Applicability analysis of palmer drought index in Yunnan-Guizhou Plateau in China

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Abstract. Monitoring and assessment of droughts is of primary importance for meteorologists, ecologists, freshwater managers and government decision makers. As a widely used drought monitoring index, the applicability of PDSI is very important. This study evaluates the applicability of PDSI over the Yunnan-Guizhou Plateau in China by utilizing time series and correlation analysis between ground observations and actual drought and flood records. The main conclusions were as follows: 1) the dry and wet conditions in the study area were divided into two periods. The climate was wet from 1951 to 2003, except for 1961, 1963-1964, 1988-1990, and the wetting level reached medium strength in 1966, 1968, 1983-1984, 1992, 1996, 1998 and 2000. Since 2003 to 2015, there had been a trend of drought, and the degree of drought is large, especially in 2006 and 2010-2014, some years reached severe drought. The spatial distribution characteristics of multi-year PDSI was not obvious in the plateau area. There had been a slight drought in south-central Yunnan province and south-eastern Guizhou province. 2) The water loss caused by surface runoff was serious in plateau area. There was a high positive correlation between PSDI and surface runoff at a 99% probability level, which further indicated that surface runoff was the main factor leading to drought in this region. 3) The assumptions of PDSI model is suggested to be modified in the region like Yunnan-Guizhou Plateau: when the upper soil’s water content reaches the lower soil’s water content, surface runoff occurs. It is expected to provide references for the applicability analysis of PDSI in different underlying surface/subsurface conditions.

1. Introduction
Drought is a recurring phenomenon that has plagued civilization throughout history, and it is also a recurring extreme climate event over land characterized by below-normal precipitation over a period of months to years and it occurs over most parts of the world, even in wet and humid regions [1]. Few extreme events are as economically and ecologically disruptive as drought, which affects millions of people in the world each year [2]. To better monitor and quantify drought, various drought indices have been developed [3-9]. The PDSI is the most prominent index of meteorological drought widely used in the world [10-18], which is also regarded as one of the important indicators for long-term drought monitoring in the fields of meteorology, hydrology and ecology in China[7, 19-26].

PDSI is based on the principle of water balance, and some scholars have proposed that the PDSI model has some limitations in practical application. The Palmer model underestimates confluences or runoff, especially in summer and early fall or in areas of extreme drought and high runoff [27]. The effect of large-scale water conservancy projects, urbanization or changes in irrigation systems on the
calculation results is not considered in PDSI calculations [17]. In PDSI calculation, it is assumed that all precipitation forms are liquid and snowfall and snow cover are not considered [28, 29]. The effect of soil freezing on soil water holding capacity is not considered [30]. The model does not take into account changes in other factors caused by changes in terrain [31]. Variables such as wind speed, radiation, cloud conditions and water vapour are not considered in PDSI [18].

The geographical applicability of PDSI is also one of the important issues concerned by hydro-meteorological research and operational workers [18, 27, 28, 30, 31]. For example, in different climate regions, different underlying surface conditions, and different soil structure, PDSI credibility is also significantly different, which can cause a totally different result. The two-layer soil structure division and bottom layer accumulation and full yield flow hypothesizes in PDSI may not be applicable in some specific areas [27, 29, 31].

Yunnan-Guizhou plateau is located in southwest China, which is one of the four major plateau regions in China. The height of this region fluctuates greatly, with an elevation of 400 ~ 3,500 meters. Compared with the "native environment" of PDSI, northern Texas of the United States [8], Yunnan-Guizhou plateau region is a subtropical humid region with a subtropical monsoon climate. Influenced by the southwest monsoon, this region has formed the characteristics of water resources with distinct dry seasons in winter and summer. In addition, the region has a long dry season, seasonal drought, especially the spring drought is very serious.

This study attempts to analyze the applicability of PDSI by verifying the correlation between ground observations and actual drought and flood records in the Yunnan-Guizhou Plateau. It is expected to provide references for the applicability analysis of PDSI in different underlying surface/subsurface conditions.

2. Materials and method

2.1. Data and processing
The scope of this study includes Guizhou Province and Yunnan Province of China. The main rivers and water systems include Jinsha River, Nanpan River, Yuan River, Min River, Nu River and Dulong River. The data needed for the study includes automatic station data, hydrological data, soil moisture station data and flood disaster data, with the total number of the stations of 214, 11 and 10 respectively. The main data elements of automatic weather stations are monthly temperature and precipitation, which are obtained from monthly data set of surface meteorological elements in China by the National Meteorological Information Centre [32]; hydrological station total number is 11, which are obtained from National Hydrological Yearbook, and the main element is the annual runoff. Soil moisture station total number is 10, the main element is the soil moisture of 50cm depth, which are obtained from China Agro-meteorological soil moisture data set (1981-2010). Flood disaster data are from Rainstorm and flood disaster data set of China Meteorological Administration [33]. In addition, the available soil moisture content at a depth of 100cm corresponding to the automatic station in the study is obtained from the National Automatic Soil Moisture Observation Network [34, 35]. The station distribution map is shown in Figure 1 below.

