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Research Article

Evolution of Hydrological Drought in Human Disturbed Areas: A Case Study in the Laohahe Catchment, Northern China

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A case study on the evolution of hydrological drought in nonstationary environments is conducted over the Laohahe catchment in northern China. Using hydrometeorological observations during 1964–2009, meteorological and hydrological droughts are firstly analyzed with the threshold level method. Then, a comprehensive analysis on the changes within the catchment is conducted on the basis of hydrological variables and socioeconomic indices, and the whole period is divided into two parts: the undisturbed period (1964–1979) and the disturbed period (1980–2009). A separating framework is further introduced to distinguish droughts induced by different causes, that is, the naturalized drought and human-induced drought. Results showed that human activities are more inclined to play a negative role in aggravating droughts. Drought duration and deficit volume in naturalized conditions are amplified two to four times and three to eight times, respectively, when human activities are involved. For the two dry decades 1980s and 2000s, human activities have caused several consecutive drought events with rather long durations (up to 29 months). These results reflect the considerable impacts of human activities on hydrological drought, which could provide some theoretical support for local drought mitigation and water resources management.

1. Introduction

Drought is a recurring natural phenomenon primarily induced by successive reduction of precipitation over a period of time [1–4]. Different from aridity which is a permanent feature of climate condition, drought is a consequence of climate variability reflecting temporal water deficiencies and can be observed in many regions rather than constrained to dry climate zones [5]. In view of the widespread impacts of droughts, including economic, agricultural, hydrological, and ecological losses and costs, much concern is given to droughts in recent years. Climate changes associated with global warming and other climate extremes have aggravated the damage of droughts, even in some areas such as southern Europe and West Africa; droughts with higher peaks and severity levels have been frequently observed during recent decades [6].

Drought can be classified into four types according to the variable that is used, that is, meteorological (precipitation), agricultural (soil moisture), hydrological (streamflow, water level, reservoir storage, and groundwater discharge), and socioeconomic droughts [7]. Among them, the hydrological drought is mostly related to our social activities, which can be defined as inadequate surface and subsurface water resources for established water uses of a given water resources management system [4].

The development scheme of hydrological drought is rather complex and is subject to the effects of climate and catchment control or a combination of the two factors. Among various climatic variables, precipitation and temperature are two key variables which largely determine the weather pattern and antecedent condition for the occurrence of hydrological drought. Meanwhile, since a sustained change in precipitation or temperature is commonly induced by variation in large-scale circulations, analyzing the relationship between hydrological drought and atmospheric circulation indices (e.g., the El Niño Southern Oscillation (ENSO) and high-pressure areas) is also a hot issue in recent drought researches [8]. Catchment control also plays an important

role in drought propagation and influences processes like pooling, attenuation, lag, and lengthening [9]. Some studies further investigated the individual roles of climate and catchment control in governing hydrological drought characteristics, and the conclusion is highly dependent on spatial scales. Globally, hydrological drought duration and deficit volume are more related to climate than to catchment control. However, for regional scale where climate is assumed to be relatively uniform, catchment characteristics like geology, area, slope, and groundwater system play an important role in governing hydrological drought duration and deficit volume [10].

In fact, the impacts on hydrological drought are not limited to the above-mentioned natural factors (i.e., climatic and catchment factors), and influences from human activities in forms of land cover change, reservoir regulation, agricultural irrigation, and water withdrawal from streams or river channels should not be ignored. From the perspective of hydrology science, human activities influence the process of hydrological cycle, for example, infiltration and evapotranspiration processes, and further alter flow regimes and their spatiotemporal distributions [11]. Accordingly, the process of hydrological drought would also be influenced. With this in mind, the traditional understanding of hydrological droughts should never be limited to the naturalized dry situation; drought caused by human activities has become a new challenging issue that needs to be noticed and discussed.

The focus of our study is to investigate the impact of human activities on hydrological drought. In this paper, we call drought induced by climate variability the "naturalized drought" and drought caused by human activities the "human-induced drought." As aforementioned, human activities potentially influence underlying surfaces, which further leads to a nonstationary response in hydrological variables (e.g., runoff). Here comes the question, will these changes influence the characteristics of hydrological droughts and what is the difference between naturalized and human-induced droughts? Based on the above questions, a comprehensive investigation on the evolution of hydrological droughts is conducted in the Laohahe catchment in northern China (this catchment is selected due to its representative runoff change pattern influenced by combined effects of climate change and human activities, which is quite common in China water-stressed regions), combined with a separating framework for distinguishing the naturalized and human-induced droughts.

