Letter of Response (hess-2017-261)

We would like to thank the Editor for handing the manuscript, and to thanks the Referees for their insightful comments, which have helped improving the manuscript. We provide below our detailed response to each comment. All page and lines numbers refer to the revised marked manuscript.

To Reviewer #1:

General Comments:

It has been a pleasure reading through this contributions. This work characterizes the drought by linking climate anomaly with the change in precipitation-runoff relationship in China's Loess Plateau, and discusses the policy implications of the study to water resource management in a water-limiting environment. The study is scientifically valid, the methods and data sources are well explained, and the results are clear and well presented, though there are some aspects need to ameliorate. Overall, I would recommend this manuscript for publication in Hydrology and Earth System Sciences, with some comments and suggestions.

[Response]We thank the reviewer for supporting the publication of this MS. The MS has been revised carefully, following the reviewer's comments and suggestions. Our detailed responses follow.

[Reviewer #1 Comment 1]*Section 2.4.1. Parameters estimation: The paper chooses seven commonly functions as the candidate margins distribution for drought duration and severity, there are some deficiencies in fitting margin distribution function. For example, "by comparison…", I hope the authors can provide quantitative value to determine distribution functions. "drought and severity are fitted with weibull and gamma …", the authors need to show relevant statistical indicators.*

[Response]Based on this comment, we provide quantitative values to assess the fit of the marginal distribution functions. We use the root mean square error (RMSE) and the Kolmogorov-Smirnov (K-S) test to select the best-fitting distribution. Table 3 (Page 36) lists the estimated parameters and the results of the goodness-of-fit tests. We find that not all the distributions pass the K-S test at the 95% (α=0.05) significance level. Further, considering the RMSE, the Weibull and gamma distributions provide the best-fitting marginal distributions for drought duration and severity, respectively. The results for these distributions are shown in bold and underlined in Table 3.

[Reviewer #1 Comment 2]*Section 2.4.2. Only the method of Squared Euclidean Distance(SED) is used* *to perform the goodness-of-fit of joint distribution function, I recommend the authors can adopt more methods to evaluate the fitted copula, such as root mean square error(RMSE), the Akaike information criterion(AIC)…*

[Response] We thank the reviewer for this comment. In addition to the squared Euclidean distance (SED) method, we have employed the root mean square error (RMSE) and the Akaike information criterion (AIC) to further evaluate the fitted copula. As shown in Table 4 (Page 37), the Frank copula is the optimal joint distribution function in most watersheds examined in this study, except for the Jialu, Dali and Beiluo watersheds. The optimal goodness-of-fit values obtained using different methods are also shown in bold and underlined.

[Reviewer #1 Comment 3]*The English expression in this MS is sub-standard; it needs to be improved. The authors should further review the whole paper, although I have pointed some in specific suggestions. In addition, some sentences in the paper are very long, without clear phrasing, so that the reader is sometimes left wondering what the main point of the sentence was. The authors need also notice these problems.*

[Response]We have asked a native English-speaking scientist to help us with the language of the revised MS.

Specific suggestions:

[Reviewer #1 Suggestion 1]*Page1.L4, not all readers will know that this re-vegetation is anthropogenic, you need to explicitly state this.*

[Response]We explain the details of the revegetation programme. China experienced severe droughts in 1997 and serious floods in 1998, and these events caused serious economic and environmental damage (Tian et al., 2016). In the wake of these disasters, the Chinese government took unprecedented conservation measures (Xu and Cao, 2001), one of which was the Grain for Green Programme (GGP). This initiative was introduced in 1999 to protect the degraded environment (Zhang et al., 1999). The objective of this programme was to convert cropland to plantations and grasslands on steep slopes by compensating farmers with subsidies (Page 3, Lines 17-18 and Page 4, Lines 20-21).

[Reviewer #1 Suggestion2]*Page1.L5, delete "in the area".*

[Response]We have deleted “in the area” accordingly. The sentence has been changed to read “*This* *case study characterizes drought by linking climate anomalies with changes in the precipitation-runoff relationship (PRR) on the Loess Plateau of China, a water-limited region where ongoing revegetation makes drought a major concern*." (Page 1, Lines 4-6)

[Reviewer #1 Suggestion3]*Page3.L11,delete "reflect".*

[Response]We have deleted the word "reflect" accordingly. The sentence has been changed to read "*Thus, analysing drought characteristics in terms of the changes in the PRR that occur in response to multi-year dry periods is of great importance in estimating the effects of drought and the ecological reconstruction of the Loess Plateau as a whole.*" (Page 3, Lines 25-28)

[Reviewer #1 Suggestion4]*Page3.L20, as the climate is changing over what years are these long-term averages calculated?*

[Response]We state clearly in the revised MS that the long-term averages are calculated for the period of 1960–2000 (Page 4, Lines 6-7).

[Reviewer #1 Suggestion5]*Page4. L21, "propose use"?*

[Response]We have modified this sentence to read "Here, we use the copula function (Shiau, 2006)." (Page 5, Line1)

[Reviewer #1 Suggestion6]*Page6.L9, states that 7 dry periods are identified yet on Fig 8(a) there are 15 events. This is confusing.*

[Response] "Based on the drought identification method developed in this study, 7 dry periods are identified (including major dry periods and single-year dry periods) on the Loess Plateau as a whole during 1961-1999 (Page 7, Lines 20-22). The purpose of this study is to focus on the changes of the PRR during the major dry periods. Further, considering the variability of the PRR during the dry periods in each watershed (section 3.3), there are 15 dry periods (including significant and non-significant changes) in the 13 studied watersheds, in which the drought regressions fall under the overall regression lines (Page 13, Lines 4-5). We have clarified this point in the revised MS.

[Reviewer #1 Suggestion7]*Page6.L19, "In1991–1999 (p=0.000) there was a significant decrease change significantly in the PRR", expression is repeated.*

[Response]We have modified this sentence to read “However, a significant decrease in the PRR can be identified for 1991–1999 (p=0.000).” (Page 8, Lines 7-8)

[Reviewer #1 Suggestion8]*Page8.L6, "multi_yeat".*

[Response]We have revised “multi_yeat” to “multi_year”.

[Reviewer #1 Suggestion9]*Page8.L10, "Compared to"*

[Response]We have revised this sentence to read “*Compared with the annual average precipitation in separate watersheds during 1961–1999, the watersheds where no significant changes in the PRR occurred (Kuye, Dali, Qingjian, Yanhe, and Jinghe) received greater amounts of precipitation.*” (Page 10, Lines 6-7)

[Reviewer #1 Suggestion10]*Page10.L24, hey you are introducing a new model and a new dataset in the Discussion section. This is very non-standard the structure is all over the place.*

[Response] We agree with the reviewer that, in a standard structure, the net primary production (NPP) data that are derived with the terrestrial Carnegie-Ames-Stanford approach (CASA) that we employ in the discussion section on Page 10 L24 should be first explained in section 2.1.

However, we have replaced the NPP data in this section with satellite-derived Leaf Area Index (LAI), according to the comments of Reviewer #2 (see our response to Reviewer #2, general comment 4). In line with this comment, we describe the LAI data in section 2.1 in the revised MS. (Page 4, Lines 17-20)

[Reviewer #1 Suggestion11]*Fig 5, Precipitation, and many other hydrological variables, have the dimensions of depth / time, and you need to include the time of integration into you units. So your X-axis should have the units of mm/year. When assessing annual trends of annual (or actual E, potential E or Epan) the units are mm/year/year, as in such a plot the X-axisis years, and the Y-axis of an annual P time-series is mm/year, so the slope (or trend)of delta_Y / delta_X has the units of mm/year/year.*

[Response]We have revised this figure so that the X-axis and Y-axis represent P (mm/year) and runoff (mm/year), respectively in the revised MS, as shown in Figure 5 (Pages 25-27).

References

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To Reviewer #2:

General Comments:

The authors analyze the drought impacts on the runoff ratio in China's Loess Plateau. The climate anomaly, relationships between precipitation-runoff, the implications for ecosystem, and the water resource management were discussed in the manuscript. The structure of the manuscript and the problems description are well organized, but there are several serious flaws in the data analysis, methods description, and interpretations of results. Thus, this version of the manuscript can not be accepted for publication in HESS.

[Response]We thank the reviewer for these comments. We have carefully considered all the reviewer's comments, and our responses are shown below. We believe the MS has been substantially improved, and the issues noted by the reviewer have all been addressed.

[Reviewer #2 Comment 1]*First, the amount of the water consumption for the local communities (domestic and industrial usage) is vital for the runoff ratio in the study period, especially for during the drought. The authors should at least investigate the changes in the water supply for the local communities.*

[Response] We agree that the amount of water consumed by the local communities is vital for the runoff ratio, especially during drought periods. For example, Bouwer et al. (2006) concluded that increasing water consumption for irrigation and the degree of runoff variability caused hydropower is three times higher than the variations in runoff under climate change in a densely populated region in the main agricultural irrigation area in India (Page 11, Line 26 to Page 12, Lines 1-3). However, the water consumption for the local communities is not a major issue in our study area, which is composed of 13 hilly catchments on the Loess Plateau.

The catchments examined in our study lie in the part of the Loess Plateau with the greatest relief, and the Mu Us Desert is located in the northwest and the Weihe Plain is located in the southeast (Page 11, Lines 23-25). The water consumed by the local communities on the Loess Plateau is fed to the residential areas, which are mainly located in the flat areas at the outlets of the catchments (the distribution of residential areas is shown in Fig. 1, Page 21). Moreover, the population shows a tendency to move from the catchment area to the major cities, which are located along the mainstream of the river basin in the Weihe Plain (i.e., Baoji, Xi'an, these cities contain 57.35% of the population within the study area) because of the accelerated urbanization that has taken place in this area since the 1980s (Hu et al., 2001). (Page 12, Lines 5-9)

In line with these considerations, in the studies of runoff variability of the same catchments, the water supply to the local communities is also not included as a factor influencing runoff. Instead, the anthropogenic factors that drive the changes in runoff in the 13 studied catchments include terrace building and soil conservation measures (Wang et al., 2009; Shi et al., 2013; Chang et al., 2015) (Page 12, Lines 14-17). We have added explanations of this point to the revised MS.

[Reviewer #2 Comment 2]*The precipitation-runoff relationships can be influenced by the land use, surface water diversion, irrigation scheme, groundwater abstraction, and the water storage in the(sub) catchment. These issues should be addressed for identifying the influence of drought on the water yield.*

[Response] We agree with the reviewer that the precipitation-runoff relationships can be influenced by factors other than climate conditions. We have carefully considered each possible factor in our study, as described below.

The catchments lie in the part of the Loess Plateau with the greatest relief, and the vegetation in the catchments is mostly rain-fed. Thus, the effects of irrigation schemes within the study area can be neglected (Feng et al., 2016) (Page 11, Lines 23-26). The thickness of the loess within the catchments is greater than 100 m (Derbyshire et al., 1998), and the groundwater is minimally impacted by the surface eco-hydrological processes; thus, groundwater recharge and groundwater discharge are not considered in the study area (Page 11, Lines 26-29). Finally, any diversions of surface water and water storage are found in the residential areas at the outlets of these catchments Therefore, their effects are not included as potential impact factors affecting the precipitation-runoff relationships (Page 12, Lines 10-12).

However, soil conservation measures, including the construction of terraces and sediment-trapping dams, have been implemented in the Loess Plateau since the 1950s (Wang et al., 2016) (Page 12, Lines 14-15). We have added a description of the influence of these human-stimulated effects on precipitation-runoff relationships in the revised MS. The partial correlation method is used to isolate the impacts of anthropogenic influences from climate-related factors (Page 12, Lines 17-18).

For the entire period of 1982–1999, the runoff displays a decreasing trend (Fig. 8, Page 30).Terrace construction played an important role in producing the reduction in the runoff ratio from the 1980s to the 1990s (*p*=0.048, Fig. 9, Page 31). The effects of other anthropogenic activities, including dam construction, tree plantations and pastures, did not cause the observed change in the runoff ratio in this period. Terrace construction contributed 25% of the reduction in the runoff ratio in the 1990s. Thus, drought events are the major factor driving the reduction in runoff in the study area (Page 12, Lines 20-23). We have added a description of this analysis to the revised MS.

[Reviewer #2 Comment 3]*Section 2.2 The proposed classification method of drought events, drought periods, the interpretations of results, and the upscale processes from 13 sub catchments to regional precipitation anomaly are not clear enough to support the publication of this version of the manuscript in HESS.*

[Response]We thank the reviewer for this comment. We have rewritten section 2.2 to clarify the classification method. The relevant text reads as follows in the revised MS.

"I*n this study, we define drought based on annual precipitation for two aspects. On the one hand, the amount of precipitation is the most important climatic control of drought conditions (Mishra and Singh, 2010). Moreover, because we are interested in determining whether the runoff response differs for multiyear droughts, we do not consider runoff in identifying drought events.*

We first calculate the precipitation anomaly (PA) values in the studied watersheds on the Loess Plateau. The time series of anomaly values are divided by the mean annual precipitation and smoothed with a 3-year moving average. Positive PA values indicate that the observed precipitation is higher than the median. On the other hand, negative PA values indicate that the observed precipitation is below the median and imply the possible occurrence of a drought. Each drought event is characterized in terms of *its duration and severity. Studies have shown that the drought events with shorter durations but greater intensities or lower intensities but greater durations cause serious water-supply and other drought-related problems (Shiau, 2006; Naresh et al., 2009). Therefore, the basic rules for identifying drought events in this study are (1) a PA value for a single year of ⩽ -10% or (2) mean PA values of less than 0 for more than three consecutive years. Note that the PA value of the starting year of each drought period is negative.*

In this study, the cumulative PA values during each drought period are used to measure drought severity (for convenience, drought severity is multiplied by -1 to obtain a positive value). Based on the rules mentioned above, we identified all of the drought events that occurred in each watershed. To reflect the response of the PRR to drought events over the years, we must ensure that the dry periods are sufficiently long and severe. In the subsequent analysis, we consider only drought events with durations ⩾ 5years and mean annual PA values ⩽ -5% during the drought period. Finally, the dry events are classified into major dry period and single-year dry period.

We use the Kolmogorov-Smirnov (K-S) (Massey, 1951) test to determine whether annual precipitation and runoff data follow a roughly normal distribution. A Box-Cox transformation is applied to those data that are not normally distributed (Box and Cox, 1964). After identifying the major drought events, we examine whether the change in the PRR is statistically significant compared to the historic record using Student's t-test (p ⩽ 0.05). The historical records refer to scatterplots of annual precipitation-runoff during the period of 1961–1999, except for particular major drought periods. For example, when the drought that occurred in 1970–1974 is considered, the corresponding historical record includes a precipitation-runoff scatter plot that includes data from 1961–1969 and 1975–1999. For the drought that occurred in 1991–1999, the corresponding historical record refers to a precipitation-runoff scatterplots containing data from 1961–1990."