Figure 2 shows that the multi-year average monthly minimum temperature, average temperature in the study area are 7.6°C and 16.1 °C respectively, and the multi-year average monthly minimum precipitation and average monthly precipitation are 18.7mm and 94.1mm respectively. The multi-year average annual precipitation is 1129.7 mm.
2.2. PDSI
Palmer drought index, PDSI, is based on the water supply and demand balance principal, which is defined as the amount of water supplied to an assumed closed area over a long time scale equal to the amount of water lost. Based on water balance, by calculating the climate appropriated rainfall $\bar{P}$, duration factor $K$, calculating the abnormal moisture index $Z$, finally the PDSI can be calculated [8]. The specific calculation method is,

$$D= P-(\alpha \cdot PE + \beta \cdot PR + \gamma \cdot PRO - \delta \cdot PL)$$  \hspace{1cm} (1)

$$K = \frac{PE+R}{P+L}$$  \hspace{1cm} (2)

$$Z = D \cdot K \cdot \frac{PE+R}{P+L}$$  \hspace{1cm} (3)

$$PDSI_i = a \cdot DPDSI_{i-1} + Z_i$$  \hspace{1cm} (4)

Where $\alpha$, $\beta$, $\gamma$ and $\delta$ are the evapotranspiration coefficient, water replenishment coefficient, runoff coefficient and water coefficient, which mean the ratio of the perennial average of the actual loss and the perennial average of the potential loss in a month. PE is potential evapotranspiration, R is runoff and L is water loss, the units are mm. The $a$ and $b$ are the parameters, which need to be calculated according to the actual climate conditions of analysed area.

The inputs of the model include monthly or weekly precipitation, maximum and minimum air temperature, effective soil moisture content and station latitude values; the outputs include monthly or weekly drought index values. There are 10 grades from extreme wet to extreme drought (Table 1).

| PDSI   | Type     | PDSI   | Type       |
|--------|----------|--------|------------|
| $\geq 4.00$ | Extreme wet | 0.50 ~ 0.99 | Initial drought |
| 3.00 ~ 3.99 | Serious wet | 1.00 ~ 1.99 | Mild drought |
| 2.00 ~ 2.99 | Moderate wet | 2.00 ~ 2.99 | Moderate drought |
| 1.00 ~ 1.99 | Slight wet | 3.00 ~ 3.99 | Severe drought |
| 0.50 ~ 0.99 | Initial wet | $\leq$ 4.00 | Extreme drought |
| 0.49 ~ 0.49 | Normal | / | / |

PDSI is a complex and multi-factor drought monitoring index commonly used in meteorology, agriculture and other fields.

3. Drought characteristics in Yunnan-Guizhou Plateau
Monthly PDSI in the Yunnan-Guizhou plateau region from 1951 to 2015 is calculated, which shows that the results of multi-year PDSI in the study area can be divided into two sections (Figure 3). The
climate is wet from 1951 to 2003, except for 1961, 1963-1964, 1988-1990, and the wetting level reached medium strength in 1966, 1968, 1983-1984, 1992, 1996, 1998 and 2000. Since 2003, there has been a trend of drought, and the degree of drought is large, especially in 2006 and 2010-2014, some years have reached the degree of severe drought.

The drought records about Yunnan-Guizhou plateau area from data set of rainstorm and flood disaster of China Meteorological Administration as follows: from January to May 1963, south China, Yunnan, western Guizhou and southern Sichuan suffered from a severe drought, with precipitation anomaly of -40% ~ -85%; the total rainfall is only 100-300 mm, 5-80 percent less than usual, and early rice is seriously affected; Guangdong, Guangxi, Fujian, Yunnan and other provinces were affected by the drought in a total area of 2,933 thousand hectares, among which 373.3 thousand hectares of early rice in south China could not be transplanted due to the drought[33]. The drought results reflected by PDSI are shown in Figure 4 below.

Figure 3. Monthly variation trend chart of multi-year PDSI in study area.

Figure 4. PDSI distribution in Yunnan-Guizhou plateau from January to June 1963.

It can be seen from Figure 4 that serious drought occurred in Yunnan and Guizhou from January to May in 1963, especially in the southeast of Yunnan, the drought was most severe in May. PDSI showed severe drought, and some areas reached extreme drought. PDSI results are basically consistent with the records in literature [33], indicating that PDSI results could be used as a reference to measure the drought and flood situation in this region.