2. Study Area and Data

The Laohahe catchment (41°N~42.75°N, 117.25°E~120°E) located in northern China is selected as an example considering its drastic runoff change pattern which is a common and typical phenomenon for water-stressed regions in northern China. The drainage area of the Laohahe catchment is 18,112 km^2, and its elevation ranges between 427 m and 2054 m with a general increasing trend from northeast to southwest. The climate belongs to the semiarid zone, according to the observation during the period 1964–2009; mean annual temperature, precipitation, and runoff

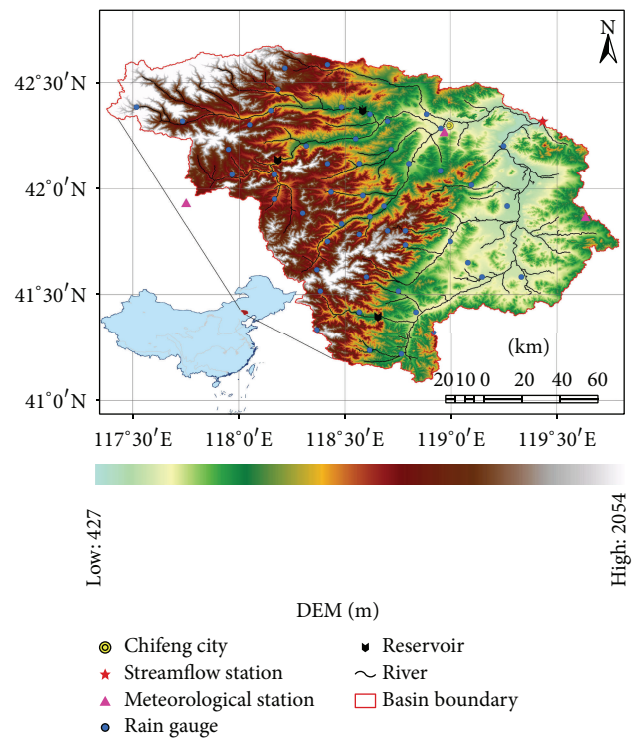

Figure 1: Location of the study area and the geographic distribution of hydrometeorological stations and reservoirs.

are 7.58°C, 418.3 mm, and 28.7 mm, respectively. Due to the temporally unevenly distributed precipitation (80% of annual precipitation concentrated between May and September) and temperature, the Laohahe catchment presents a strong seasonality in runoff. Normally, winter is cold and dry with relatively low streamflow observed, while in summer it is hot and wet with most peak flow occurring during this season.

The data used in this study includes materials for hydrological drought identification and input forcing for hydrological modeling. Daily precipitation of 52 rain gauges and streamflow records of the Xinglongpo hydrological station situated at the outlet of the Laohahe basin during 1964–2009 is provided by the Water Resources Department of the Inner Mongolia Autonomous Region. Streamflow data is further converted to catchment runoff by averaging the runoff amounts over the catchment area. Daily meteorological forcing (1964–2009) including maximum and minimum air temperature, wind speed, relative humidity, and sunshine duration of 3 national standard meteorological stations in and around the Laohahe catchment is downloaded from the China Meteorological Data Sharing Service System (http://data.cma.gov.cn/). Their geographic distributions are shown in Figure 1. Besides, locations of three large reservoirs (Erdaohezi, Dahushi, and Sanzuodian) within the Laohahe catchment are also given in Figure 1 considering their potential impacts on runoff.

Geographic information is obtained as follows: 3-arcsecond (about 90 m) digital elevation from the shuttle radar topography mission (SRTM) digital elevation model, soil types from the 5-minute FAO dataset [12], and land

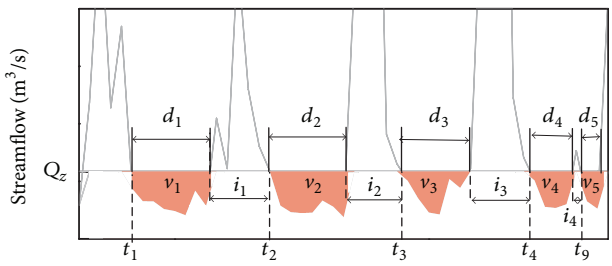

FIGURE 2: Illustration of threshold level method: time of occurrence, t_i, duration, d_i, deficit volume or severity, v_i, drought interval, i_k, and the threshold level, Q_z.

