Drought Analysis and the Characteristics of Hydro-meteorological Changes in the Jinsha River Basin

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Abstract: The Jinsha River Basin (JRB) is the most important tributary of the Changjiang River and the most ecological vulnerable region to climate change. Therefore, to better understand the hydro-meteorology characteristics of JRB and enhance hydrological forecasts, a temporal-spatial analysis of historical hydro-meteorological elements and drought characteristics is required. In this study, 45 meteorological stations and 5 hydrologic stations in JRB for the last 60 years of historical data were utilized for analyze the temporal-spatial distribution and trends of hydro-meteorological elements, while drought characteristics in this basin were assessed using SPI values at six-month scales (SPI-6). The results show that: (1) the three daily temperature types (minimum, mean and maximum) and precipitation of the JRB all show an increase from the upper to lower reaches. (2) the Mann-Kendall test analysis of hydro-meteorological elements' annual values reveals that the mean temperature of 42 stations is rising, while precipitation is rising at 25 stations. The runoff at all five hydrologic stations is increasing. The temperature and precipitation in the upper reaches are the areas with the greatest increase in the JRB, while the precipitation in the lower reaches is the only one that is on a downward trend. (3) In the drought analysis based on SPI-6, the downstream of JRB, which is located in Sichuan and Yunnan provinces, is the region with the most severe drought. There is no visible trend in drought duration at most stations, and the drought magnitude analysis is dominated by a decreasing trend. However, the drought intensity analysis is dominated by an uptrend, especially in the mid- and lower streams.

1 INTRODUCTION

Drought, the most complex natural phenomena, is characterized by strong progressivity, a wide range of influence, and large losses, which have attracted widespread attention (Keyantash & Dracup, 2020). For example, some areas in southern China, including Yunnan, Guangdong, Guangxi, and Shanxi, experienced heavy drought conditions in the winter of 2020 and spring of 2021, and a total of 470,000 rural residents experienced drinking water difficulties as a result of the drought. Generally, droughts can be classified into three major types based on its cause: meteorological, agricultural and hydrological droughts (Wang et al., 2016). Meteorological drought is mainly caused by poor precipitation and atmospheric circulation anomalies (van Loon et al., 2015); agricultural drought, also known as soil moisture drought, is defined by a lack of soil water (Van Hateren et al., 2020); and hydrological drought is associated with water shortage in rivers, lakes, groundwater and other water bodies (van Loon, 2015). To assess the drought characteristics, several drought indices are the most widely used (McKee et al., 1993; Welford et al., 1993; Shukla et al., 2008), including the standardized precipitation index (SPI) (McKee et al., 1993), the soil moisture drought index (SMDI) and the standardized runoff index (SRI). In recent decades, numerous research based on various drought indicators, including drought duration and drought severity, have been carried out in some watersheds of China. For example, Xu et al. (2015a) based on the 3-month scale SPI constructed a multidimensional clustering method to assess drought risk of China during 1961-2012. The findings show that two of the most extreme drought swept through more than half of China's non-arid regions, occurring from 1962 to 1963 and from 2010 to 2011. Zhai et al. (2010) used monthly scale degree data to calculate annual average SPI and PDSI values for approximately five hundred meteorological stations in China over the last 50 years. They discovered that

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the upper and lower Changjiang River or the mountainous northwest region have significant positive trends in these indices. Xiang et al. (2020) combined a multidimensional Copula function hydrological approach that can applied in hydrological drought risk assessment, especial. According to the findings, mild to moderate hydrological droughts dominated the study area from 1961 to 2018.