[Reviewer #2 Comment 4]*The NPP estimation based on the remote sensing data (2000-2008) could not support the analysis results of the drought on the ecosystem from 1961 to 1999. The authors need to find at least the data in one of the main drought period defined in this manuscript and another normal period to illustrate the difference for determining the drought impacts.*

[Response]We agree with the reviewer that we need to examine data for both drought periods and normal periods to illustrate the impacts of drought. Due to the lack of NPP data before 1999, we have used the AVHRR GIMMS LAI3g data, which covers the period from 1982 to 1999 (Page 4, Lines

17-18). We choose the drought period of 1991–1999 as an example, and we find that the LAI decreases significantly (p=0.032, Student's t test) in 1991–1999 compared to 1984–1990 (Fig. 11, Page 33; Page 13, Lines 2-3). We have included this new analysis in the revised MS.

[Reviewer #2 Comment 5]*The English should be substantial improved to a certain level that the readers can not misunderstand the correct information.*

[Response]We have asked a native English-speaking scientist to help us to revise the language in the MS.

Specific comments:

[Reviewer #2Comment 1]*Affiliation: Shaanxi? should be Shanxi.*

[Response]The correct affiliation is Shaanxi. Shanxi is a different province in China, which is not related to this MS.

[Reviewer #2Comment 2]*Page 1, line 1, "is" should be "are".*

[Response]This sentence has been changed to read "*The frequency and intensity of drought are increasing dramatically as global warming progresses*." (Page 1, Line 1)

[Reviewer #2Comment 3]*Page 1, line 5, only the re-vegetation that makes the drought a major concern?*

[Response]The vegetation restoration programme in China represents the largest investment that has been made to restore the ecosystem in this developing country. Given the limited water resources on the Loess Plateau, the sustainability of vegetation restoration programs is a major concern of scientific research and policy makers there (Feng et al., 2016) (Page 13, Lines 18-20). We have clarified this point in the revised MS.

[Reviewer #2Comment 4]*Page 1, line 12 delete the "around" after "precipitation"*

[Response]We have deleted the word " around " where it follows " precipitation".

[Reviewer #2Comment 5]*Page 1, line 13-14,"NPP" and "PRR" should not be abbreviation in first appearance.*

[Response]We have changed this sentence to read "*At the same time, multiyear drought events also lead to significant changes in the leaf area index (LAI).*" (Page 13, Lines 18-20). Here, NPP has been replaced with LAI. A detailed explanation of this change can found in the response to general comment 4 of Reviewer #2.

[Reviewer #2Comment 6]*page 2, line 9-11, weird sentence.*

[Response] We are sorry that this part of the text was unclear. The sentence has been changed to read "*For example, the soil moisture indicator (Xia et al., 2014), the crop drought indicator (Duff et al.,1997) and the crop water demand indicators are used to identify agricultural drought events, which are periods that feature dry soil conditions and result from below-average precipitation, intense but less frequent rain events, or above-normal evaporation. All of these factors lead to reductions in crop production and plant growth.*" (Page 2, Lines 14-18)

[Reviewer #2Comment 7]*Page 2, line 30, replace the "with" with "by".*

[Response]We have revised the sentence to read "*Therefore, the shift in the PPR caused by an extended drought will eventually have an adverse effect on the ecosystem service of water yield.*" (Page 3, Lines 10-11)

[Reviewer #2Comment 8]*Page3, line 25, please indicate the data length or periods.*

[Response]In the revised MS, we have indicated that the data extend from 1961 to 1999 (Page 4, Lines 14-15).

[Reviewer #2Comment 9]*Page 3, line 27, website in the bracket does not match the text.*

[Response]According to this comment, we have revised the website in the brackets to http://www.yellowriver.gov.cn/.

[Reviewer #2Comment 10]*Page 4, line 2, replace "its" with "in".*

[Response] Following this comment, we have modified the sentence to read "*We first calculate the precipitation anomaly (PA) values in the studied watersheds on the Loess Plateau. The time series of anomaly values are divided by the mean annual precipitation and smoothed with a 3-year moving average.*" (Page 4, Lines 29-30)

[Reviewer #2Comment 11]*Page 4, line4, conditions 2 should be page 6, clarified.*

[Response]We have checked condition 2 on Page 4, line 4 in the MS. As one of the basic rules for identifying drought events in this study, we think putting it in section 2.2 ((Page 5, Lines 7-8) is more appropriate.

[Reviewer #2Comment 12]*Page 6, line 21, please indentify the time period for "long term".*

[Response] In the revised MS, we have clarified that the phrase “long term” refers to the period from1961 to 1990 (Page 8, Lines 9-10).

[Reviewer #2Comment 13]*Page 7, line 25-27, long sentence.*

[Response]This sentence on Page 7, line 25-27 has been revised to read “*The return period of the drought period that occurred in 1970-1974 is approximately 5.74 years, given the corresponding drought characteristics. Therefore, the next drought event similar to the drought period that took place from 1970 to 1974 occurred around 1980. In 1979–1983, the drought duration reached 5 years, which is close to the estimated return period.*” (Page 9, Lines 17-21)

[Reviewer #2Comment 14] section 3*.3, please re-write the first paragraph.*

[Response]We have rewritten the first paragraph of section 3.3. It now reads as follows.

“*Prolonged multi-year drought causes significant damages in natural environments. Fig. 5 demonstrates the range of changes in the PRR under sustained precipitation decreases. According to the direction of change, the dry period regression line is mainly located above or below the overall regression line, and the PRR in the 13 studied watersheds exhibits no significant change when the regression line of the dry period is above the total regression line. Of the 15 cases in which dry events fell under the overall regression line in the 13 watersheds from 1961 to 1999, significant changes in the PRR ($p < 0.05$) occurred in 9 cases, accounting for approximately 60% of the total cases. In these cases, the dry period regression line lies lower than nearly all of the other parts of the historical record, indicating unprecedentedly low runoff generation rates for the given precipitation values. Thus, we conclude that reduced runoff occurs in years with decreased precipitation due to the reduction in precipitation; moreover, less runoff than expected occurs during multi-year drought periods.*”

[Reviewer #2Comment 15]*Page 8, line 10, where are the basins with significant changes in precipitation in table 1?*

[Response] We apologize for the confusion. The phrase " significant changes " on Page 8, line 10 refers to those watersheds which display significant changes in the PRR. Comparing the annual mean precipitation in separate watersheds during 1961–1999 (Table 1, Page 34), we find that multiyear drought events are more likely to cause significant changes in the PRR of basins that receive less precipitation. We have clarified this point in the revised MS.

[Reviewer #2Comment 16]*Page 9, line 5, replace the "as well as " with "and "*

[Response]We have modified this sentence to read "*Prolonged multi-year drought events cause significant damages to both the natural environment and the development of human societies (Belal* et al.*, 2014).*" (Page 11, Lines 5-6)

[Reviewer #2Comment 17]*Page 9, line11, should be "http://www.mwr.gov.cn"*

[Response]We have revised this link to "http://www.mwr.gov.cn".

[Reviewer #2Comment 18]*Figure 1, where is the Yellow river? it is indicated on the up-left small plot that the Yellow river flows through the loess plateau.*

[Response]The Yellow River flows through the Loess Plateau. We have labelled the Yellow River in the inset map in the upper left-hand corner of Fig. 1 (Page 21).

[Reviewer #2Comment 19]*Figure 2, Do you use the average of rainfall for the 13 watersheds? The description of drought events for condition 1 and 2in section 2.2 may not be applied on the year 1974, when the 3- year moving average should be lowest in the first main drought period. But the 3-year moving average in1970 in the figure is lowest.*

[Response]Yes, we used the average rainfall for the 13 watersheds in Figure 2. After re-examining the calculation of the original data, we found a mistake in our computation of the 3-year moving average. After revising the results, the first main drought period is shown to have occurred in 1970–1974. As shown in Fig. 2 (Page 22), the rainfall anomaly in 1974 is -23%, which is consistent with condition 1 in section 2.2. In the first main drought period, the 3-year moving average of 1974 is only smaller than in 1972. We have corrected this mistake in the revised MS.

[Reviewer #2Comment 20]*Figure 3, What are the historical records? Apparently, the historical records in three plots are different, why? better to use the same scale for x-axis in three plots.*

[Response]The historical records in Figure 3 refer to scatterplots of annual precipitation-runoff during the period of 1961–1999, except for particular major drought periods. For example, when the drought that occurred in 1970–1974 is considered, the corresponding historical record includes a precipitation-runoff scatter plot that includes data from 1961-1969 and 1975–1999. For the drought that occurred in 1991–1999, the corresponding historical record refers to a precipitation-runoff scatterplot containing data from 1961–1990 (Page 5, Lines 23-28). Because three different multiyear dry periods occurred on the Loess Plateau during 1961–1999, the corresponding historical records are different in the three plots. We have clarified this point in the revised MS.

[Reviewer #2Comment 21]*Figure 5, the drought periods in different sub-catchments are not identical, why? again, what are these historical records?*

[Response]The drought periods vary spatially, as shown in Figure 5. The drought period in each catchment is identified using the local precipitation data and changes in the precipitation-runoff relationship.

As in Figure 3, the historical records refer to the annual precipitation-runoff scatter plot for the period of 1961–1999, except for particular major drought periods. A detailed explanation is provided in the response to comment 20 of Reviewer #2.

[Reviewer #2Comment 22]*Figure 7, what is the drought event corresponding to the return period in figure 7d?*

[Response]The drought event corresponding to the return period in Fig. 7d has a drought duration and severity that caused a significant change in the PRR in 8 of the studied watersheds (Page 10, Lines 22-25). We have clarified this point in the revised MS.

[Reviewer #2Comment 23]*Figure 8, at least show the whole legend of Figure 8a. is it the average return period of the drought events in 8b?*

[Response]Based on this comment, the legend of Fig. 10 (Page 32) has been revised to read " *(a) Characteristics of drought events with significant changes and (b) spatial distribution of the joint return period(four regions).*" It is the average return period of the drought events in Fig. 10(b).

[Reviewer #2Comment 24]*Figure 9, add "change" after the significant in the caption.*

[Response] The Figure 9 had been deleted in the revised manuscript.

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Characterizing drought ~~by~~ in terms of changes in the precipitation-runoff relationship: a case study of the Loess Plateau, China

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Abstract. The frequency and intensity of drought ~~is~~ are increasing dramatically ~~with~~ as global warming. ~~Yet~~However, few studies have characterized drought ~~from~~ in terms of its impacts on ~~the~~ ecosystem services, the mechanisms through which ecosystems support life. As a result, little is known about the implications of increased drought ~~on~~ for resource management. This case study characterizes drought by linking climate ~~anomaly~~ anomalies with ~~the~~ changes in the precipitation-runoff relationship~~s~~ (PRR), ~~in~~ on the Loess Plateau of China, a water-limited region where ongoing re~~-~~vegetation ~~in the area~~ makes drought a major concern. We ~~analyze~~ analysed drought~~s~~ events with ~~duration greater than 5 years and annual precipitation anomalies more negative than -5%~~ drought durations ≥ 5 years and mean annual precipitation anomaly (PA) values ≤ -5% during drought periods~~,~~. ~~we found~~ The results show that continuous precipitation shifts ~~is~~ are able to change ~~watershed~~ water balance of watersheds in the water limited areas~~,~~ and multi-year drought cause~~d~~ the ~~precipitation-runoff relationship~~PRR to change with a significantly ~~descending~~ decreasing trend ($p < 0.05$) compared to other historical records. For the ~~whole~~ Loess Plateau as a whole, the average runoff ratio decreased from 10 percent to 6.8 percent in 1991–1999. The joint probability and return period gradually increase~~d~~ with ~~the~~ ~~increase~~ increasing of drought duration and severity. The ecosystem service of water yield ~~was~~ is easily affected ~~easily when the~~by drought events with duration~~s~~ ~~is not less than~~equal to or greater than six years and ~~the~~ drought severity ~~is~~ values equal to or greater than ~~or equal to~~ 0.55 (precipitation ~~around~~ ~~≤~~≤212 mm). At the same time, ~~the growth ratio of annual NPP is also susceptible to prolonged drought, the growth ratio is lower in these watersheds which had a significant change in the PRR.~~ multiyear drought events also lead to significant changes in the leaf area index (LAI)~~.~~. Such studies are essential ~~to~~ for ecosystem management in ~~a~~ water-limited area~~s~~.

1 Introduction

Drought is a complex and recurrent ~~climatic~~ climate-related phenomenon~~, causing~~ that has far-reaching ~~and negative~~ adverse impacts on agriculture, water resources, the environment and human life (Ghulam et al., 2007; Goddard et al., 2001). Few types of extreme events ~~are~~ have been as economically and ecologically disruptive as droughts over the past half ~~a~~ century (Dai, 2011). For example, multi-year droughts across the globe have triggered an increase in ~~tress~~ tree mortality ~~which~~ that is linked to climate change (Allen et al., 2010). At regional scales, during 1998–2001, one-third of ~~Iran's~~ the territory of Iran ~~territory~~ was affected by the most severe drought in the ~~country's~~ history of the country. ~~with m~~More than half of the country's population ~~facing~~ faced food shortages and ~~insufficient~~ a lake of drinking-water supplies (Raziei et al., 2009). The annual economic losses caused by droughts in the United States are estimated as being up to US$6-$8 billion (Wilhite, 2000). As a result of these impacts ,~~-an~~ increasing numbers of studies ~~are now focusing on~~ now focus on characterizing drought events, including drought identification and frequency analysis, and the ~~necessary~~ resource management actions ~~drought bring~~ required by droughts (Michele et al., 2013).

Many drought indices have been developed to monitor~~ drought evolution~~ the evolution of drought events on regional and global scales (Yan et al., 2016). Meteorological drought can be identified ~~by~~ from ~~sample~~ anomalies in precipitation data, ~~such~~ as assessed by the Palmer ~~D~~drought ~~S~~severity ~~I~~index(PDSI) (Palmer, 1965), the ~~S~~standardized ~~P~~precipitation ~~Index~~-index(SPI) (Mckee et al., 1993), the ~~P~~precipitation ~~A~~anomaly (Moron, 1994) and the Bhalme-Mooley ~~I~~index (Bhalme and Mooley, 2009). Others researchers have recognized the necessity of developing drought indicators that reflect the causes and impacts of drought, and the resulting ~~these definitions of~~ drought ~~index~~ indices incorporate many different physical, biological and socioeconomic variables (Sheffield et al., 2004). ~~Examples as: the soil moisture indicator (Xia et al., 2014), crop drought indicator (Duff et al., 1997) and the crop water demand indicators that are used to reflect the decreased harvests of crops suffering water stress under drought conditions.~~ For example, the soil moisture indicator (Xia et al., 2014), the crop drought indicator (Duff et al.,1997) and the crop water demand indicators are used to identify agricultural drought events, which are periods that feature dry soils conditions and result from below-average precipitation, intense but less frequent rain events, or above-normal evaporation. All of these factors lead to reductions in crop production and plant growth. ~~For h~~Hydrological~~-~~droughts ~~indicators~~ (Herbst et al., 1966;~~ MOHAN and RANGACHARYA~~ Mohan and Rangacharya, 1991), ~~droughts~~ are usually identified ~~based by~~using run-length theory and are characterized as periods where water demand exceeds supply because of long- term precipitation shortages. In addition, socioeconomic drought ~~can~~ reflects the undesirable social and economic impacts induced by the other ~~above-mentioned drought~~ types of droughts mentioned above. All of these drought indicators ~~are based on defining a~~employ single variables to quantify ~~a~~ drought events. However, drought conditions are associated with multiple variables~~,~~; thus,~~a~~ no single drought indicator ~~can not be sufficient to characterize~~ provides a satisfactory characterization of the ~~complicated~~ complex conditions associated with droughts ~~condition and reflect its wide~~ or their broad impacts (Hao and Singh, 2015). At the same time, because ecosystem services are closely related to ~~our lives~~ the living conditions experienced by human beings(Burkhard et al., 2014; Zheng et al., 2016), these drought indicators ~~can also not~~ also cannot reflect ~~its~~ the impacts of droughts on ecosystems and ~~remain less~~ provide relatively little ~~informative~~ information to ~~the~~ policy makers and resource ~~management~~managers.

