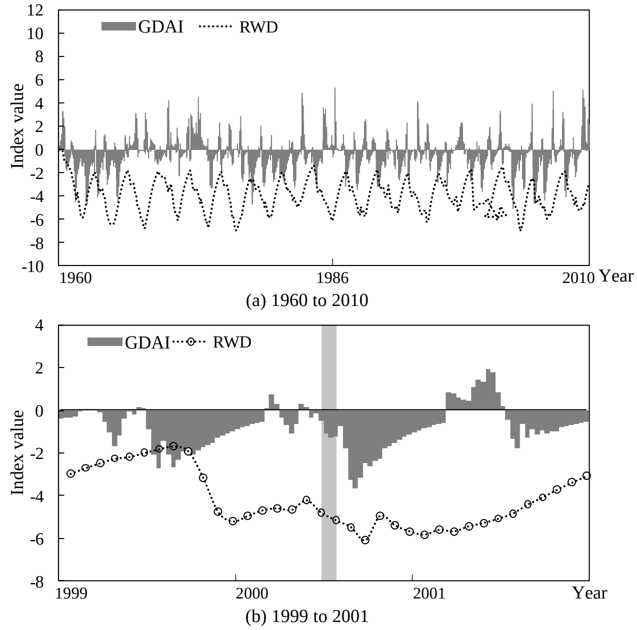

Figure 15. Compared the GDAI with the RWD in Lishu County.

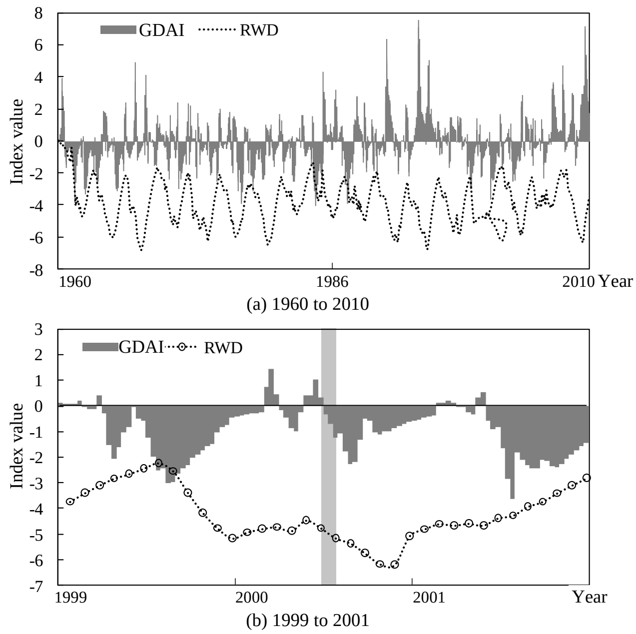

Figure 16. Compared the GDAI with the RWD in Gongzhuling city.

ter resources systems, the PDSI did not consider water resources systems, but the climatically appropriateness for existing conditions.

The water resources shortage of the GDAI is expressed by water supply and water demand of water resources systems. The GDAI considered the characteristics 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 anthropogenic activities, especially hydraulic engineering regulation.

4.2.2 Spatial distribution

In order to compare different aspects at different places and during different time periods, Palmer assumed the climatic characteristic coefficient (K), and chose weather data of western Kansas, central Iowa, and northwestern North Dakota to be correct. However, the PDSI did not consider the impact of different soil types and different land uses/land covers, and the influence of human activities, especially irrigation water supply. Therefore, the differences of drought frequency of 64 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 versus the RWD

Figures 15 and 16 shows that the results simulated by the RWD are generally less than the GDAI no matter interannually or annually. 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 7); however, soil water resources are important to agricultural system and ecosystem. Therefore, the results simulated by the RWD show that the DRB is affected by drought for a long time, and drought frequency of 64 assessment units is greater. The drought frequency of the entire DRB is over

80 % (Fig. 17). Because the RWD is defined as the ratio of the water resources shortage and the water demand, and the water resources shortage equals the water demand minus the water supply. The water supply here does not consider surface effective evapotranspiration. So the water demand is bigger than the water supply. Therefore the entire area presents a drought frequency over 80 %. The RWD may be not suitable for assessing the agricultural drought and evaluating the space difference of drought.