cover data provided by the Chinese Academy of Science. We also collect socioeconomic statistics of the Chifeng city from the local statistical bureau, including population, agricultural production, gross industrial product (GIP), and gross domestic product (GDP). In addition, the baseflow and baseflow index (BFI) are calculated by the Hydrological Utility Package (http://www.cnhup.com/) using the recursive digital filtering method (RDF, [13]). BFI itself is not a catchment characteristic but it integrates storage and release properties of a catchment [14] and has been shown to have a close relationship with hydrological drought duration [15, 16]. Therefore, we use this index to reflect varied catchment characteristics.

3. Methodology

3.1. Hydrological Drought Analysis. The threshold level method is so far the most commonly used approach in view of recent hydrological drought researches. Originating from the statistical theory of runs introduced by [17], this method is commonly used to analyze a sequential time series with a time resolution of one month or longer. Figure 2 gives the general illustration of this method. A sequence of drought events can be derived from a streamflow hydrograph when the flow falls below a certain threshold level, Q_z. Accordingly, drought characteristics including the time of occurrence, t_k, drought duration, d_k, deficit volume, v_k, and drought interval, i_k (the time period between two consecutive drought events) can be obtained.

The selection of threshold value Q_z is subjective but essential since it influences the number of events, drought duration, and deficit volume. For perennial streams like our studied catchment, threshold levels between the 70-percentile flow and the 95-percentile flow from the flow duration curve (FDC) are recommended [18]. In this study, the 70-percentile flow is used to identify meteorological and hydrological droughts from precipitation and streamflow series, respectively.

3.2. The Framework for Separating Naturalized and Human-Induced Drought. Distinguishing droughts induced by different factors is essential for objective understanding of the underlying causes of varied regional drought, which also makes sense for water planning and management. In this section, a framework developed by van Loon and van Lanen [19] is applied to separate naturalized and human-induced droughts. Part of this framework is similar to the common method used in hydrology of assessing the impacts of climate change and human activities on hydrological system, while the remaining part focuses on quantitative analysis on hydrological drought.

Specifically, this framework can be divided into three sections. In the first step, the time series of observed hydrometeorological variables are tested so as to find possible change points. The whole period can then be divided into two parts by the change point, that is, the baseline period ("undisturbed") and changed period ("disturbed"). For change point detection, a number of methods are available, such as the Pettitt test [20], Kendall test [21], and the precipitation-runoff double cumulative curves method. The second section focuses on hydrological model simulation and reconstructing runoff series of the changed period. For this purpose, the hydrological model should be firstly calibrated using meteorological forcing of the baseline period. Then, keeping optimized parameters unchanged, the simulation driven by meteorological forcing of the changed period is the reconstructed (simulated) series for which no human disturbances are involved. For hydrological model simulation, various hydrological models can be chosen as long as they are capable of reproducing the natural situation, especially during low flow and drought. The Variable Infiltration Capacity (VIC) model [22] is adopted in this study, and its specific description is given in the following section. The third step is the core of this framework. Hydrological droughts induced by different causes during the changed period can be derived by identifying observed and simulated runoff series with the threshold level method, respectively. The former represents a combination of naturalized and human-induced droughts, while the latter refers to droughts that develop in natural conditions. Therefore, their difference is the human-induced droughts. The threshold values are calculated based on the undisturbed period and applied to the entire time series. Meanwhile, to reduce the impact of modeling errors on drought separation, different threshold values are calculated from observed and simulated runoff series, respectively.

3.3. A Brief Description of the VIC Model. The semidistributed, three-layer Variable Infiltration Capacity (VIC) model [22] is chosen for hydrological modeling. It has been used in many drought related researches, such as reconstructing and analyzing drought events [23–25] and drought prediction [26]. The VIC model considers the dynamic variation in both water and energy balance according to the subgrid heterogeneity represented by soil moisture storage, evaporation, and runoff generation. Partitioning of rainfall into infiltration and surface runoff is controlled by a Variable Infiltration Capacity curve [27]. Vertical water movement occurs within discrete soil layers through diffusion and baseflow is modeled from a lower soil moisture zone as a nonlinear recession [28]. A separate routing model is employed to transport grid cell surface runoff and baseflow to the outlet then into the river system, including a linear transfer function model used to calculate the within-cell

Table 1: Physical meanings and ranges of the sensitive parameters in the VIC model.