China is suffering from severe water scarcity, with per capita water resources that are only one-third of the global average. Extreme weather is becoming more common due to the climate change and the intensification of human activities, which makes extreme droughts the most serious disaster in terms of impact (Schubert et al., 2016; Mishra et al., 2010), and has resulted in significant economic losses in the affected regions. According to statistics, during the period of 1997-2009, the affected areas and economic losses in the country were clearly above the average of the last 30 years, with a mega-drought occurring almost every two years (Leng et al., 2015). According to the data from the Ministry of Water Resources' Water and Drought Disaster Bulletin, the loss of cash crops due to drought in 2003 amounted to RMB 53.8 billion, while 33 million people were suffering from drinking water shortages. Other examples include, the 2006 mega-drought in provinces of Sichuan and Chongqing (Yu et al., 2014), at the same time the most severe meteorological drought event since meteorological records were kept in the southwest from 2009 to 2012, which had disastrous and far-reaching consequences for agriculture, society and the economy. Extreme weather has become more common in recent years, with the intensification of global warming and the impact of human activities, and drought disasters will continue to pose a significant threat to China's food security, human and animal drinking water safety, and ecological environment security. Therefore, relevant departments and scientific research institutions need to pay more attention to drought disasters and conduct more in-depth research (Xu et al., 2015a; Xu et al., 2015b).

The Jinsha River Basin (JRB) is abundant in hydroelectric resources and is China's largest planned hydropower base. This basin has significant spatial and temporal differences in climate and is susceptible to climate change (Wang et al., 2013), as well as drought disasters have been frequented in recent years, causing significant losses to local economic and social development. However, the awareness of drought in this basin is still insufficient, and the ability of drought management and forecasting capabilities are still limited. Therefore, research on the hydro-meteorological changes' spatiotemporal features and droughts in the JRB is essential for strengthening drought control and prevention in this basin. In this paper, 45 meteorological stations and 5 hydrologic stations of JRB for the last 60 years of historical data were utilized to clarify the spatiotemporal distribution and trends of hydro-meteorological elements, while drought characteristics, including meteorological and hydrological drought, in the basin were assessed using SPI values at six monthly scales.

2 STUDY AREA

The JRB is the section of the Yangtze River from its headwaters to Yibin (Figure 1). It includes the Tongtian River and Tuotuo River, is located on the western edge of China's Qinghai-Tibet Plateau, Yunnan-Guizhou Plateau, and the Sichuan Basin, and spanning five provinces (regions): Qinghai, Tibet, Sichuan, Yunnan, and Guizhou. The area of JRB is about 500,000 km^2, accounting for 27.8% of the total area of the Yangtze River Basin; the length of the river is approximately 3,500 km, accounting for 55.5% of the Yangtze River's total length; and the drop is approximately 5,100 m, which is rich in hydropower energy.

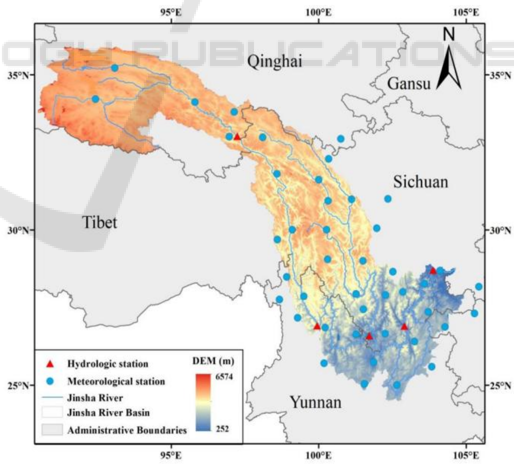

Figure 1: The map of Jinshajiang River Basin (JRB), where blue dots are meteorological stations and red triangles are hydrologic stations.

Influenced by the landform and terrain, the climate characteristics of JRB has clear distinct distribution. A plateau climate dominates the basin's upper and middle regions, while the lower portion of the main stream from Qiaojia to Pingshan is the warm temperate climate. The temperature increases progressively from upstream to downstream, from northwest to southeast. It is cold in the Qinghai-Tibet Plateau, where the average temperature is below 0°C for 7 months of the year. And for more than 65% of the regions, the annual average temperature is below 0°C. The general precipitation distribution in JRB also increases gradually from northwest to southeast. From June to October is the flooding season of JRB when 75%-85% precipitation happens.