The precipitation-runoff relationship (~~PPR~~PRR) is an important issue in engineering hydrology, water resource planning and management, and watershed system evolution (Guo et al., 2016; Nourani et al., 2015). ~~The focus of c~~Current ~~researches~~ studies focus on ~~involving the~~ changes ~~and transformation process of~~ in the precipitation-runoff relationship and the processes by which these changes occur. Charlier et al. (2015) applied the wavelet transform method to detect ~~the change of~~changes in the PPR. Sun et al. (2016) assessed hydrologic trends in urban catchments ~~by using~~using a conceptual urban precipitation-runoff model, which is beneficial ~~to~~ for the stormwater management and planning. There is no doubt that ~~the~~ variations in the PPR reflect~~s~~ the actual integrated volume of precipitation and runoff. The ratio between the annual runoff and the annual precipitation, the so-called "runoff ratio" (Savenije, 1996; Feng et al., 2016b)~~, can usually~~is frequently ~~be used~~ employed to quantify the ecosystem service of water yield. This ecosystem service is of major concern in water-limited areas because it represents the water resource available to human beings. Studies have shown that protracted drought may affect runoff generation and cause changes in the PPR (Petrone et al., 2010; Saft et al., 2015). ~~So the~~Therefore, the shift in the PPR caused ~~with~~ by an extended drought will eventually have an adverse effect on the ecosystem service of water yield. Based on this perspective, we want to characterize drought events ~~by~~ in terms of the changes in the PRR that they produce and investigate the characteristics and frequency of these dry events, thus contributing to further ~~optimize~~ optimizations of ecosystem management.

Drought stress is the main environmental factor limiting terrestrial ecosystem productivity in arid and semi-arid areas (Boyer, 1982). The vegetation restoration programme in China represents the largest investment that has been made to restore the ecosystem in this developing country. Given the limited water resources on the Loess Plateau, the sustainability of vegetation restoration is a major concern of scientific research and policy makers there (Feng et al., 2016b). ~~In China's Loess Plateau,~~ As a typical ~~human and nature~~ coupled human-natural system on the Loess Plateau of China, the ecosystem service of water yield is of concern ~~not only to~~ for both the sustainability of ~~the~~ re~~-~~vegetation programme ~~but also related to~~and the objective of raising the level of ~~human~~ economic development (Wang et al., 2015; Feng et al., 2016a). ~~As one of the hydrological services, water yield plays a vital role in developing human society while maintaining ecological security.~~ In recent years, the climate of the Loess Plateau climate has ~~been~~ become ~~warming~~ warmier and ~~drying~~ drier (Lü et al., 2014) as ~~the~~ global temperatures have ~~increases~~increased, a change that will eventually affect the balance between ~~regional~~ the water supply and demand of the region. Thus, ~~So analyzing~~analysing drought characteristics ~~based on the response~~ in terms of the changes ~~of~~ in the PRR that occur ~~change~~ in response to multi-year dry periods is of great importance in estimating ~~reflect~~ the effects of drought and the ecological re~~-~~construction of the ~~whole~~ Loess Plateau as a whole.

The objectives of our study are to characterize droughts ~~in~~ on the Loess Plateau. We first link climate conditions and the PRR to define drought~~;~~. ~~we~~ We then simulate~~d~~ the drought frequency and return period of ~~different~~ drought events of different magnitudes. Finally, we discuss the policy implications of our study ~~to~~ for ecosystem management.

2. Materials and Methods

2.1. Study area

The Loess Plateau (Fig. 1) is located between 100°54′E-114°33′E and 33°43′N-41°16′N~~, covering~~and covers a total area of 624,000 km^2. It has a semi-arid and semi-humid climate~~ with~~. From 1960 to 2000, the annual precipitation ~~ranging~~ ranged from 200 mm in the northwest to 700 mm in the southeast. It is a key area in ~~the~~ current and past efforts to conserve soil and water in the Yellow River basin. The ecology of the Loess Plateau is sensitive to climate change.

In this study, we ~~use~~ examine the 13 primary watersheds~~, which comprise the main watershed~~ of the Loess Plateau(Fig. 1)~~.~~, which make up approximately 35% of the area of the Loess Plateau. The ~~R~~river runoff from these thirteen watersheds ~~(about 35% of the Loess Plateau area)~~ contributes 65% of the discharge into the middle reach of the Yellow River. The attributes of each basin are shown in Table 1. Runoff and meteorological data for these 13 watersheds covering the period from 1961 to 1999 were obtained from the Yellow River Conservancy Commission (~~http://tghl.forestry.gov.cn/~~ http://www.yellowriver.gov.cn/) and the National Meteorological Information ~~Center~~ Centre (NMIC; http://cdc.nmic.cn/home.do) of the Chinese Meteorological Administration (CMA), respectively. The AVHRR GIMMS LAI3g datasets covering the period from 1982 to 1999 were also used in this study. These datasets were generated from AVHRR GIMMS NDVI3g data using an Artificial Neural Network (ANN) based model (http://sites.bu.edu/cliveg/). Some studies have shown that the Grain for Green

Program(GGP), which began in 1999, resulted in the a reduction of runoff in from the Loess Plateau (Zhang et al., 2008; Feng et al., 2016b), so the study period is selected from 1961 to 1999.

2.2. Drought identification

~~We first calculated the precipitation anomalies in the whole Loess Plateau its separate watersheds, the anomaly series were divided by the mean annual precipitation and smoothed with a 3-year moving average. The basic rules for identifying drought events are (1) A single year's precipitation anomaly more negative than -10%; (2) The precipitation anomaly negative 0 for more than three consecutive years.~~

~~The precipitation anomaly of drought events with condition (1) or cumulative value of (2) is taken as the corresponding drought severity (for convenience, drought severity is multiplied by -1 to obtain a positive value). Based on the rules above mentioned, we recognized all dry events in every watershed. There is a limit to the duration and severity of drought events: this is to reflect the response of PRR to drought events over the years. The drought events studied here mainly had a duration of not less than five years and a mean annual precipitation anomaly more negative than -5% during the drought period. Then we classified these dry events as the main dry period, others as the single dry period.~~

In this study, we define drought based on annual precipitation for two aspects. On the one hand, the amount of precipitation is the most important climatic control of drought conditions (Mishra and Singh, 2010). Moreover, because we are interested in determining whether the runoff response differs for multiyear droughts, we do not consider runoff in identifying drought events.

We first calculate the precipitation anomaly (PA) values in the studied watersheds on the Loess Plateau. The time series of anomaly values are divided by the mean annual precipitation and smoothed with a 3-year moving average. Positive PA values indicate that the observed precipitation is higher than the median. On the other hand, negative PA values indicate that the observed precipitation is below the median and imply the possible occurrence of a drought. Each drought event is characterized in terms of its duration and severity. Studies have shown that the drought events with shorter durations but greater intensities or lower intensities but greater durations cause serious water-supply and other drought-related problems (Shiau, 2006; Naresh et al., 2009). Therefore, the basic rules for identifying drought events in this study are (1) a PA value for a single year of $\leqslant$ -10% or (2) mean PA values of less than 0 for more than three consecutive years. Note that the PA value of the starting year of each drought period is negative.

In this study, the cumulative PA values during each drought period are used to measure drought severity (for convenience, drought severity is multiplied by -1 to obtain a positive value). Based on the rules mentioned above, we identified all of the drought events that occurred in each watershed. To reflect the response of the PRR to drought events over the years, we must ensure that the dry periods are sufficiently long and severe. In the subsequent analysis, we consider only drought events with durations $\geqslant$ 5years and mean annual PA values $\leqslant$ -5% during the drought period. Finally, the dry events are classified into major dry periods and single-year dry periods.

We used the Kolmogorov-Smirnov (K-S) (Massey, 1951) test to determine whether annual precipitation and runoff data followed an roughly normal distribution~~, if~~. ~~they did not, they were transformed with a Box-Cox transformation~~ A Box-Cox transformation is applied to those data that are not normally distributed (Box and Cox, 1964). After identifying the ~~main~~ major drought events, we ~~tested~~ examine whether the change in the PRR ~~change was~~is statistically significant compared to the historic record using Student's ~~T~~t-test ($p \leqslant 0.05$). The historical records refer to scatterplots of annual precipitation-runoff during the period of 1961–1999, except for particular major drought periods. For example, when the drought that occurred in 1970–1974 is considered, the corresponding historical record includes a precipitation-runoff scatter plot that includes data from 1961–1969 and 1975–1999. For the drought that occurred in 1991–1999, the corresponding historical record refers to a precipitation-runoff scatterplots containing data from 1961–1990.

2.3. Drought frequency analysis

Drought can be characterized by multiple variables, such as duration, severity, and spatial extent (Steinemann and Cavalcanti, 2006; Hayes et al., 2012), but how to determine the joint distribution between these variables ~~has become~~remains an important issue. Here, we ~~propose~~ use the copula function (Shiau, 2006). We ~~chose~~ construct a joint distribution function using two main ~~factors affecting~~ drought characteristics, drought duration and severity~~, to construct a joint distribution function~~. If the marginal distribution functions of drought duration(d) and drought severity(s) are $F_D(d)$ and $F_S(s)$ respectively, a copula C~~,~~ exits that combines these two marginal distributions to give the joint distribution function, $F_{D,S}(d, s)$:

$$F_{D,S}(d,s) = C(F_D(d), F_S(s))$$

(1)

If the marginal distributions $F_D(d)$ and $F_S(s)$ are continuous, $f_D(d)$ and $f_S(s)$ are the density functions corresponding to $F_D(d)$ and $F_S(s)$,respectively, ~~then~~ and the joint probability density function becomes:

$$f_{D,S(d,s)} = c(F_D(d), F_S(s))\, f_D(d)\, f_S(s)$$

(2)

where c is the density function of C, which is defined as:

$$c(F_D(d), F_S(s)) = \frac{\partial^2 C(F_D(d), F_S(s))}{\partial F_D(d)\,\partial F_S(s)}$$

(3)

2.4. The criteria used ~~for~~ in ~~deciding~~ determining the values of the parameters and goodness-of-fit testing

2.4.1. Parameter~~s~~ estimation

The ~~M~~maximum ~~L~~likelihood (ML), ~~I~~inference ~~F~~functions for ~~M~~margins (IFM) and ~~C~~canonical ~~M~~maximum ~~L~~likelihood (CML) methods are commonly used in parameter estimation (Mirabbasi et al., 2012; Lee et al., 2013). Here, we use~~d~~ ML and IFM to estimate the parameters of the marginal distribution function and the joint copula functions of drought duration and severity, respectively. We ~~chose~~ employ seven common~~ly used~~ distributions to describe the univariate probability distributions as the candidate margins for drought duration and severity. ~~They~~ These distributions are the exponential, gamma, log-normal, extreme value, generalized extreme value, Poisson and Weibull distributions. The K-S test ~~was~~ is used to establish the optimal marginal distribution function. ~~By comparison, drought duration and severity are fitted with Weibull and gamma distributions respectively and the Kendal correlation coefficient of their empirical distribution and theoretical distribution function are tested by 0.05 significance T-test. Using~~ The ML method is used to estimate the distribution parameters of drought duration (α_1,β_1) and severity (α_2,β_2), and ~~then calculating~~ the parameters of copula function are then calculated usingby the following formula:

$$\ln L(d,s;\alpha_1,\beta_1,\alpha_2,\beta_2,\theta)=\ln L_C(F_D(d),F_S(s);\theta)+\ln L_D(d;\alpha_1,\beta_1)+\ln L_S(s;\alpha_2,\beta_2)$$

(4)

where $\ln L_C$ is the log-likelihood function of the copulas.

2.4.2. The determination of the optimal joint distribution function

Five commonly used two-dimensional functions were are constructed using the marginal distribution function of drought duration and drought intensity severity (Table 2). The goodness-of-fit test was is performed by calculating the Squared Euclidean Distance(SED) between the theoretical copula and the empirical copula (Berg, 2009). The empirical copula and SED are defined as:

$$\hat{C}(u)=\frac{1}{n+1}\sum_{j=1}^{n} I\{Z_{j1}\le u_1,\ldots,Z_{jd}\le u_d\}$$

(5)

$$d^2=\sum_{i=1}^{n}\left|\hat{C}(u_i,v_i)-C(u_i,v_i)\right|^2$$

(6)

In addition to the SED method, the root mean square error (RMSE) and the Akaike information criterion (AIC) are adopted to further evaluate the fitted copula.

2.5. Drought return period

N is the drought series length and n is the number of drought events. The return period of a single variable can be obtained from the definition of the copula function definition as:

$$T(d)=\frac{N}{n[1-F(d)]}$$

(7)

$$T(s)=\frac{N}{n[1-F(s)]}$$

(8)

The joint distribution function of drought duration and severity is:

$$F(d,s)=P(D\le d,S\le s)=\int_{-\infty}^{s}\int_{-\infty}^{d} f(s,d)d_u d_v=C(F_D(d),F_S(s))$$

(9)

The joint return period of the two characteristic variables is calculated as:

$$T_a(\mathrm{d},s)=\frac{N}{nP(D\ge d\cup S\ge s)}=\frac{N}{n(1-C(F_D(d),F_S(s)))}$$

(10)

3. Results

3.1. Drought events ~~in~~ on the Loess Plateau

~~There are 17 years, out o~~Of the 39 years that make up ~~of~~ the study period, ~~when~~ the precipitation anomaly is negative in 17 years. Based on the drought identification method developed in this study, 7 dry periods are identified (Fig.~~–~~2), including ~~the main~~ both major dry periods and single-year dry periods~~)~~. We ~~found~~ find that the periods of ~~1968~~1970–~~-~~1974, 1979–~~-~~1983 and 1991–~~-~~1999 ~~were~~ all represent droughts with ~~the~~ durations longer than five years. ~~having~~ The corresponding drought ~~severity~~ severities ~~up to~~are ~~0.43~~0.51, ~~0.41~~-0.32 and 0.61, ~~(~~ and the ~~corresponding~~ average precipitation~~s~~ values of these events are~~268~~ 231 mm, ~~277~~ 320 mm and 183 mm~~)~~, respectively.