Parameter	Physical meaning	Unit	Range
i	Infiltration curve parameter	N/A	0-1
d_1	Thickness of top thin soil moisture layer	m	0.05–0.1
d_2	Thickness of middle soil moisture layer	m	0–2
d_3	Thickness of lower soil moisture layer	m	0–2
D_s	Fraction of D_{smax} where nonlinear baseflow begins	Fraction	0-1
D_{smax}	Maximum velocity of baseflow	mm/day	0–30
W_s	Fraction of maximum soil moisture where nonlinear baseflow occurs	Fraction	0-1

routing and the linearized Saint-Venant equation serving for channel routing [29].

The description of land surface characteristics for each grid cell is mainly implemented through numerous parameters of two categories: vegetation and soil parameters. Vegetation parameters comprise vegetation leaf area index, roughness length, displacement height, architectural resistance, and minimum stomatal resistance with relevant information that can be obtained from the University of Maryland's (UMD) land cover classification [30] and estimated according to the Land Data Assimilation Systems developed by the National Aeronautics and Space Administration (NASA). As for soil parameters, some can be determined from empirical values and need not be adjusted, such as porosity, saturated soil potential, saturated hydraulic conductivity, and the exponent B for unsaturated flow (available from the 5-minute Food and Agriculture Organization data set [12]), while other parameters are subject to calibration based on the agreement between simulated and observed hydrographs. Commonly, calibration is conducted by optimizing the seven sensitive parameters (i, d_1, d_2, d_3, D_s, D_{smax}, and W_s) with two criteria: Nash-Sutcliffe Coefficient of Efficiency (NSCE) and BIAS. The specific meanings and ranges of these sensitive parameters are listed in Table 1.

4. Results and Discussion

4.1. Evolution of Meteorological and Hydrological Droughts. Meteorological drought extracted from monthly precipitation series shows that there is no significant variation trend during the past 46 years (Figure 3(a)). The drought interval is generally stable with most of drought events occurring in the dry season. In contrast, hydrological drought (Figure 3(b)) derived from monthly runoff series shows different pattern with obvious decadal fluctuations observed. Among the five decades, the 1980s (1980–1989) and 2000s (2000–2009) are the two most severe dry decades which suffer consecutive droughts with large deficit volume, whereas for the 1990s (1990–1999) almost no hydrological droughts occur. A comparison of drought characteristics between meteorological and hydrological droughts further demonstrates their difference. Figures 3(c) and 3(d) are the scatterplots of drought duration and deficit volume. Obviously, meteorological droughts occur every decade, but for hydrological droughts they are mostly concentrated in the 1980s and 2000s. Comparing to meteorological drought, the duration of hydrological drought is lengthened (up to 17 months), and deficit volume is attenuated (not more than 6 mm). Meanwhile, the relationship between drought duration and deficit volume is modified and tends to be linear for the hydrological drought.

The above-mentioned differences between the two drought categories, on the one hand, reflect a propagation scheme from meteorological drought to hydrological drought. Due to the effects of climate and catchment control, meteorological droughts are combined into a longer hydrological drought. Meanwhile, the drought signal is weakened in catchment stores during this process [31]. On the other hand, the striking contrast among decades in terms of hydrological drought seems quite abnormal and is far beyond the scope of naturalized drought propagation process. To further explore the reasons for the unusual behavior of hydrological drought during the 1990s, the flow duration curves of precipitation and runoff for each decade are compared, shown in Figure 4. For precipitation, minor decadal difference of the flow duration curves is found, especially in the low flow section, and using the 70-percentile threshold of whole periods would ensure 25%–35% of droughts (accordingly 65%–75% of nondrought) recognized for different decades. However, for runoff, rather large decadal difference is observed. Using the 70-percentile threshold of whole periods would recognize approximately 50%–60% of droughts for the 1980s and 2000s but no more than 10% for the 1990s. This shows the inconsistent behavior between meteorological and hydrological droughts. For drought propagation, catchment control plays an important role in determining process features like duration and deficit. The discrepant performances between these two drought categories suggest that the effect of catchment control is not constant but changes over time. Besides the natural hydrology system, hydrological drought at this catchment scale is potentially disturbed by human activities.