3 DATA AND METHODS

3.1 Data

The meteorological dataset was obtained from the China Meteorological Data Sharing Service System (He et al., 2020). There are 45 meteorological stations within and around the watershed, among which only 34 stations are located within the JRB. The data series range from 1950 to 2014, with 27 stations having time series spanning more than 50 years, and data gaps for some stations being filled with interpolation. Figure 2 shows the data series statistics for 30 stations in the watershed.

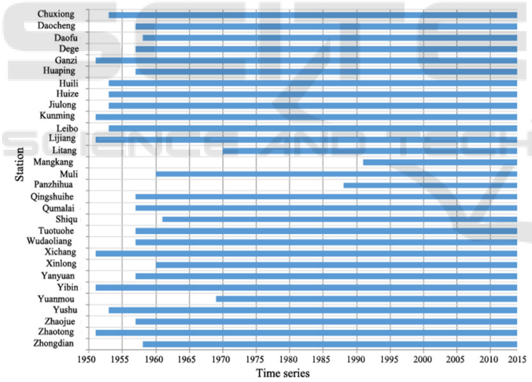

Figure 2: Period of recorded meteorological daily data for each of the 30 stations located within the JRB.

The five hydrological stations are Zhimenda, Pingshan, Shigu, Panzhihua, and Huatan. Except for a few empty values at Huatan station, the time series of the other four stations were complete. These vacant values were also filled by interpolation.The copyright form is located on the authors' reserved area.

3.2 Methods

3.2.1 Mann-Kendall Test

The Mann-Kendall (M-K) test (Kendall, 1975; Bjerklie, 2007) is used to determine whether the variable of interest has a monotonic upward or downward trend over time. Compared to parametric linear regression analysis, it is not necessary to consider whether the sequence under consideration follows a specific probability distribution. The M-K test is best seen as an exploratory technique, especially useful for evaluating hydro-meteorological data (McLeod et al., 1990), and is most useful for identifying stations that have obvious or significant changes and quantifying these findings (Hirsch et al., 1982).

According to the null hypothesis H_0, these sample sequences are all independent and therefore have:

$$H_0:\ Prob\left[Y_j > Y_i\right] = 0.5,\quad where\ T_j > T_i \tag{1}$$

$$H_1:\ Prob\left[Y_j > Y_i\right] \neq 0.5\ (2 - sided\ test) \tag{2}$$

The M-K test statistic S is formulated by equation (3) (Yue et al., 2002):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_j\right) \tag{3}$$

$$sign(x) = \begin{cases} +1 & if\ x > 0 \\ 0 & if\ x = 0 \\ -1 & if\ x < 0 \end{cases} \tag{4}$$

The M-K test statistic Z is calculated using the equation(5):

$$Z = \begin{cases} \dfrac{S-1}{\sigma} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sigma} & S < 0 \end{cases} \tag{5}$$

where the variance σ^2 is defined as:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{6}$$

where, n represents the length of the time series x_1, x_n; x_i and x_k are the values for the years i and k, respectively.

A positive (negative) of Z value indicates that the test time series has an upward (downward) monotone trend. Z is a test statistic that is used to determine the significance of a trend. The null hypothesis, H_0, is tested using this test statistic. If, the expression has a significance level, then it indicates that the null hypothesis is invalid, i.e., the trend is significant. Where α represents the significance level. Other significance levels (e.g., 0.01 or 0.05) can usually be used, but most previous studies set the significance level at 0.05 before collecting the data (Wang et al., 2020; Ahmad et al., 2015). In the following analyses, a significance level of 0.05 with a $Z_{0.025}$=1.96 has been fixed for the corresponding tests.