Applying ~~T~~the K-S test ~~on~~ to the precipitation-runoff data from 1961 to 1999 shows that the precipitation-runoff data in this time series approximate ~~to~~ a normal distribution, providing the premise for a linear relationship between precipitation and runoff. ~~Analyzing t~~The changes ~~of~~ in the PRR during ~~in~~ the three ~~main~~ major drought periods ~~of~~ on the Loess Plateau~~, the results~~ show~~s~~ that the PRR may change significantly during these drought periods (Fig. 3). No significant changes can be identified ~~D~~during the drought periods of ~~1968~~1970–1974 (p=~~0.758~~0.692) and 1979–1983 (p=0.514), ~~no significant change was found~~ although the ~~dry period~~ regression lines for these dry periods deviate~~s~~ from the overall regression line. However, a significant decrease in the PRR can be identified for~~In~~ 1991–1999 (p=0.000) ~~there was a significant decrease change significantly in the PRR~~. In this period, the dry period regression lines are lower than nearly all of the other points, indicating unprecedentedly low runoff generation rates for ~~the~~ a given amount of precipitation. The ~~long-term average~~ runoff ratio is approximately 10 percent from 1961 to 1990. In the dry period of 1991–1999, the average runoff ratio decreased to 6.8 percent.

3.2. Drought frequency ~~in~~ on the Loess Plateau

Table 3 lists the estimated parameters and the results of goodness-of-fit tests for the marginal functions. We find that not all of the distributions pass the K-S test at the 95% (α=0.05) significance level. Further considering the RMSE, the marginal distributions that provide the best fits to the drought duration and severity values are Weibull and gamma distributions, respectively. The results for these distributions are shown in bold font and underlined in Table 3. The goodness-of-fit ~~test~~ for the joint function was ~~performed~~ evaluated by calculating the SED, RMSE and AIC. ~~the squared Euclidean distance between the theoretical copula and the empirical copula according to the criterion of the smaller the distance, the better the function fits the data~~. These metrics indicate that the Frank copula function is best suited to fitting the duration and severity of the drought events in the study area, except for the Jialu, Dali and Beiluo watersheds. ~~. It can be seen from Table 3 that the Frank-copula function has the smallest squared distance except for Gushan, Dali and Weihe watersheds, indicating that the Frank-copula function is more suitable for fitting the duration and severity of the drought events in the study area.~~ Note that, for ~~those~~ the three watersheds mentioned above, the ~~distance~~ values of the SED, RMSE and AIC~~Frank-copula function is~~ are also relatively small. Finally, ~~the~~ we choose the Frank ~~-~~copula function ~~is selected as~~ to represent the joint distribution function of ~~the two characteristics of~~ drought duration and severity.

~~It can be seen from Figs~~ Fig. 4a and 4b show that the joint probability increases with ~~the increase of~~ increasing drought duration and drought severity, ~~this occurs~~ regardless of the three-dimensional joint cumulative probability ~~three-dimensional~~ or the contour lines. When the drought severity ~~is~~ ranges from

0.1~~–~~ to 0.35 (which ~~corresponding~~ corresponds to~~-~~precipitation values that range from 306 mm~~–~~ to 423 mm), the contours are ~~intensive~~ nearly vertical, and the~~ duration of~~ drought duration varies greatly (ranging from 1 to 9 years). When the drought duration is less than five years, the cumulative probability of the bivariate increases rapidly ~~with the increase in~~as drought severity increases~~;~~. ~~i~~In contrast, when the drought duration exceeds 5 years, the rate ~~increasing trend~~ of increase in the joint probability ~~slows down~~ decreases ~~with the increase in~~as drought severity increases~~when the drought duration last more than 5 years~~. When the drought severity is not more than 0.4 (precipitation ≧~~≥~~282 mm), the joint probability of drought increases rapidly with ~~the increase of~~increasing drought duration, and the ~~increasing trend~~ rate of increase of the joint probability ~~slows down~~decreases ~~with the increase in~~as drought duration increases when drought severity is greater than 0.4 (precipitation≦~~<~~282 mm). ~~It can be seen from the density of the contours that when the drought events in the Loess Plateau lasted for 4–6 years and the drought severity was in the range of 0.3–0.5 (corresponding precipitation was 235 mm–329 mm) during 1961–1999.~~ The density of the contours shows that on the Loess Plateau from 1961 to 1999, drought events with drought duration ranging from 2 to 5 years and drought severity ranging from 0.2 to 0.5 (for which the corresponding precipitation values are 235 mm – 470 mm) occurred easily. The ~~J~~joint probabilities of drought~~s~~ characteristics are~~ important for~~key to drought management. The probability that both ~~the~~ drought duration and ~~the~~ severity simultaneously exceed certain thresholds is useful information for environmental and government agencies responsible for water system management under drought conditions.

~~Figs~~ Fig. 4c and 4d show that ~~with the increase of~~, as drought duration and drought severity increase, the joint return period also shows an increasing trend. ~~During the study period, w~~When the duration and severity of drought events reach~~ed the~~a maximum during the study period, the joint return period of such drought events ~~in~~ on the Loess Plateau ~~was~~ is close to 22 years. For the three major drought events that occurred ~~in~~ on the Loess Plateau ~~from~~ between 1961 ~~to~~ and 1999, the return period ~~was~~ is about ~~7.29~~ 5.74 years~~, while the~~ for drought durations of ~~was 7~~5 years or drought severity of up to ~~0.43~~0.51 (~~1968~~1970–1974). The return period reache~~d~~s ~~5.85~~4.32 years ~~when~~ for the drought that occurred in 1979–1983~~ with~~, which displayed a duration of 5 years and a severity of ~~0.43-~~0.39. The return period of the most severe drought event in the study period, which had a duration of 9 years and a severity of 0.61, ~~was~~ is 18.31 years.~~ with duration of 9 years and a severity of 0.61~~. ~~It can be seen that for the drought event of 1968–1974, the drought period of 7 years or the drought severity up to 0.43 was about 8 years from the time commencement of the drought, and~~ The return period of the drought period that occurred in 1970–1974 is approximately 5.74 years, given the corresponding drought characteristics. Therefore, the next drought event similar to the drought period that took place from 1970 to 1974 occurred around 1980. ~~in~~ In 1979–1983, the drought ~~severity~~ duration reached ~~0.41~~5 years, which ~~was~~ is close to the ~~predicted~~ estimated return period.

3.3. Variability of the PRR during the dry periods in each watershed

Prolonged multi-year drought ~~has caused~~causes significant damages in ~~the~~ natural environments. Fig. 5 demonstrates the range of changes in the PRR under sustained precipitation decreases. According to the direction of change, the dry period regression line is mainly located ~~upward or downward~~ above or below the overall regression line, and the ~~change of the~~ PRR in the ~~studied 13 watersheds~~13 studied watersheds ~~show~~ exhibits no significant ~~test~~ change when the regression line of the dry period ~~was~~ is above the total regression line. ~~In~~ Of the 15~~ times~~cases in which dry events fell under the overall regression line ~~in the case of the total regression~~ in 13 watersheds from 1961 to 1999, t~~here are 9 times~~ significant changes in the PRR ($p < 0.05$) occurred in 9 cases, accounting for approximately~~about~~ 60% of the total ~~situation~~cases. ~~This means that sustained drought results in lowered runoff generation rates~~

for similar precipitation amounts (Saft et al., 2015). Thus in a continued years with decreased precipitation, we can conclude that lower runoff not only relate to the lower precipitation, but also less runoff than expected caused by the multi_yeat drought period. In these cases, the dry period regression line lies lower than nearly all the other parts of the historical record, indicating unprecedentedly low runoff generation rates for the given precipitation values. Thus in a sequence of years with decreased precipitation, we can conclude that lower runoff not only relate to the lower precipitation, but also less runoff than expected caused by the multi-year drought period.

There were no significant changes in the PRR in 5 of the 13 watersheds during the study period. Fig. 6 demonstrates that there is no geographical pattern in the spatial distribution of watersheds with and without significant change in the PRR. Compared to with the annual average precipitation in other basins where significant changes occurred (Table1) in separate watersheds during 1961–1999, these the watersheds where there were no significant changes in precipitation-runoff relationship the PRR occurred (Kuye, Dali, Qingjian, Yanhe and, Jinghe) had received greater amounts of higher precipitation. Thus, we conclude that the PRR has a strong response to responds strongly to protracted drought, and the persistence of drought conditions over many years multi-year drought period with the occurrence of drought for many years beingis more likely to cause a significant changes in the PRR in the basins with that receive less precipitation.

3.4. Spatial variability of drought frequency in on the Loess Plateau

The return period varies withWith the difference of drought duration and severity, the return period also showed different values. Therefore, the three major dry events that occurred on the Loess Plateau in the Loess Plateau from 1961 to 1999 were selected as the basis to study to enable study of the characteristics of the spatial distribution characteristics of the joint return period. It can be seen from Figs. 7a,7b and 7c show that, although the duration and severity of drought in differ among these three major drought events are different, the spatial distribution of the drought return period is consistent. At the same time, there are also differences in the drought return period in different also differs between watersheds, and the spatially heterogeneity heterogeneous characteristics of the different catchments in on the Loess Plateau can also be seen from the drought return period. In terms of spatial distribution, the return periods of drought events in the southern and eastern watersheds of Jinghe, Beiluo, Xinshui and Fenhe are longer in the southern and eastern watersheds of Jinghe, Beiluo, Xinshui and Fenhe, indicating that the frequency of drought events in these watersheds is relatively low,..On the other hand, while those the watersheds toin the north and west, such as Huangfu, Kuye, Tuwei and, Weihe, have a display shorter drought return periods., that is, the frequency of drought events in this region is higher than other regions, and drought events are more likely to occur. Thus, these regions are more susceptible to drought under the same drought characteristics. Analyzing We analyse the return periods corresponding to watersheds with significant changes in the relationship between precipitation and runoff. As shown in Fig. 7d, it can be seen that there are obvious differences in the return periods in these watersheds, which are affected by experience different drought characteristics. The return period in these watersheds is particularly important in ecosystem management.

4. Discussion

4.1. Reliability of the identified identification of drought events

Since the actual occurrence of drought in a region is complicated, and the practical significance of various drought indicators is different, the choice of drought definition is an important part of studying the process of drought occurrence and development. Prolonged multi-year drought events ~~has caused~~ cause significant damages to both ~~in~~ the natural environment~~s as well as~~ and ~~in~~ the development of ~~the~~ human societies (Belal et al., 2014). To ensure that the dry periods ~~are~~ would be sufficiently long and severe, Saft et al. (2015) ~~only using~~used only dry periods with drought duration ≥7 years and severity ＜-5%. In this study, the ~~duration of~~ drought duration was limited to not less than 5 years. ~~Based on the response of the PRR to drought events over the years~~ Linking climate and the change in the PRR to identify drought events on the Loess Plateau from 1961 to 1999~~, the results of drought events in the Loess Plateau during 1961–1999~~ shows~~ed~~ that 1962, 1965, 1986–1987 and 1989 are ~~single dry~~ single-year dry periods, whereas~~1968~~1970–1974, 1979–1983 and 1991–1999 are ~~the main~~major dry periods. ~~Looking at the dry events in the Yellow River basin from 1961 to 1999, t~~The years when major dry events occurred in the Yellow River basin from 1961 to 1999~~this period~~ were 1965,1972,1980,1995 and 1997 (Fu et al., 2008; http://www.mwr.gov.cn). For example, a severe drought ~~over~~ in northern China in 1997 damaged 1.94 million hectares of crops in the Yellow River basin and resulted in 226 days of zero flow from Henan province to Shandong province~~s,~~. ~~and t~~The total length of the river with zero flow was ~~about~~ approximately 687 km. ~~We can find these~~ Thus, the dry events ~~which are~~ identified by the method described in this study are consistent with ~~the statistical~~ historical data ~~in historical~~, further illustrat~~e~~ing the ~~feasibility~~ reasonableness of the method ~~in this study~~presented here.

4.2. The influence of multi-year drought events on the ecosystem service of water yield

Ecosystem services ~~is an important~~represent a key concept for policy makers, and the variability of the relationship between precipitation and runoff is vital in the study of the ecosystem service of water yield. The PRR can be influenced by factors other than climate conditions, such as land use, the diversion of surface water, irrigation schemes, groundwater abstraction and the storage of water in catchments (Farley et al., 2005; Brown et al., 2005; Zheng et al., 2009). However, the catchments examined in our study lie in the part of the Loess Plateau with the greatest relief, and the Mu Us Desert is located in the northwest and the WeiHe Plain is locatedin the southeast. The vegetation in the catchments is mostly rain-fed; thus, irrigation schemes can be neglected in the study area (Feng et al., 2016). The thickness of the loess within the catchments is greater than 100 m (Derbyshire et al., 1998), and the groundwater is minimally impacted by the surface eco-hydrological processes; thus, groundwater recharge and groundwater discharge are not considered in the study area. In addition, Bouwer et al. (2006) concluded that increasing water consumption for irrigation and the degree of runoff variability caused hydropower is three times higher than the variations in runoff under climate change in a densely populated region in the main agricultural irrigation area in India. The water consumed by the local communities on the Loess Plateau is fed to the residential areas, which are mainly located in the flat areas at the outlets of the catchments (the distribution of residential areas is shown in Fig. 1). Moreover, the population shows a tendency to move from the catchment area to the major cities, which are located along the mainstream of the river basin in the Weihe Plain (i.e., Baoji, Xi'an, these cities contain 57.35% of the population within the study area) because of the accelerated urbanization that has taken place in this area since the 1980s (Hu et al., 2001). Thus, the water consumed by the local communities does not have a major effect on runoff in our study area. Finally, any diversions of surface water and water storage are found in the residential areas at the outlets of these catchments. Therefore, the impacts of these factors are not included in the PRR.

Instead, soil conservation measures, including the construction of terraces and the construction of sediment-trapping dams, have been implemented on the Loess Plateau since the 1950s (Wang et al., 2016), and these anthropogenic factors may change water yields (Wang et al., 2009; Shi et al., 2013; Chang et al., 2015). We used the partial correlation method to isolate the impacts of anthropogenic activities from climatic factors. For the entire period of 1982–1999, the runoff ratio displayed a decreasing trend (Fig. 8).Terrace construction played an important role in the reduction in the runoff ratio from the 1980s to the 1990s (p=0.048, Fig. 9). The effects of other anthropogenic activities, including dam construction, tree plantations and pasture did not cause the observed change in the runoff ratio in this period. Terrace construction contributed 25% of the reduction in the runoff ratio in the 1990s. Thus, drought events are the major factor driving the reduction in runoff in the study area.

~~There are two main forms of the response of t~~The PRR responds to multi-year droughts in two different ways.~~: no~~ The PRR either displays no –significant change ~~and~~ or a significant downward ~~significant~~ change. Saft et al. (2015) have shown that ~~there was also~~ a significant upward trend in the PRR occurred during a period of drought ~~period~~ in watersheds in southeastern Australia~~n watersheds~~, but the probability of such ~~events~~ effects is small. It is also not clear whether ~~the~~ these observations reflect a real phenomenon ~~is real~~ or just sampling fluctuations. ~~Analyzing~~ Analysing the changes of the PRR during the three ~~main~~ major dry periods ~~in~~ on the Loess Plateau,~~ we found that runoff reductions were smaller than other historical when the precipitation sustained reductions in 1968–1974, and reductions in runoff were slightly greater than other periods in the latter two dry events. It~~ it~~can be seen~~ shows that the annual runoff tends to decrease gradually. ~~So~~ Therefore, we believe that the occurrence of dry events will aggravate the reduction of runoff, which could lead to significant changes ~~of~~ in the PRR. ~~The increase of extreme temperature indices in the Loess Plateau, such as txq90 (hot-day threshold), tn90p (warm-night threshold) and txhw90 (longest heatwave) (Vincent and Mekis, 2006; Zhou and Ren, 2011), will cause the reduction of runoff since1960s (Li et al., 2010). At the same time, the land use of the Loess Plateau changed greatly before and after the 1990s (Zheng et al., 2009), and the increase in human activities has also affected the reduction of runoff (Feng et al., 2016b). Potter et al. (2010) also attributes the significant reduction in the internal runoff of the Murray-Darling Basin to lower precipitation and the rise of temperature.~~ This study shows that sustained precipitation changes also have the capacity to transform ~~watershed water balance~~ the water balance of watersheds in water- ~~limed~~ limited areas.