The spatial distribution characteristics of multi-year PDSI is not obvious in the plateau area. There has been a slight drought in south-central Yunnan province and south-eastern Guizhou province (Figure 5).
The percentage of precipitation anomaly is the deviation degree between the precipitation in a certain period and the average state of the same period. It is bounded by 25% of the absolute value of the percentage of precipitation anomaly. 1 times is the normal range, 1~2 times is partial to drought or partial to waterlogging, and bigger than 2 times indicates severe drought or flooding [25]. Multi-year comparison between the percentage of precipitation anomaly, $P_{pa}$, in the study area and PDSI is calculated (Figure 6).

It can be seen from Figure 6 that the trend of the two analyzed variables is basically the same, and the correlation coefficient between them reaches 0.67, exceeding the significance level of 0.01. However, it is also found that there is a difference between them in individual years in the magnitude level, especially in the earliest and latest period, e.g. in 1956, 1958, 2010, 2012 and 2014 etc. In 1956, $P_{pa}$ showed moderate drought, while PDSI tended to be wet. PDSI drought level in 2010, 2012 and 2013 were moderate drought, while $P_{pa}$ were normal.

Precipitation directly reflects the drought and flood conditions of a region, but the dry and the wet conditions of a region mainly depend on the available precipitation, that is, the water which can be retained by the soil. PDSI is a comprehensive drought index, which is not only related to the input of external precipitation, but also related to the initial soil water content and soil texture. Since these characteristics above, some scholars have proposed that PDSI monitoring of drought sometimes has certain hysteresis, especially after a continuous period of drought or humid period [18]. As can be seen from Figure 6 that PDSI showed a slight wetter trend before 1955, while in 1955, the precipitation anomaly percentage showed an abnormal year with little precipitation. Because of the water accumulation in the early stage, there was a certain amount of water in the soil. The drought in 1956 caused the soil water loss. By 1958, PDSI showed a trend of drought, but it still failed to reach the drought intensity reflected by the percentage of precipitation anomaly. The reasons for the inconsistencies between the two periods need to be further analyzed from the aspects of soil effective water content and actual precipitation, which also indicates that comprehensive analysis of multiple monitoring evaluation results is needed in drought monitoring.
4. Applicability analysis

The Palmer drought index is based on a number of assumptions, including the following: (1) full runoff, which means that the model assumes that the soil is divided into upper and lower layers. The upper layer is the soil surface layer, i.e., the cultivated layer, and the lower layer is the root layer. The subsoil moisture content is related to local soil characteristics. When the demand exceeds the supply, the surface water is first used, and the upper soil water is exhausted before it starts to lose the lower water. Moreover, it is assumed that the upper and lower layers reach saturation before surface runoff is generated [36]; (2) over-permeability runoff, which means runoff occurs when there is precipitation on the surface and the infiltration rate of precipitation intensity greater than water content, that is the soil reaches saturation; (3) all the precipitation generated in a period of time is used to supplement the evapotranspiration and soil water demand in that period or as runoff loss [27].

The underlying surface of Yunnan-Guizhou plateau is characterized by karst landform with relatively thin soil layer, and most of the precipitation generated is lost in the form of surface runoff, which is difficult to accumulate. Therefore, the water balance model in PDSI model may underestimate confluence or surface runoff, bringing certain uncertainty to the calculation results.

In order to verify the rationality of the hypothesis above, the soil moisture at 50cm level of 11 soil moisture stations in the study area are selected for comparative analysis of soil moisture, PDSI of the corresponding sites and percentage of precipitation anomaly since the observation record, from 1983 to 2010, and the results shows as Figure 7 below.

![Figure 7. Comparison of percentage of precipitation anomaly, PDSI and soil moisture content.](image1)

![Figure 8. Comparison of PDSI and precipitation anomaly percentage in study area.](image2)

As can be found that there is a high Pearson correlation coefficient between PDSI and the percentage of precipitation anomaly, $R_{\text{rain,pdsi}}=0.666$, which exceeds the significance level of 0.01. Figure 8 also shows that the Pearson correlation coefficient between PDSI and precipitation anomaly in the study area are high in most of the stations, exceeding the significant correlation level of 0.01.

The correlation between the percentage of precipitation anomaly and soil moisture and soil moisture and PDSI are poor, $R_{\text{rain,soil}}=0.105$, and $R_{\text{pdsi,soil}}=0.034$, none of which reach at least the 5% significance level.