3.2.2 Drought Analysis

Mckee (McKee et al., 1993; Shukla et al., 2008) developed the SPI in 1993 to quantify the precipitation deficit over multiple time scales. On time scales less than a year, precipitation does not follow a normal distribution. As a result, the variable is changed to give the SPI has a Gaussian distribution. The following expressions are used to calculate this index.

$$SPI = +\left(t - \frac{c_0 + c_1 * t + c_2 * t^2}{1 + d_1 * t + d_2 * t^2 + d_3 * t^3}\right) \quad (7)$$

$$t = \sqrt{ln\left(\frac{1}{H(P)^2}\right)} \quad (8)$$

$$for\ 0 < H(P) < 0.5$$

$$SPI = -\left(t - \frac{c_0 + c_1 * t + c_2 * t^2}{1 + d_1 * t + d_2 * t^2 + d_3 * t^3}\right) \quad (9)$$

$$t = \sqrt{ln\left(\frac{1}{\left(1 - H(P)\right)^2}\right)} \quad (10)$$

$$for\ 0.5 < H(P) < 1$$

Where *P* denotes the total precipitation that happend in the given time-scale, *H(P)* denotes the cumulative probability of the observed precipitation during this period, while $c_0, c_1, c_2, d_1, d_2, d_3$ are mathematical constants. The interpretation of the SPI's possible values is depicted in Table 1.

Table 1: Period classification based on the values of the standardized precipitation index (SPI).

SPI	Description
≥ 2.0	Extremely wet
(1.5, 2.0]	Very wet
(1.0, 1.5]	Moderately wet
(−1.0, 1.0]	Near normal
(−1.5, −1.0]	Moderately dry
(-2.0, -1.5]	Severely dry
≤ -2.0	Extremely dry

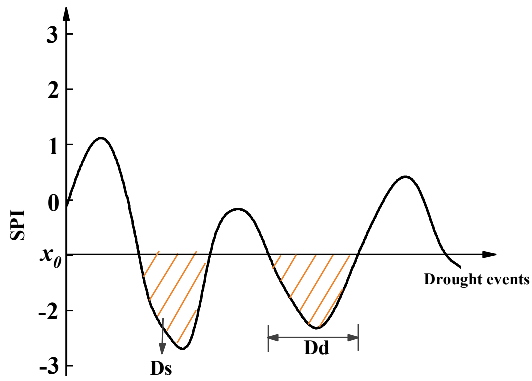

Figure 3: Diagram of the run theory, where Dd was defined as the number of months in order with SRI values less than the threshold x_0, and Ds was the sum of the absolute values of all SRIs during the drought. (Guttman, 1999).

As noted previously, the SPI is intended to assess the precipitation deficit for multiple timescales, which can effectively measure the regional drought conditions. Meteorological and soil moisture conditions (agriculture) respond to anomalies in precipitation on relatively short time scales (1-6 months), while water bodies such as streams and reservoirs respond to precipitation anomalies on longer time scales.

SPI on 1-month scale (SPI-1): the SPI values at the 1-month scale map can show the percentage of normal precipitation over a 30-day period. It is relatively short in duration, but can more clearly reflect the subtle changes of drought than other time scales.

SPI on 3-month scale (SPI-3): SPI-3 is calculated by counting precipitation over a three-month period, which primarily reflects short- and medium-term moisture conditions and assesses precipitation's seasonal status. At the same time ,it also is the most commonly used of several time scales and can accurately reflect seasonal variations in drought.

SPI on 6-month scale (SPI-6): SPI-6 represents the precipitation trend over the medium term. It can be very useful in displaying precipitation over time. SPI-6 drought information can also be expressed on a stream or reservoir level, depending on geological conditions and the timing of unusual precipitation in the area.

SPI on 12-month or 24-month scale (SPI-12 or SPI-24): These long-term precipitation patterns are reflected in these time-scale SPIs. These time-scale SPIs are also linked to stream and reservoir levels, as well as longer-term groundwater levels.