The ~~D~~drought regressions fell under the total regression line~~s~~ 15 times in the 13 watersheds, ~~including~~ indicating the occurrence of both significant ~~changes~~ and non-significant changes ~~in~~ during the study period. During ~~the~~ drought periods, the runoff ~~was reduced~~decreased as expected when the precipitation ~~sustained reductions~~decreased, which ~~will~~ decreases the runoff ratio and affects the ecosystem service of water yield. Based on the analysis of the duration and severity of the 15 dry events (Fig. ~~8a~~10a), ~~it is~~we concluded that the occurrence of a drought event is more likely to result in a significant ~~descending~~ decreasing trend ~~of~~ in the PRR when ~~that~~ the drought duration is ≥~~is not less than~~ 6 years and the drought severity is ≤~~is greater than or equal to~~ 0.55 (i.e., the precipitation≤212 mm). ~~Containing less~~ The occurrence of less runoff than expected ~~is a~~causes problems for the ecosystem service of water yield~~,~~. ~~t~~The shift in the PRR ~~will~~ induces a contradiction between the expected runoff ~~expectations~~ and the actual amount of water in a watershed~~s~~ if the runoff ~~fail to~~is not predicted accurately when the PRR changes. This result suggests that we must ~~concern~~ consider the impacts of prolonged drought events on ecosystems and optimize the ~~modeling~~ modelling techniques used to assess the PRR~~of precipitation-runoff~~ to cop~~y~~e with the effects of long-term~~longer term~~ droughts that occur ~~influences~~ in response to changed climatic conditions.

4.3. Policy implications tofor ecosystem management

In order to solve the problem of serious ecosystem degradation in the Loess Plateau and to effectively control soil erosion, in 1999 the Chinese government began a large-scale project of returning farmland to forest and grassland. In late 1999, China implemented a massive revegetation programme in the name of ecological restoration. This restoration involved returning croplands on steep slopes (> 25) to woodlands, shrublands or grasslands. Based on the spatial distribution of drought events in on the Loess plateau, the 13 watersheds were are further divided into four regions. It can be seen that tThe drought return periods in the northern and western regions is are lower than that those in the central and eastern regions, and we can see the distribution of the effects of the project in the four different regions (Fig. 8b10b). The different spatial distributions of the return period further reflect regional differences.

Drought eventscan affect ecosystem productivity and reduce the carbon sink capacity of terrestrial ecosystems (Burton and Zak, 1998; Ciais et al., 2005; Tian et al., 1998). As an important ecosystem structural parameter, the leaf area index (LAI) characterizes the physiologically functioning surface area through which energy, mass (e.g., water and CO_2) and momentum are exchanged between the vegetated land surface and the planetary boundary layer (Myneni., 2002). During 1982–1999, the LAI displays an obvious increasing trend in the 1980s over the Loess Plateau (Fig. 11). To illustrate the impacts of drought on the ecosystems, we choose the major drought period of 1991–1999 and the normal period of 1984–1990. We find that the LAI decreases significantly (p=0.032, Student's t-test) in 1991–1999 compared to that of 1984–1990. We used the terrestrial Carnegie-Ames-Stanford Approach (CASA) ecosystem model to estimate ecosystem net primary productivity (NPP) from remotely sensed data, specific method refers to (Feng et al., 2013), the change in annual NPP showed an increasing trend during 2000-2008 across the Loess Plateau. Compared the average growth rate of annual NPP in watersheds between Fig. 9a and Fig. 9b, the results illustrate average growth rate of annual NPP in Fig 9b is about 1.2 times higher than those watersheds which have a significant change in the PRR. Since the responses of different vegetation types respond differently to drought events at over different time scales are not the same, the regional drought return period and vegetation types should be taken into account in future policyies, and appropriate policies should be formulated according to the specific regional conditions, so as to control the adverse effects of drought on ecosystem productivity. We must pay more attention to these drought characteristics, what which can induced significant changes in the PRR had a significant change, combined and the return period (Fig. 7d),).thereby avoiding This practice will help avoid the waste of capital investment and will effectively improveimproving the implementation of the GGP effectively.

The results of this study provides a basis for the guidance of for ecosystem management policy. In addition, the specific measures used in for adapting to drought should also be improved. For example, drought-resistant crops, such as millet and maizes, should be chosen, . fFarmers can also increase the soil water storage capacity by reclaiming level terraces and practicing, contour strip farming (Panagos et al., 2015) and ridge-furrow cropping (Gan et al., 2013). At the same time, implementing water-saving irrigation technology, such as drip irrigation or micro-irrigation (Zou et al., 2013) would not only improve the utilization efficiency of water resources, but also resolve the issue of soil salinization caused by flood irrigation. Vegetation can affects the conversion of surface energy, water, momentum and biochemicals through its physical and physiological processes, thus affecting the atmospheric conditions (Bonan, 2008), and further changing the regional precipitation and hydrological processes (Ellison et al., 2012). In theDuring afforestation, managers should select tree species with less water consumptionthat consume less water, reduce the density of planting, and consider the optimal distribution ~~pattern between~~ of woodlands, shrubs and grasslands to cope with the effects of warmer and ~~dryer~~ drier conditions. For example, ~~adopting~~ fish-scale pits (Wang et al., 2014) can be used to enhance the infiltration of atmospheric precipitation and soil moisture. Especially in areas with steep slopes, the use of rainwater harvesting measures, such as fish-scale pits, will boost the survival of trees and avoid ~~soil~~ drying of the soil.

5. Conclusions

This article characterizes drought by linking climate ~~anomaly~~ anomalies with ~~the~~ changes in ~~precipitation-runoff relationships~~the PRR. We found that multi-year drought caused the PRR to ~~have~~ display a significant ~~descending~~ decreasing trend ($p < 0.05$) compared to the historical records. For the ~~whole~~ Loess Plateau as a whole, the average runoff ratio decreased to 6.8 percent of the average annual precipitation in 1991–1999 compared to 10 percent of the annual average precipitation in ~~1991~~1961–199~~9~~0. In ~~9~~ 8 of the 13 studied watersheds, ~~studied~~ significant changes in the PRR occurred during 1961–1999. When we compared the annual average precipitation in separate watersheds and ~~analyzed~~ analysed their drought characteristics, we concluded that this situation is likely to ~~happen~~ occur when the drought duration is not less than 6 years and the drought severity is ~~greater than or~~ equal to or greater than 0.55 (i.e., the annual precipitation is ⩽212 mm).

Our analysis revealed great spatial variability in drought across the Loess Plateau. We chose the Frank~~-~~copula function as the optimal joint distribution function of drought duration and severity. The results demonstrated that the joint probability and return period gradually increased with ~~the increase of~~ increasing drought duration and severity. At the same time~~s~~, the spatially ~~heterogeneity~~ heterogeneous characteristics of different watersheds ~~in~~ on the Loess Plateau can be seen from the spatial distribution of the drought return period. By ~~analyzing~~ analysing the annual ~~NPP~~ LAI over the Loess Plateau during 1982–1999, ~~we also found that pronged drought can also affect the growth ratio of NPP, the average annual growth ratio is lower in these watersheds which had a significant change in the PRR.~~ we found that the LAI significantly decreases in drought periods compared to normal periods. Long-term drought is also ~~an indispensable~~a key factor ~~when~~ in considering the ~~influencing~~ influence of ~~NPP~~ LAI trends in the future.

These results should lead to better water regulation and more effective strategies of ecosystem management. We can consider different plant species~~, combining~~ and the spatial variability in drought events~~,~~ to maximize the function of the ecosystem, based on the stability of the ecosystem structure.

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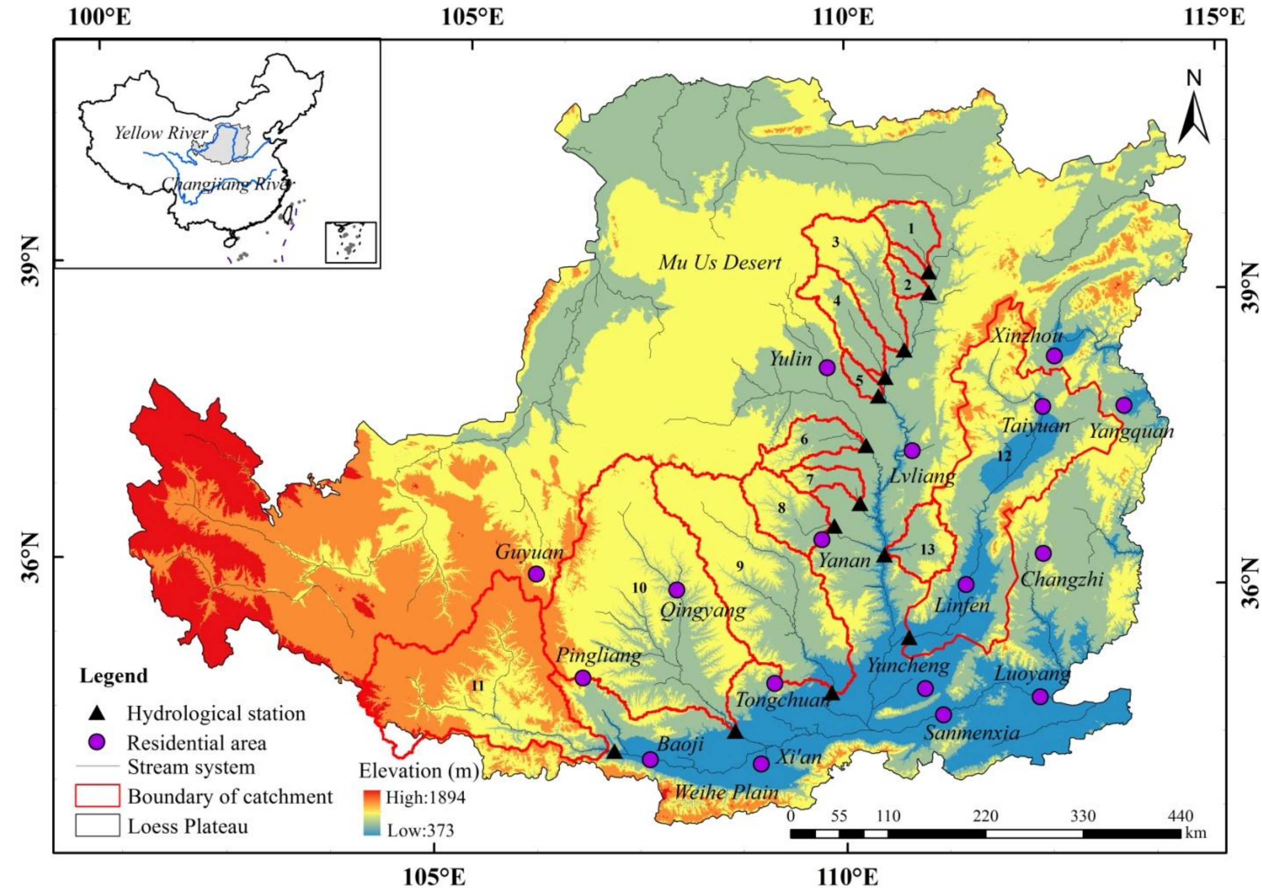

Figure 1. The study area.

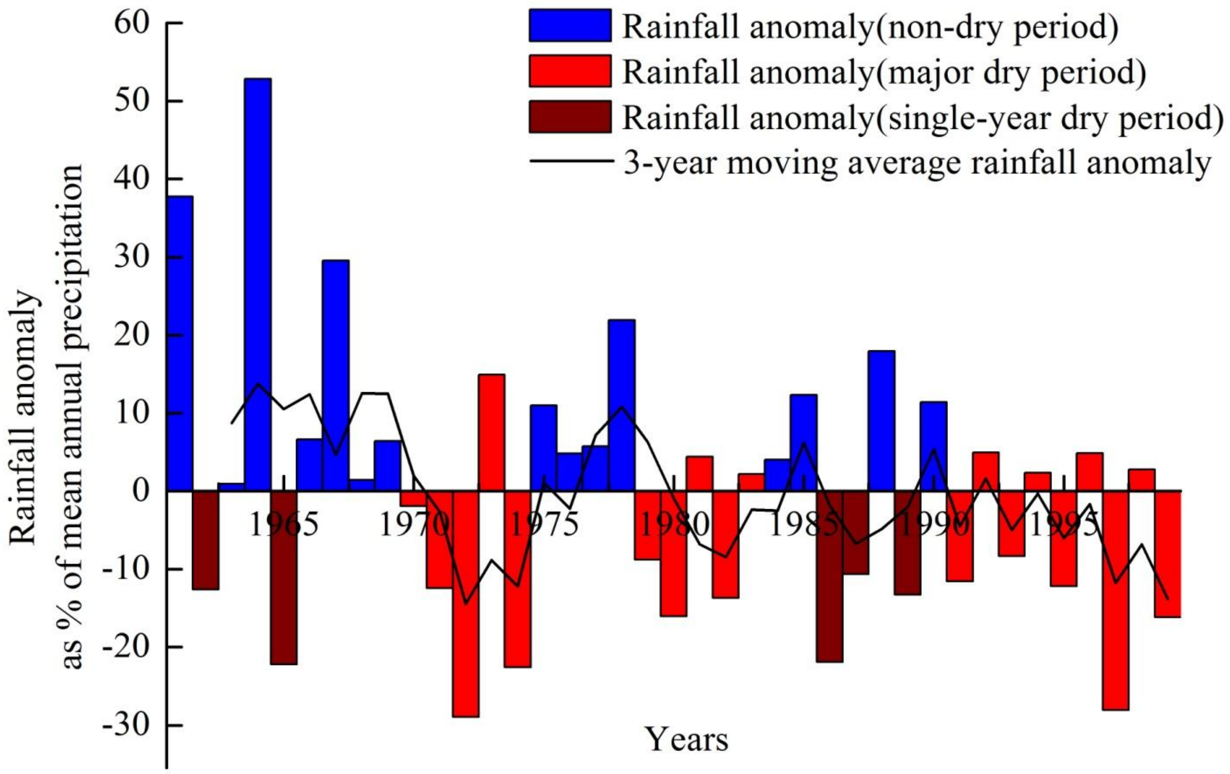

Figure 2. Time series with identified drought periods ~~in~~ on the Loess Plateau during 1961-1999.