Though the SPI, the PDSI, the RWD and the GDAI indexes have their respective advantages and disadvantages, the GDAI is more suitable for expressing the characteristics and the evolutionary rules of droughts that happen in the Dongliao River basin. Since it considers the functions of the reservoirs to relieve droughts, it may help water managers make appropriate decisions in water conservancy project planning and water resources management. It may also help make decisions for the interconnected river and lake system project to relieve droughts, such as for planning water diversion project from Fengman Reservoir in the Di'er Songhua River basin to the Dongliao River basin. In addition, improving irrigation water use coefficient and reducing evaporation from farmland soil surface can be used to cope with the droughts. For example, the irrigation method can be changed from broad irrigation to sprinkling irrigation or drip irrigation. Besides, rainwater harvest and utilization projects can be constructed to make full use of rainwater resources.

5 Conclusions

Drought is firstly a resource issue with a shortage of water resources, but with its development it evolves into a disaster issue which affects natural and socioeconomic 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 systems for assessing drought events.

To demonstrate this new drought assessment approach, a drought-prone case study site, the Dongliao River basin in northeastern China was selected. 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).

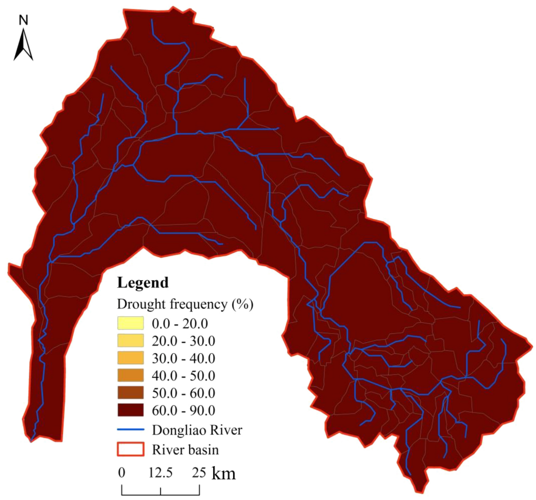

Figure 17. Spatial distribution of drought frequency simulated by the RWD in the DRB.

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

The proposed drought assessment methodology will provide water managers a tool to distinguish between natural and human effects and adapt their management accordingly. This would help adapt to droughts and reduce their negative impact.

Appendix A

Table A1. All acronyms used in this paper.

Acronym	Mean
ACC	Anthropogenic climate change
DRB	Dongliao river basin
GDAI	Generalized drought assessment index
GDD	Generalized drought duration
GDS	Generalized drought severity
GDT	Generalized drought times
HER	Hydraulic engineering regulation
IA	Impervious area
IF	Irrigated farmland
MGDD	The maximum generalized drought duration
MGDS	The maximum generalized drought severity
NCV	Natural climate variability
NF	Non-irrigated farmland
PDSI	Palmer drought severity index
RWD	Rate of water deficit index
SPI	Standard precipitation index
SV	Soil vegetation
UCC	Underlying conditions change
WB	Water body
WEP	Water and energy transfer process model

Table A2. All variables used in this paper.

Variable	Mean
D	Water resources shortage
SW	Water supply
DW	Water demand
$\overline{\mathrm{DW}}$	10 days average water demand
$\overline{\mathrm{SW}}$	10 days average water supply
$\overline{\lvert D \rvert}$	Average absolute D
K', K	Climatic characteristic coefficients, which are considered by referencing for the PDSI. Using the above correct indices, the water resources shortage in different assessment units and different assessment periods can be compare
Z	Water resources shortage index
$Z(i)$	The Z for the ith 10 days
DI	Generalized drought assessment index
DI(i)	The DI for the ith 10 days
DI($i-1$)	The DI for the $(i-1)$th 10 days
DD	Generalized drought duration which is expressed in 10 days during which a drought parameter is continuously below the critical level
S	Generalized drought severity which indicates a cumulative deficiency of a drought parameter below the critical level
L	Drought inter-arrival time between $(n+1)$th drought and nth drought
$-$DI	Taking logarithm of the generalized drought assessment index
X_0, X_1, X_2	Thresholds of the generalized drought assessment index; for mild drought, they are 0, 1.0, and 2.0; for moderate drought, they are 1.0, 2.0, and 3.0; for severe drought, they are 2.0, 3.0, and 4.0; for extreme drought, they are 3.0, 4.0, and 5.0, respectively

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