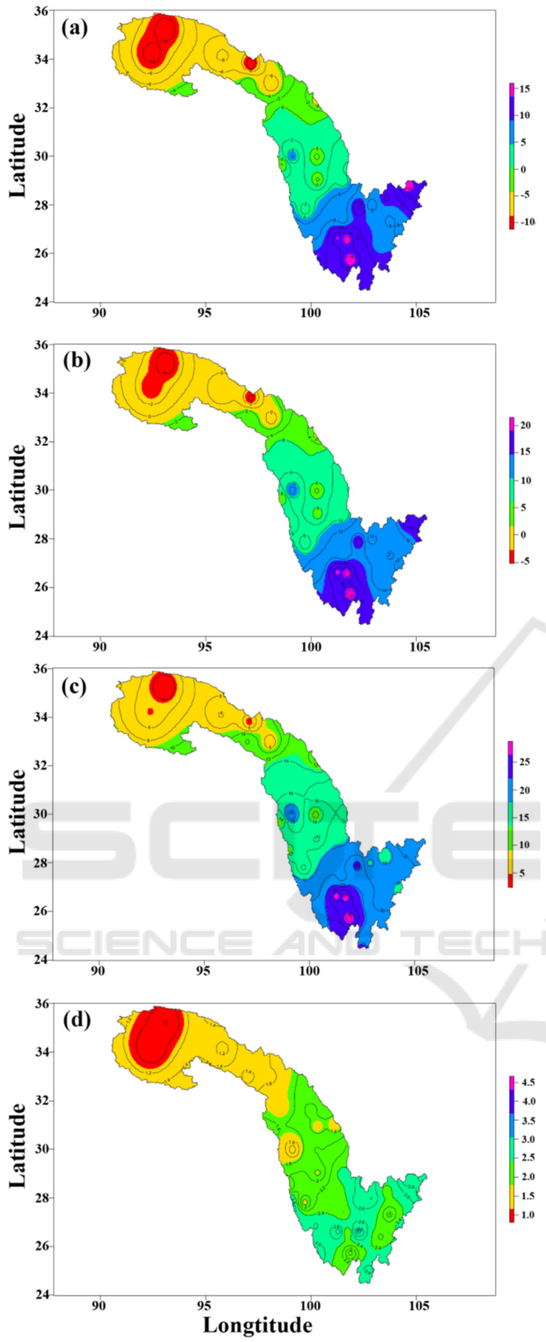

Figure 4: Spatial distribution of the average of (a) daily minimum temperature, (b) mean temperature, (c) maximum temperature and (d) precipitation in the JRB over the period 1951-2014.

In this paper, the SPI-6 values are used to define drought occurrence. According to run theory (Figure 3) (Zelenhasić & Salvai, 1987), three drought characteristic indicators exist: drought duration (Dd), drought severity (Ds), and drought intensity (Di). Previous studies used a threshold value of -0.5 (McKee et al., 1993; Wu et al., 2019) or -1.0 (Kwak et al., 2016) to statistics drought events. The threshold value in this paper was set at -1.0.

4 RESULTS AND DISCUSSION

4.1 Basic Statistical Analysis of Hydro-meteorological Series

The statistical analysis of the daily minimum temperature, mean temperature, maximum temperature and precipitation time series has been performed on the basis of the 34 meteorological stations data within the JRB. As shown in Figure 4, the three temperature types and daily precipitation of the JRB all show a phenomenon of increasing from the upper to lower reaches. The average daily temperature in the Yangtze River source region is below 0 °C all year, with a maximum temperature of no more than 10 °C. The Yunnan administrative region of JRB has the highest average daily temperature, with temperatures reaching 15 °C or higher. In Figure 5, the graphical relationship between the elevation of each meteorological station and the values of the daily minimum, mean and maximum temperature series is presented, and a linear regression has been established between those variables. According to the high values of the coefficient R^2, which are all greater than 0.8, the fit of the models can be considered suitable.