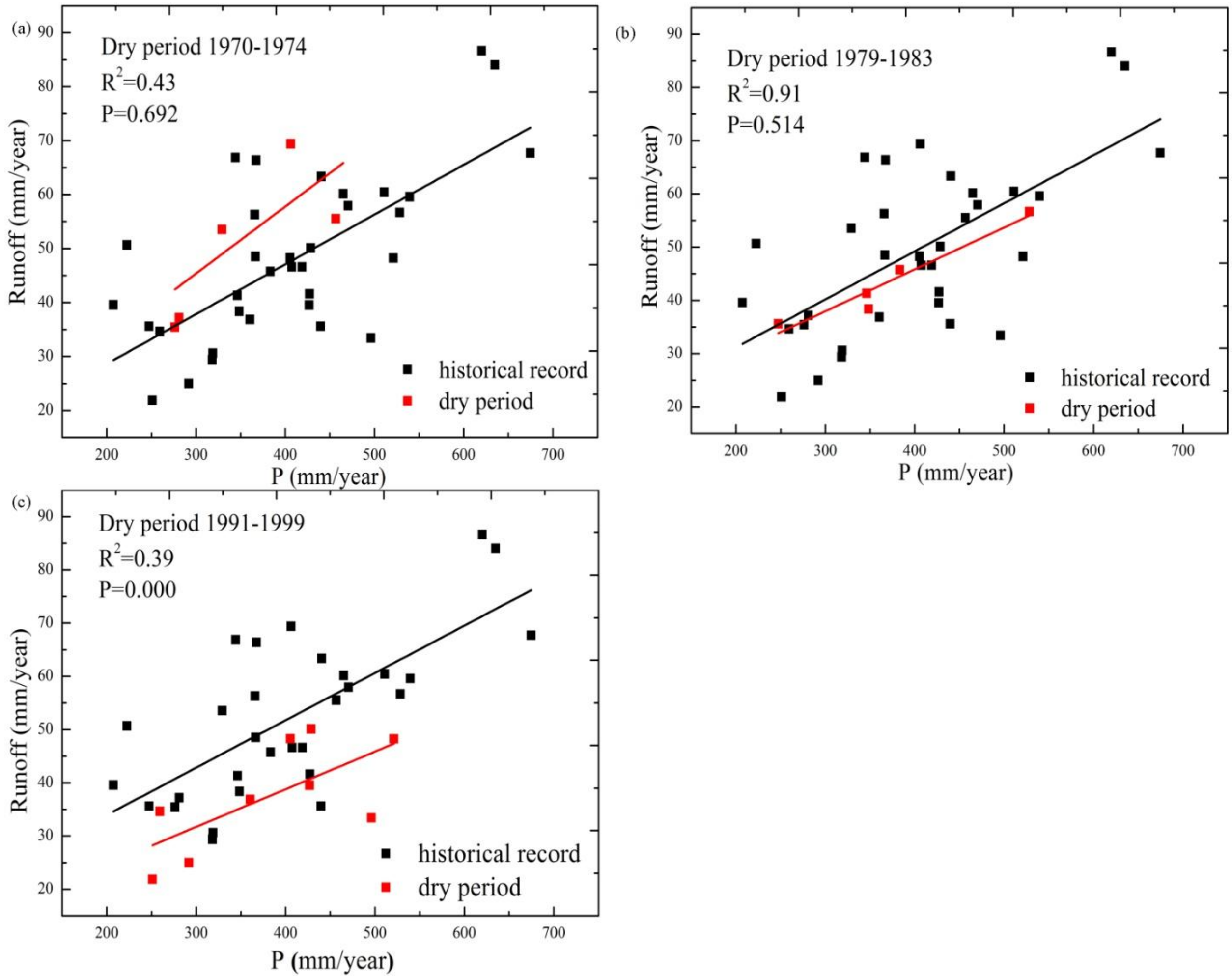

Figure 3. Precipitation-runoff relationships during drought periods:(a,) and (b) show no significant changes in the precipitation-runoff relationship and, whereas (c) shows a significant downward change in the precipitation-runoff relationship.

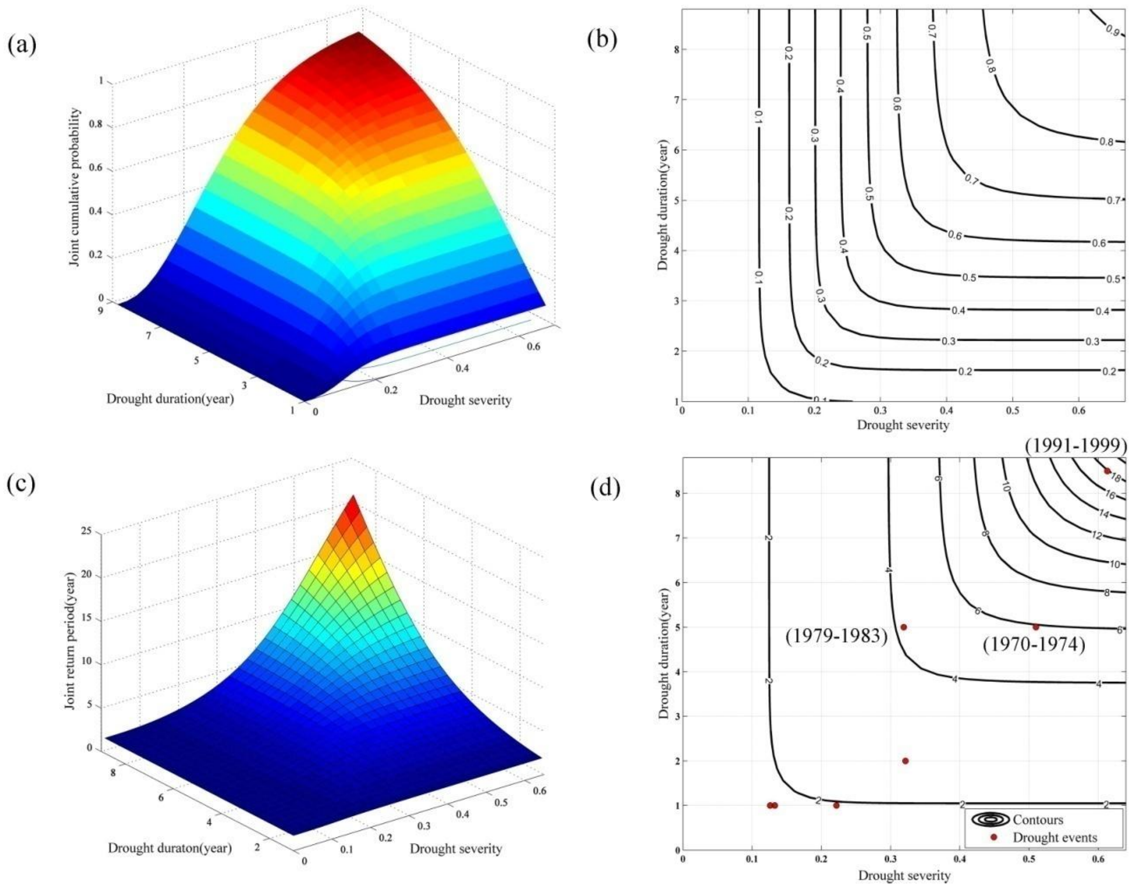

Figure 4. The joint probability distribution of drought duration and drought severity and the joint return period: (a) and (b) are the three-dimensional and contour maps of the joint probability density function of the Frank-copula, respectively; (c) and (d) are the three-dimensional and contour maps of the joint return period of drought duration and drought severity, respectively.

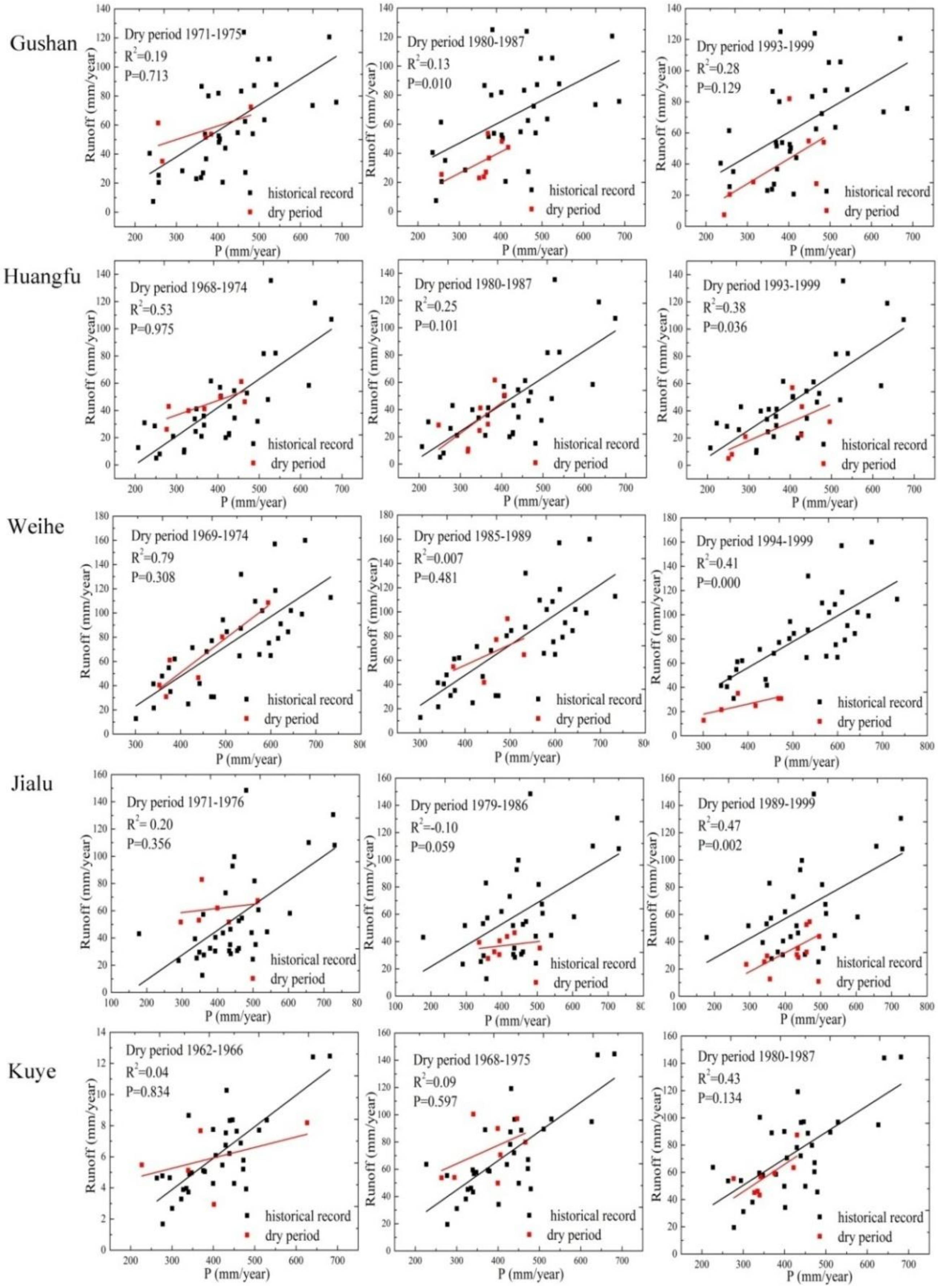

Figure 5. The annual precipitation-runoff ~~scatter plot~~scatterplot for ~~in~~ each watershed.

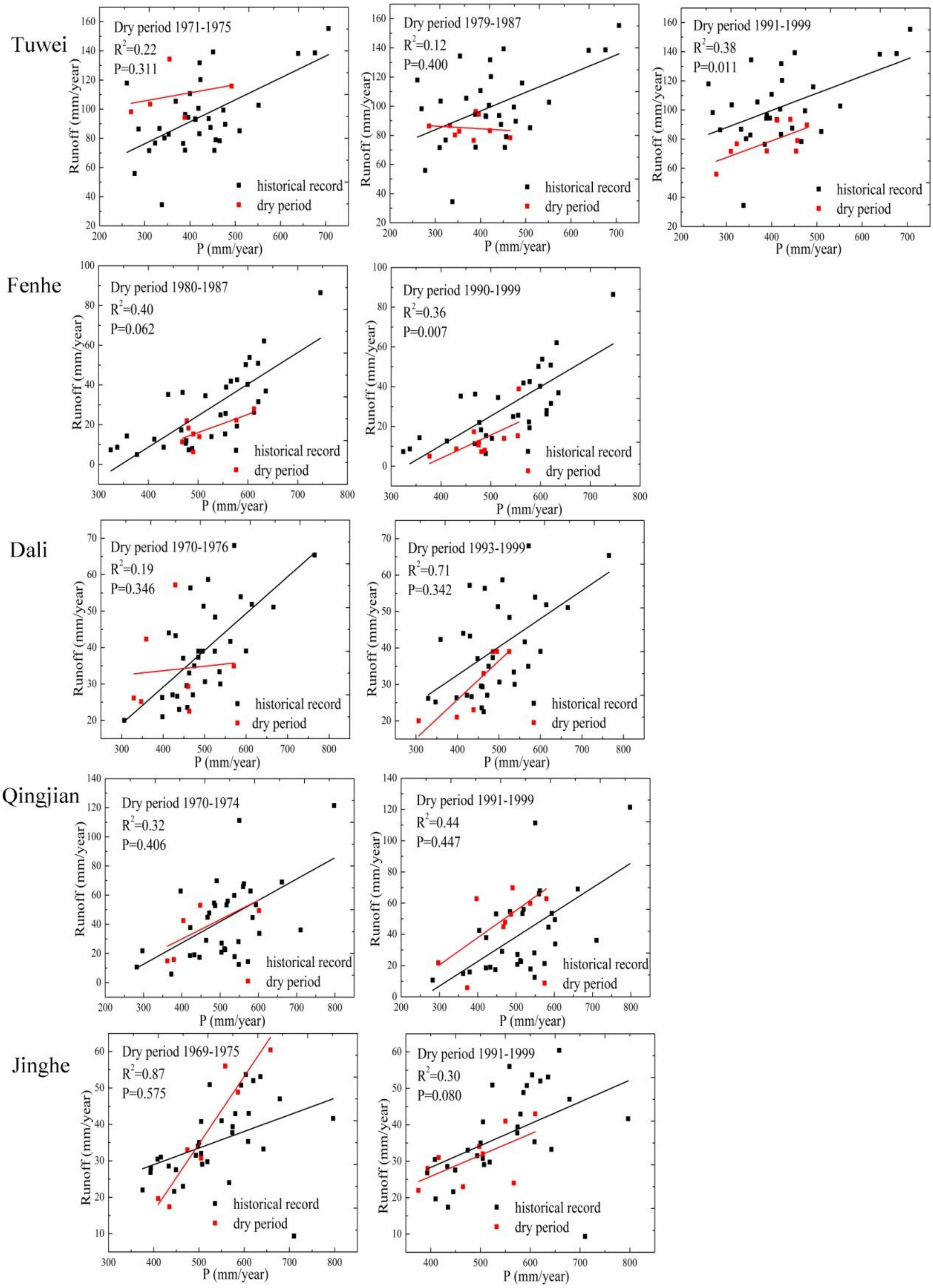

Figure 5. (continued).