Without considering the difference in demand, for a fixed area, the most direct factor to measure its dry and wet condition is water quantity, namely the difference between input and output, and the condition of drought and waterlogging is determined by both input and output. Yunnan-Guizhou plateau is a typical karst terrain with a wide distribution of limestone. Due to the special underlying surface characteristics, although there is abundant precipitation in this region, a large amount of ground precipitation cannot infiltrate and is lost in the form of surface runoff [37].
Figure 9 below is the comparative analysis result of annual runoff measured by hydrological stations in the study area and PDSI calculated by nearby automatic stations, and there is a list of hydrological stations with needed input data in the Table 2.

**Table 2.** Hydrological stations in the study area.

| River                  | STATION | Short Name | The catchment area (km²) | Period(year) | PDSI Station N. |
|------------------------|---------|------------|--------------------------|--------------|-----------------|
| Lancang River          | Yunjinhong | YJH       | 137948                   | 1956-1987    | 56959           |
| Yuan River             | Yuanjiang | YJ         | 21554                    | 1954-1972, 1977-1985 | 56966           |
| Wu River               | Huangmaocun | HMC     | 759                      | 1961-1983    | 57814           |
|                        | Sinan    | SN         | 51270                    | 2006-2013    | 57731           |
| Upper reaches of       |          |            |                          |              |                 |
| Jinsha River           | Tacheng  | TC         | 1156                     | 1961-1987    | 56543           |
|                        | Huangping | HP        | 829                      | 2007-2013    | 56649           |
|                        | Dacun    | DC         | 811                      |              | 56652           |
| Lower reaches of       |          |            |                          |              |                 |
| Jinsha River           | Qixingqiao | QXQ      | 1823                     | 1954-1987, 2007-2013 | 56785           |
|                        | Malucun  | MLC        | 3737                     | 1959-1987, 2007-2013 | 56594           |
| Nu River               | Daojieba | DJB        | 118760                   | 1957-1985    | 56741           |
The results show that there are high positive correlation between river runoff and PDSI in the study area (except for DJB and YJH), which reach the significance level of 0.01, which indicate that the greater the runoff, the more serious the water loss, and the greater the actual degree of drought. However, the calculated results of PDSI are just the opposite. The larger the PDSI is, the wetter it is, according to the definition of PDSI drought and flood level, which is exactly opposite to the runoff. In addition, there is no significant correlation between the runoff and PDSI at DJB and YJH hydrological stations, and the reasons need to be further analyzed. Through the detailed results above, it can be concluded that the PDSI index has certain limitations in drought monitoring in areas with underlying surface conditions similar to Yunnan-Guizhou plateau.

5. Conclusions and discussions
The study evaluates the applicability of PDSI over the Yunnan-Guizhou Plateau in China by utilizing time series and correlation analysis between ground observations and actual drought and flood records. The main conclusions were as follows:

1) The dry and wet conditions in the study area were divided into two periods. The climate was wet from 1951 to 2003, except for 1961, 1963-1964, 1988-1990, and the wetting level reached medium strength in 1966, 1968, 1983-1984, 1992, 1996, 1998 and 2000. Since 2003 to 2015, there had been a trend of drought, and the degree of drought is large, especially in 2006 and 2010-2014, some years reached severe drought. The spatial distribution characteristics of multi-year PDSI was not obvious in the plateau area. There had been a slight drought in south-central Yunnan province and south-eastern Guizhou province.

2) The water loss caused by surface runoff was serious in plateau area. There was a significant positive correlation between PDSI and streamflow at a 99% probability level, which further indicated that surface runoff was the main factor leading to drought in this region. The PDSI model based on soil water balance principle had some limitations in its applicability in areas similar to the underlying surface of Yunnan-Guizhou plateau.

The core of PDSI is the balance of water supply and demand. For a closed area, the water supply is equal to the water loss over a long time scale. The model assumes that the surface runoff occurs when precipitation intensity is greater than the water infiltration rate. This hypothesis condition has great
limitations under the special underlying surface condition of large runoff in Yunnan-Guizhou plateau and needs to be adjusted according to the actual situation. In the original model, the soil is divided into two layers, the upper tillage layer and the lower root layer. When the water demand exceeds the supply, the surface water is used first, and the lower water is lost only after the upper soil water is used up. It is also assumed that surface runoff will not occur until both the upper and lower layers reach saturation. According to the actual situation of the study area, the assumptions of PDSI model need to be modified. When the upper soil’s water content reaches the lower soil’s water content, surface runoff occurs. Since the soil layer in this area is thin and dominated by limestone, water infiltration is difficult, and a large amount of surface runoff occurs when there is a little precipitation.

Besides, in order to improve the scientific nature of the decision, it was suggested to use a variety of methods to judge the drought monitoring results comprehensively.

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