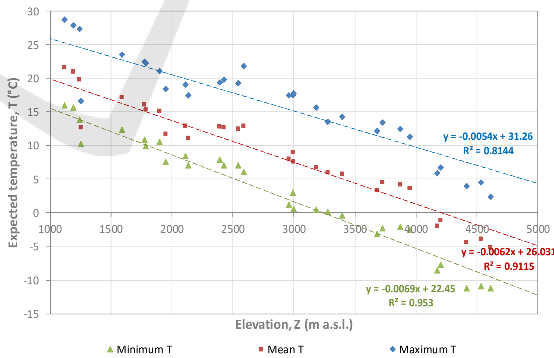

Figure 5: Relation between the daily minimum, mean and maximum temperatures and elevation of the 34 meteorological station.

4.2 Trends Analysis of Hydro-meteorological Series

The annual values of hydro-meteorological elements were first extracted for each station, and then the M-K test was performed (Figure 6). The results show that the mean temperature of 42 out of 45 stations has an increasing trend, with 37 stations exhibiting a significant increase. Meanwhile, for precipitation, 25 stations, which are mainly found in the mid- and upper regions, have an upward trend, while 20 downstream stations have a downward trend, where only 8 of them are significant. For runoff, all five hydrologic stations have an increasing trend, but only Huatan station is significant.

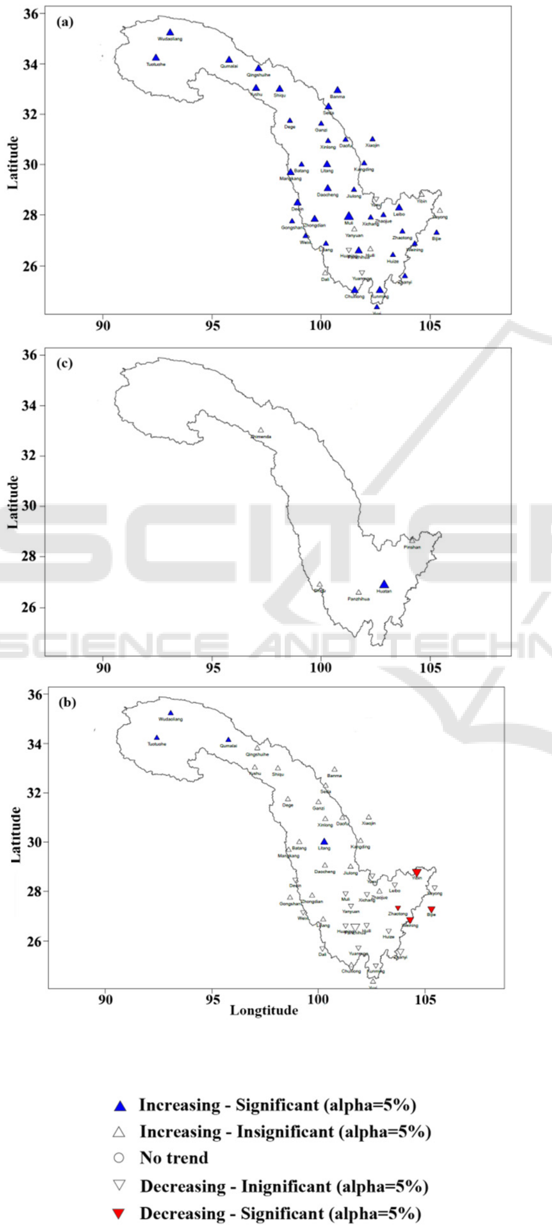

Figure 6: Trend results in daily (a) mean temperature, (b) precipitation and (c) runoff from 1951 to 2014 using the Mann-Kendall test and with a significance level of 5%, the size of the triangles is proportional to the slope of the detected trend.

The increasing(decreasing) trend of temperature or precipitation detected in each part of the basin (upper, middle and lower) over the 64 years of the analysis period are also represented in Figure 7 (only significant trends have been taken into account). The average volume of annual precipitation is presented as well. The temperature and precipitation in the upper reaches are the areas with the greatest increase in the JRB, while the precipitation in the lower reaches is the only one that is on a downward trend.