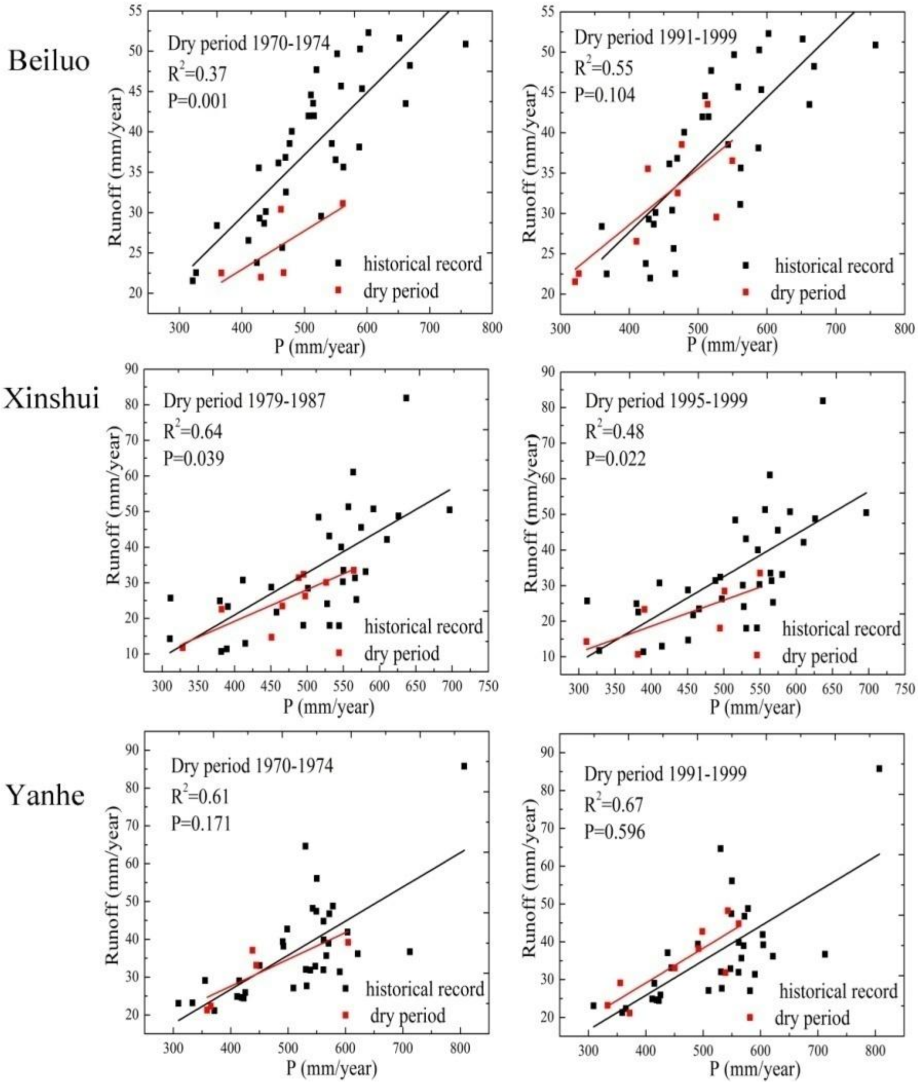

Figure 5. (continued).

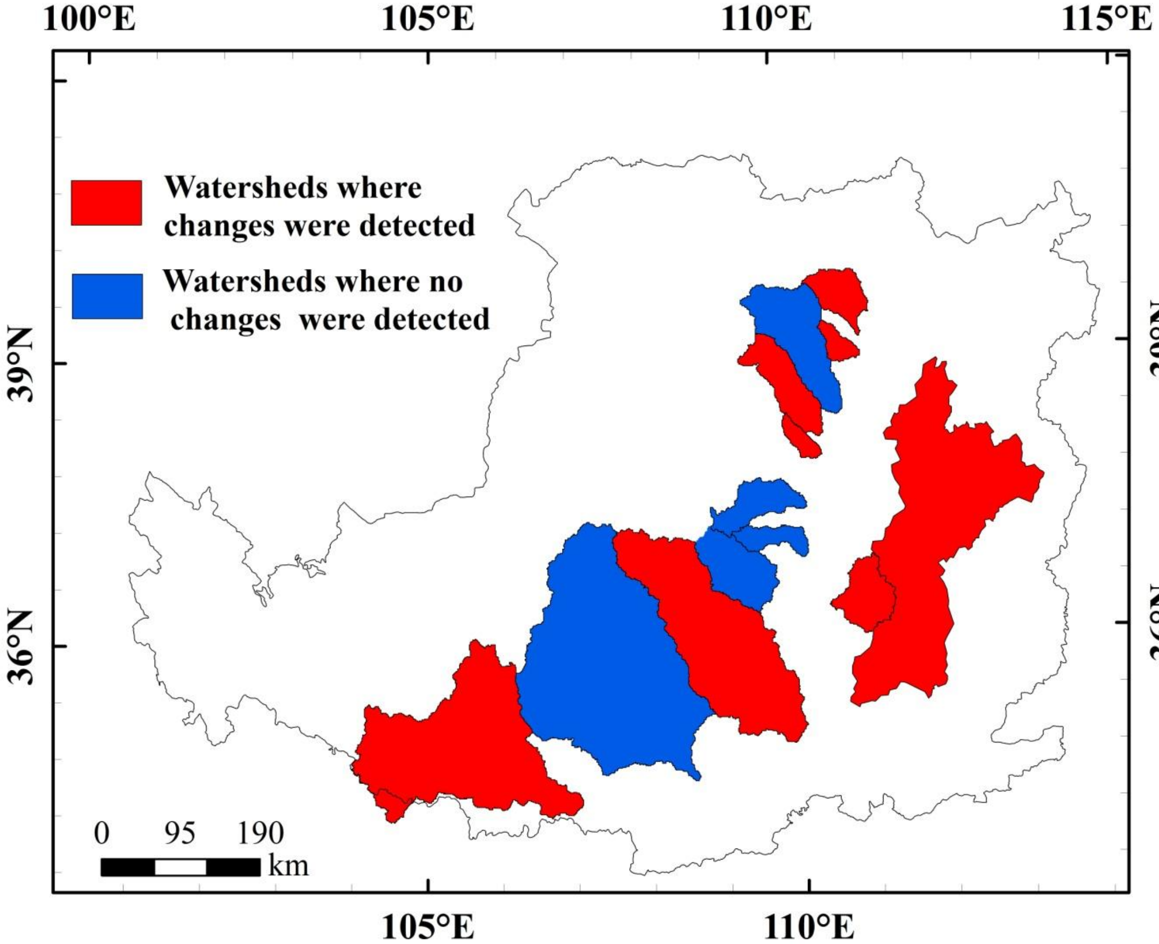

Figure 6. Spatial distribution of watersheds with and without significant change in the PPR during the drought periods.

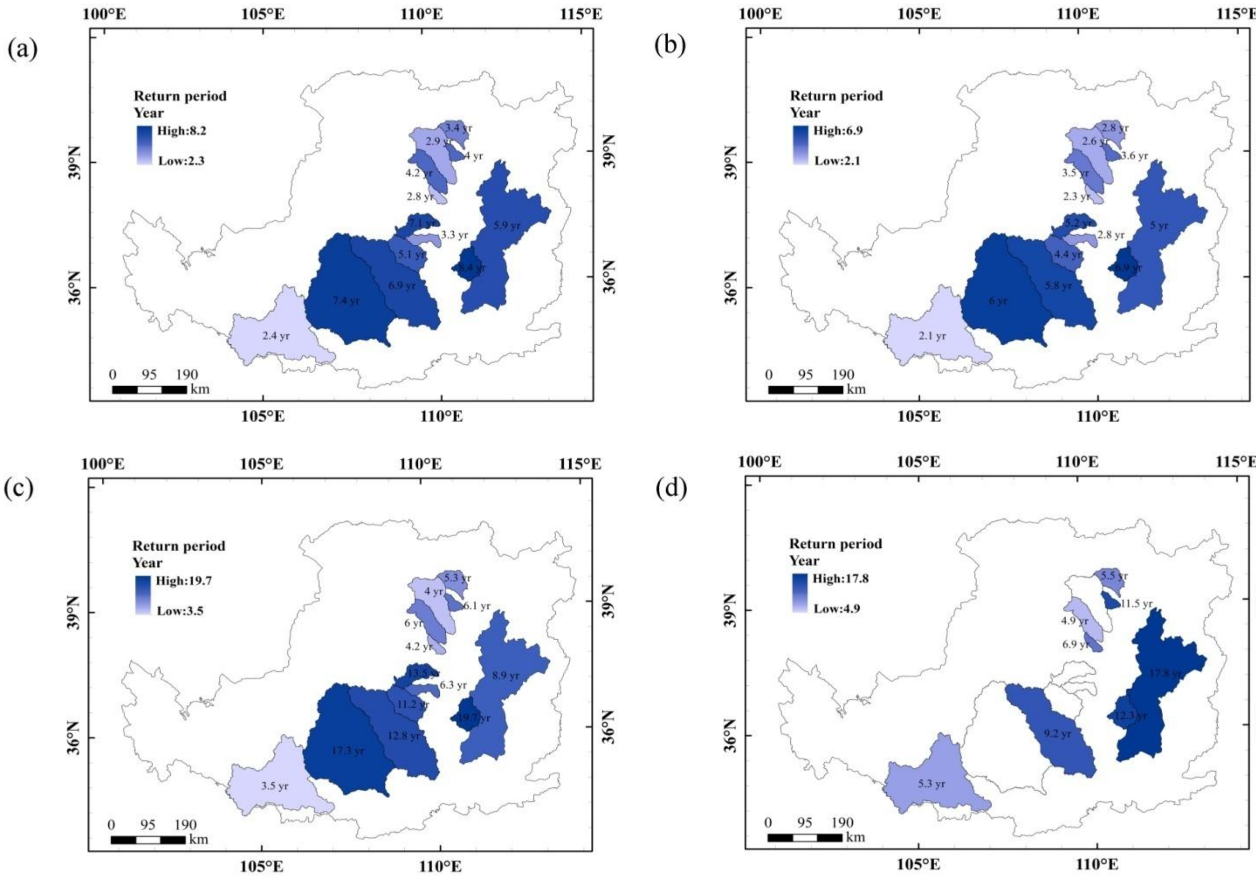

Figure 7. Spatial distribution of the return period of drought events ~~return period~~ in watersheds: (a)~~return period~~ spatial distribution of the return period of ~~dry~~ drought events in ~~1968~~1970–1974; (b)~~return period~~ spatial distribution of the return period of ~~dry~~ drought events in 1979–1983; (c) ~~return period~~ spatial distribution of the return period of ~~dry~~ drought events in 1991–1999; (d) return period of drought events corresponding to watersheds with significant changes in the PRR.

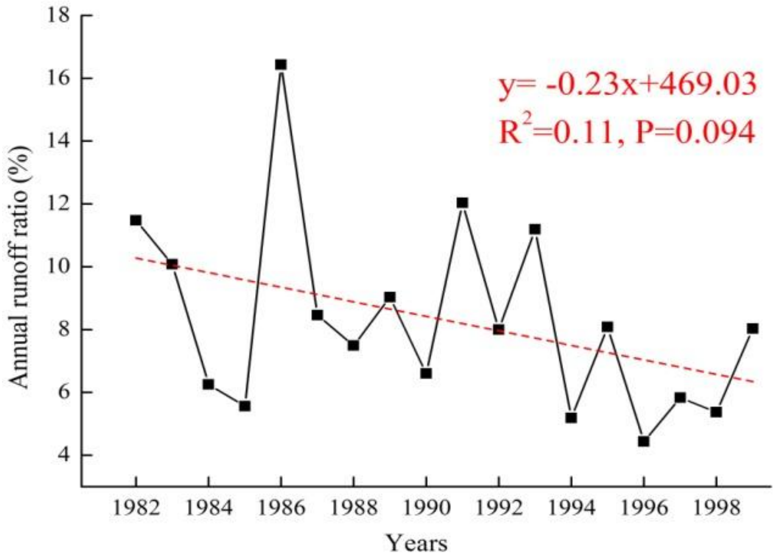

Figure 8. Trend ~~of~~ in the annual runoff ratio ~~during~~ from 1982~~–~~ to 1999

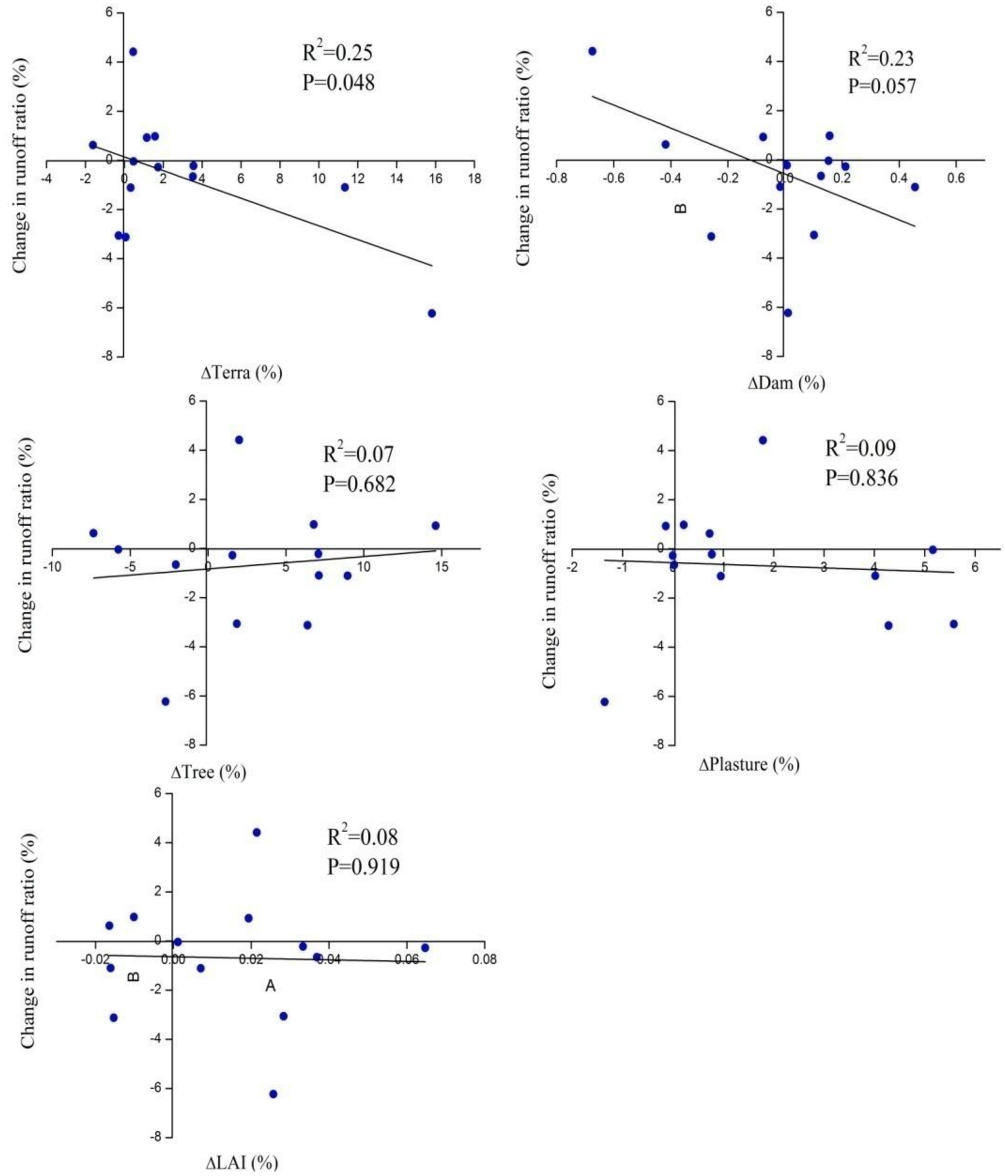

Figure 9. Anthropogenic factors of runoff ratio change in the 1980s *vs.* the 1990s (ΔTerra, ΔDam, ΔTree and ΔPasture are the changes in the percentage area of terraces, check-dams, tree plantation and natural pastures, respectively. ΔLAI is change in the GIMMS LAI for each catchment)