4.3 Drought Analysis

The SPI-6 is calculated for 45 stations within the JRB, and then according to these values to assess the drought event and the drought characteristics. The spatial distribution of drought characteristics based on SPI-6 values in December 2011 is illustrated in Figure 8, which the Figure 8b is obtained by spatial interpolation on the basis of Figure 8a. From this, it is clear that the downstream of JRB, where is located in the provinces of Sichuan and Yunnan, is the region with the most severe drought in December 2011.

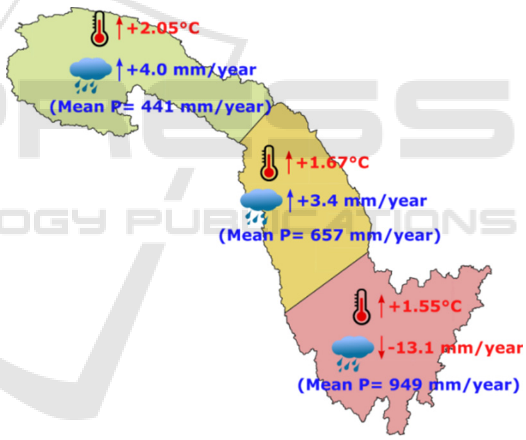

Figure 7: The increasing (or decreasing) trend of the temperature and precipitation over the entire period (1951-2014) in the upper (green), middle (yellow) and lower (pink) parts of JRB.

Several studies (Xu et al., 2015b; Zhang et al., 2012; Li et al., 2011) have concluded that the southwestern region of China, as well as the mid- and upper streams of the Changjiang River (including the lower Jinsha River), are the most frequent drought hazard regions in China, causing enormous losses to the ecology and agricultural economy each year. For example, Yunnan was hit by a once-in-a-century drought in 2010, and western Guizhou and northwestern Guangxi have reached mega-drought status, with over 200,000 rural residents facing water shortages (Zhang et al., 2012; Li et al., 2011).

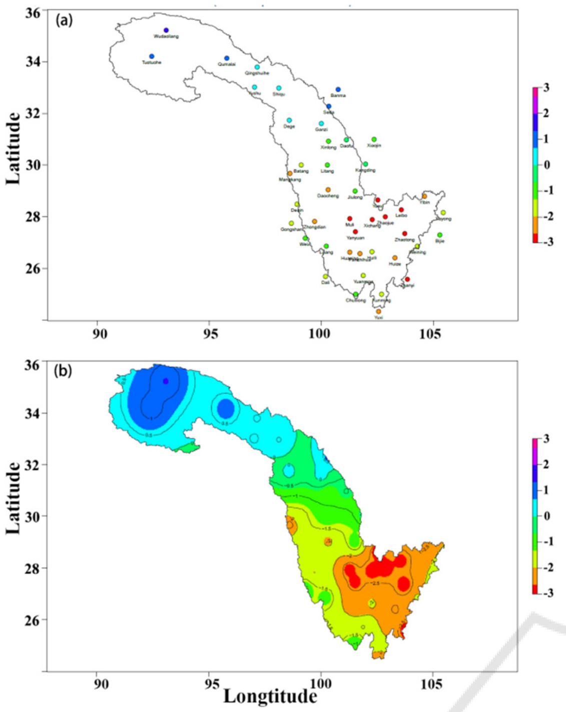

Figure 8: The spatial distribution of drought characteristics of the JRB based on SPI-6 values in December 2011.

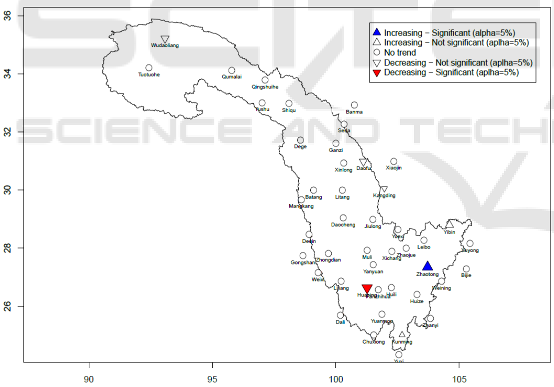

Figure 9: Trends in the drought duration based on SPI-6 using Mann-Kendall test with a 5% significance level.