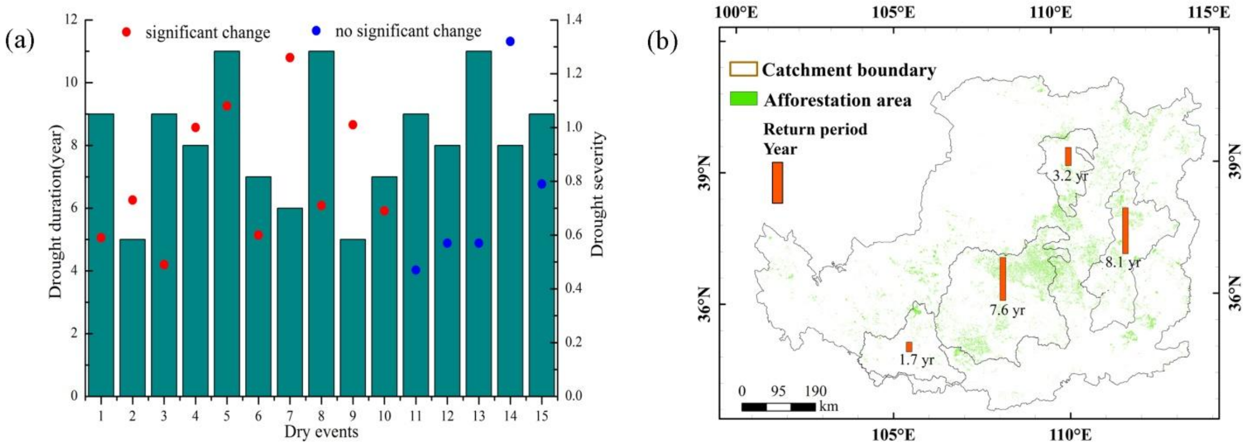

Figure 810. (a) Characteristics of drought events with significant changes and (b) spatial distribution of the joint return period(four regions).

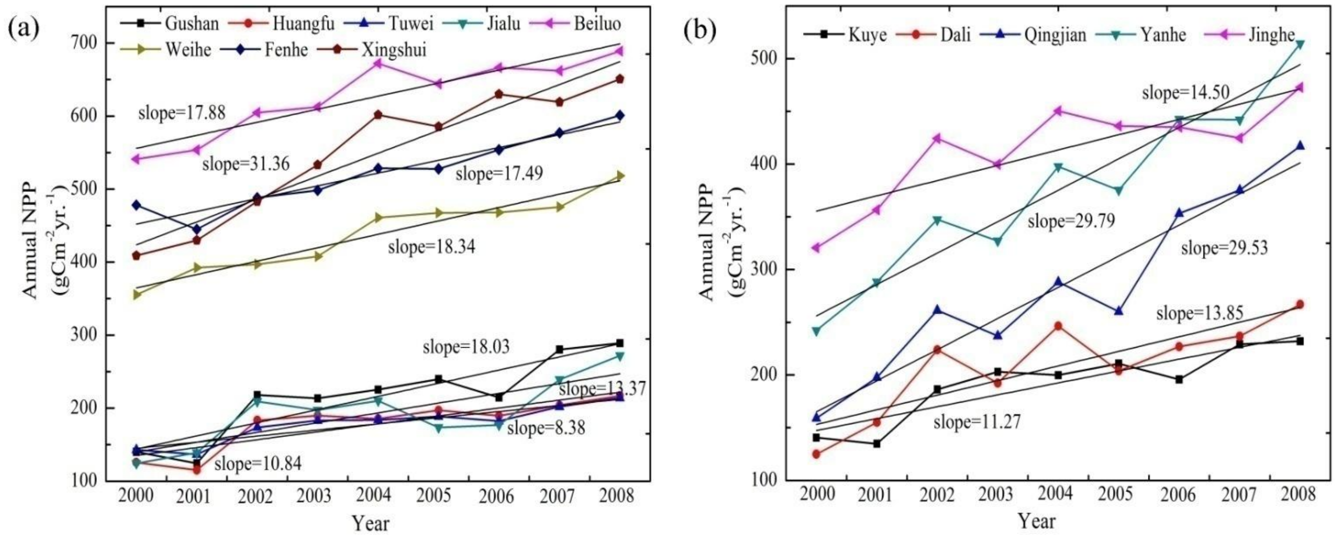

Figure 9. Dynamic course of annual NPP in each watershed during 2000–2008: (a) interannual change trend corresponding to watersheds with significant in the PRR; (b) interannual change trend corresponding to watersheds with no significant in the PRR.

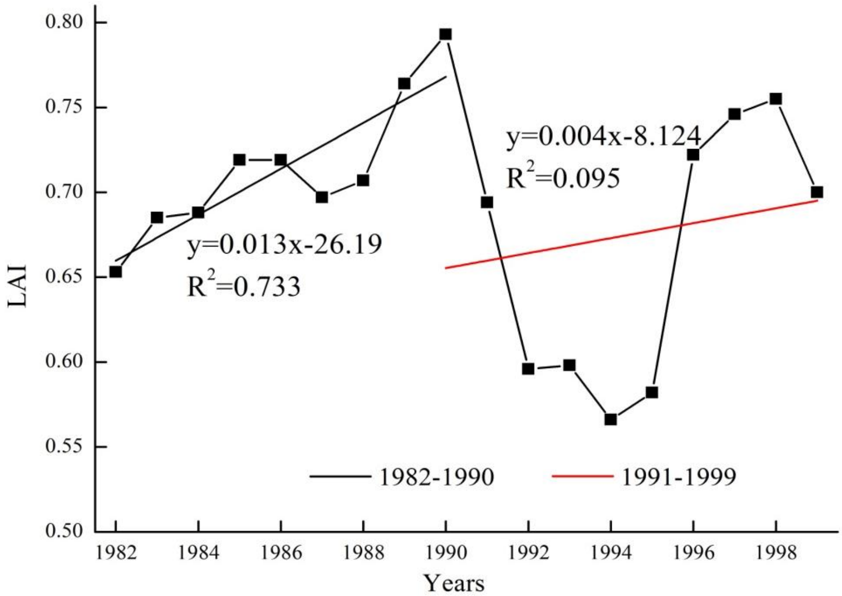

Figure11. Trend in the LAI from 1982 to 1999

Table 1. Watershed characteristics and hydrological data for the study period 1961-1999

ID	Watershed name	Gauging station name	Area(km^2)	Elevation(m)	PPT(mm yr^{-1})	Runoff(mm yr^{-1})
1	Huangfu	Huangfu	3230	1162	400	37
2	Gushan	Gaoshiya	1260	1167	415	50
3	Kuye	Wenjiachuan	8621	1263	407	60
4	Tuwei	Gaojiachuan	3307	1215	416	89
5	Jialu	Shenjiawan	1138	1117	440	48
6	Dali	Suide	3861	1202	485	37
7	Qingjian	Yanchuan	3600	1186	502	38
8	Yanhe	Ganguyi	5857	1282	506	34
9	Beiluo	Zhuangtou	25723	1283	504	35
10	Jinghe	Zhangjiashan	43106	1420	533	33
11	Weihe	Linjiacun	30122	1895	502	65
12	Fenhe	Hejin	38728	1135	520	23
13	Xinshui	Daning	4186	1217	498	29

ID, ~~W~~watershed identification number; PPT, ~~A~~annual precipitation.

Table 2. Common two-dimensional copula function families

Family	$C(u,v)$	Parameter range
Frank	$-\frac{1}{\theta}\ln[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}]$	$(-\infty,\infty)$
Clayton	$\max([u^{-\alpha}+v^{-\alpha}-1]^{-1/\alpha},0)$	$[-1,\infty)\setminus\{0\}$
Gumbel	$\exp(-[(-\ln u)^{\alpha}+(-\ln v)^{\alpha}])^{1/\alpha}$	$[1,\infty)$
t-copula	$\int_{-\infty}^{t_k^{-1}(u)}\int_{-\infty}^{t_k^{-1}(v)}\frac{1}{2\pi\sqrt{1-\rho^2}}[1+\frac{s^2-2\rho st+t^2}{k(1-\rho^2)}]^{-(k+2)/2}d_s d_t$	$(-\infty,\infty)$
Normal	$\int_{-\infty}^{\phi^{-1}(u)}\int_{-\infty}^{\phi^{-1}(v)}\frac{1}{2\pi\sqrt{1-\rho^2}}\exp[-\frac{s^2-2\rho st+t^2}{2(1-\rho^2)}]d_s d_t$	$(-\infty,\infty)$

Table 3 Parameters and goodness-of-fit values of the marginal distributions

Distribution	Parameters	RMSE	K-S test	
			Statistic	*p*_value
(Duration) Exponential(exp)	param_exp =3.714	0.617	0.223	0.306
Gamma(gam)	param_gam1=1.421 param_gam2=2.614	0.625	1	0
Log-normal(lno)	param_lno1=3.714 param_lno2=3.253	0.668	1	0
Extreme value(ev)	param_ev1=5.319 param_ev2=3.089	0.498	1	0
Generalized extreme value(gev)	param_gev1=3.722 param_gev2=0.008 param_gev3=1.002	0.668	1	0
Poisson(poisson)	param_poisson =3.714	0.645	1	0
Weibull(wbl)	**param_wbl1=3.975** **param_wbl2=1.213**	**0.581**	**0.248**	**0.231**
(Severity) Exponential(exp)	param_exp =0.309	0.112	0.280	0.883
Gamma(gam)	**param_gam1=3.690** **param_gam2=0.084**	**0.090**	**0.267**	**0.892**
Log-normal(lno)	param_lno1=0.310 param_lno2=0.254	0.237	0.423	0.423
Extreme value(ev)	param_ev1=0.393 param_ev2=0.168	0.127	0.280	0.883
Generalized extreme value(gev)	param_gev1=0.111 param_gev2=0.119 param_gev3=0.227	0.092	0.276	0.885
Poisson(poisson)	param_poisson =0.310	0.329	0.714	0.028
Weibull(wbl)	param_wbl1=0.351 param_wbl2=2.071	0.098	0.286	0.822

Table3. The goodness-of-fit about copula function(d^2)

Watershed name	Gauging station name	Normal	t-Copula	Clayton	Frank	Gumbel
Huangfu	Huangfu	0.2772	0.2715	0.2593	**0.2488**	0.2501
Gushan	Gaoshiya	0.1180	0.1186	**0.1027**	0.1029	0.1054
Kuye	Wenjiachuan	0.1383	0.1395	0.2171	**0.1266**	0.1305
Tuwei	Gaojiachuan	0.2270	0.2230	0.3026	**0.2199**	0.2239
Jialuo	Shenjiawan	0.1319	0.1323	0.1469	**0.1267**	0.1371
Dali	Suide	0.3778	0.3740	**0.3358**	0.3438	0.4625
Qingjian	Yanchuan	0.1879	0.1888	0.2565	**0.1720**	0.1976
Yanhe	Ganguyi	0.1986	0.2166	0.2186	**0.1979**	0.2059
Beiluo	Zhuangtou	0.2467	0.2480	0.2376	**0.2264**	0.2351
Jinghe	Zhangjiashan	0.3142	0.3358	0.3668	**0.3093**	0.3234
Weihe	Linjiacun	0.1784	0.1751	0.1743	0.1604	**0.1594**
Fenhe	Hejin	0.3766	0.3753	0.4339	**0.3726**	0.3827
Xinshui	Daning	0.5453	0.5379	0.5567	**0.5267**	0.6052
All		0.2037	0.1972	0.2141	**0.1891**	0.1897

Table 4 The goodness-of-fit values of the copula functions

ID	Normal			t-Copula			Clayton			Frank			Gumbel		
	d^2	AIC	RMSE	d^2	AIC	RMSE	d^2	AIC	RMSE	d^2	AIC	RMSE	d^2	AIC	RMSE
1	0.277	1.481	0.233	0.272	1.088	0.224	0.259	1.251	0.228	**0.249**	**1.044**	**0.223**	0.250	1.585	0.235
2	0.118	-3.912	0.154	0.119	-3.294	0.143	**0.103**	-2.961	0.154	**0.103**	**-3.928**	**0.143**	0.105	-3.753	0.145
3	0.138	-1.868	0.166	0.140	-1.819	0.167	0.217	0.836	0.208	**0.127**	**-2.403**	**0.159**	0.131	-2.220	0.162
4	0.227	1.103	0.213	0.223	0.997	0.211	0.303	2.828	0.246	**0.220**	**0.912**	**0.210**	0.224	1.022	0.211
5	0.132	-2.129	0.169	0.132	-2.112	0.163	0.147	-1.590	0.171	**0.127**	-1.936	0.162	0.137	**-2.328**	**0.159**
6	0.378	5.186	0.275	0.374	5.116	0.274	**0.336**	4.525	0.259	0.344	**4.436**	**0.262**	0.462	6.062	0.304
7	0.188	-0.360	0.194	0.189	-0.335	0.194	0.257	1.197	0.227	**0.172**	**-0.108**	**0.186**	0.198	-0.800	0.199
8	0.199	0.685	**0.199**	0.217	1.291	0.208	0.219	1.355	0.209	**0.198**	**0.661**	**0.199**	0.206	0.936	0.202
9	0.247	2.802	0.222	0.248	2.845	0.223	0.238	2.503	0.218	**0.226**	2.417	0.217	0.235	**2.117**	**0.213**
10	0.314	5.580	0.259	0.336	6.180	0.249	0.367	6.974	0.271	**0.309**	**5.438**	**0.251**	0.323	5.834	0.254
11	0.178	-0.619	0.179	0.175	-1.15	0.189	0.174	-0.711	0.187	**0.160**	**-1.182**	**0.176**	0.159	-0.735	0.187
12	0.377	5.164	**0.274**	0.375	5.140	0.275	0.434	6.156	0.295	**0.373**	**5.089**	**0.274**	0.383	5.278	0.277
13	0.545	10.541	0.330	0.538	10.419	0.328	0.557	10.727	0.334	**0.527**	**10.229**	**0.325**	0.605	11.480	0.348
All	0.204	4.974	0.265	0.197	5.642	0.288	0.214	5.113	0.301	**0.189**	**4.312**	**0.249**	0.190	5.230	0.254