Figures 9 to 11 show the trends of the drought characteristics (drought duration, drought magnitude and drought intensity) at 45 meteorological stations within and near the JRB based SPI-6 values using M-K test. There is no visible trend in drought duration at 38 of 45 stations, 4 with a decreasing trend and 1 with an increasing trend. The drought magnitude analysis is dominated by a decreasing trend, with 27 of the 45 stations showing a decreasing trend, but only 2 are significant. The drought intensity analysis, on the other hand, is dominated by an increasing trend, with 26 out of 45 stations in a increasing trend, while the middle and lower regions of the JRB is more visible.

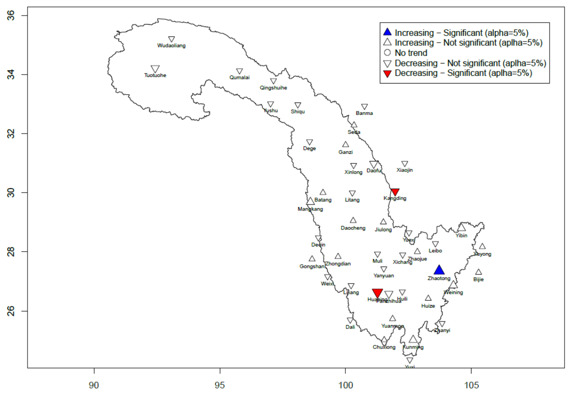

Figure 10: Trends in the drought magnitude based on SPI-6 using Mann-Kendall test with a 5% significance level.

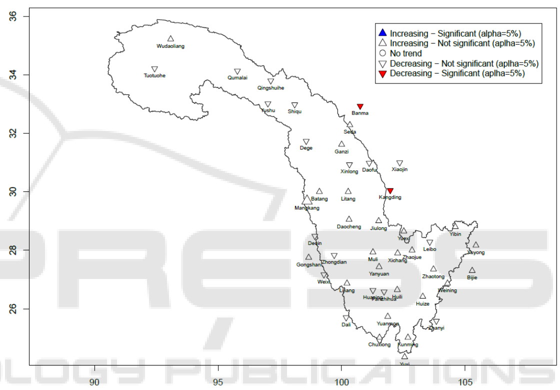

Figure 11. Trends in the drought intensities based on SPI-6 using Mann-Kendall test with a significance level of 5%.

5 CONCLUSIONS

Based on the multi-year data series of meteorological and hydrologic stations within and around the basin, the temporal-spatial variations of hydro-meteorological elements in the JRB were analyzed, and the basin drought characteristics were also assessed using SPI-6 values. The following conclusions are drawn:

The three temperature types (minimum, mean and maximum) and daily precipitation of the JRB all show a increasing from the upper to lower reaches. The relationship between temperature and station elevation is significantly negative linear, and the coefficient of determination R^2 is greater more than 0.8.

The M-K test of annual values of mean temperature, precipitation, and runoff reveals that the mean temperature of 42 of 45 stations is rising, while precipitation is rising at 25 of them.The runoff at all five hydrologic stations is increasing. The temperature and precipitation in the upper reaches are the areas with the greatest increase in the JRB, while the precipitation in the lower reaches is the only one that is on a downward trend.

In the drought analysis based on SPI-6, the downstream of JRB, where is sited in the provinces of Sichuan and Yunnan, is the region with the most severe drought in December 2011. There is no significant trend in drought duration at 38 of 45 stations, and the drought magnitude analysis is dominated by a decreasing trend. There is, however, a statistically significant increase trend of drought intensity the middle and lower reaches.

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