4.2. Analysis on the Changing Environments. To further explore the causes of the abnormal pattern in hydrological drought, a comprehensive analysis on drought related variables (including precipitation, runoff, runoff coefficient, baseflow, and BFI) is conducted. Among them, precipitation provides the antecedent condition for the occurrence of hydrological drought and governs drought deficit volume. Runoff coefficient represents the proportion of runoff in precipitation and can be used to reflect temporally varied

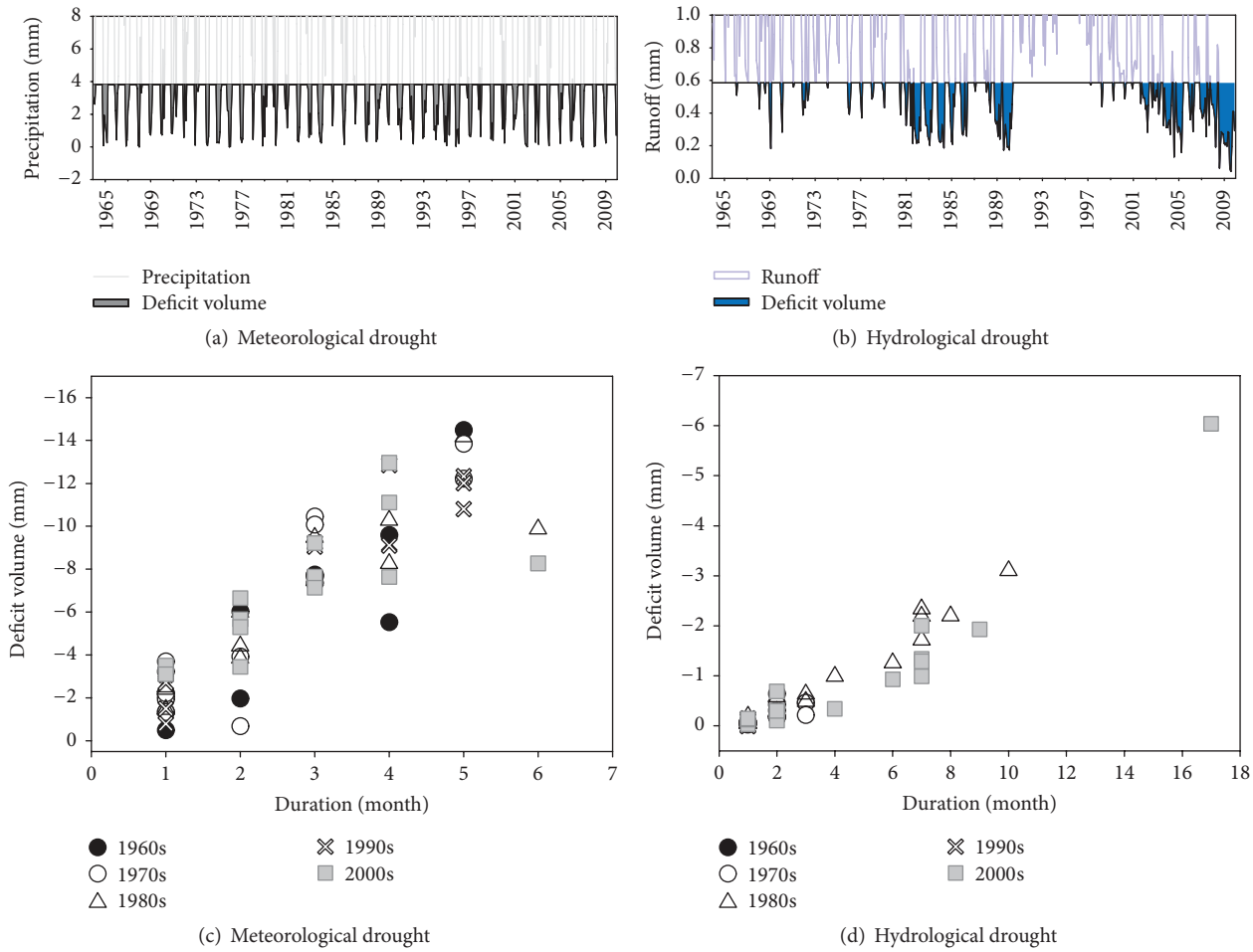

Figure 3: Temporal evolutions of identified (a) meteorological drought (derived from precipitation) and (b) hydrological drought (derived from runoff), and the scatterplots of drought duration and deficit volume for (c) meteorological and (d) hydrological droughts.

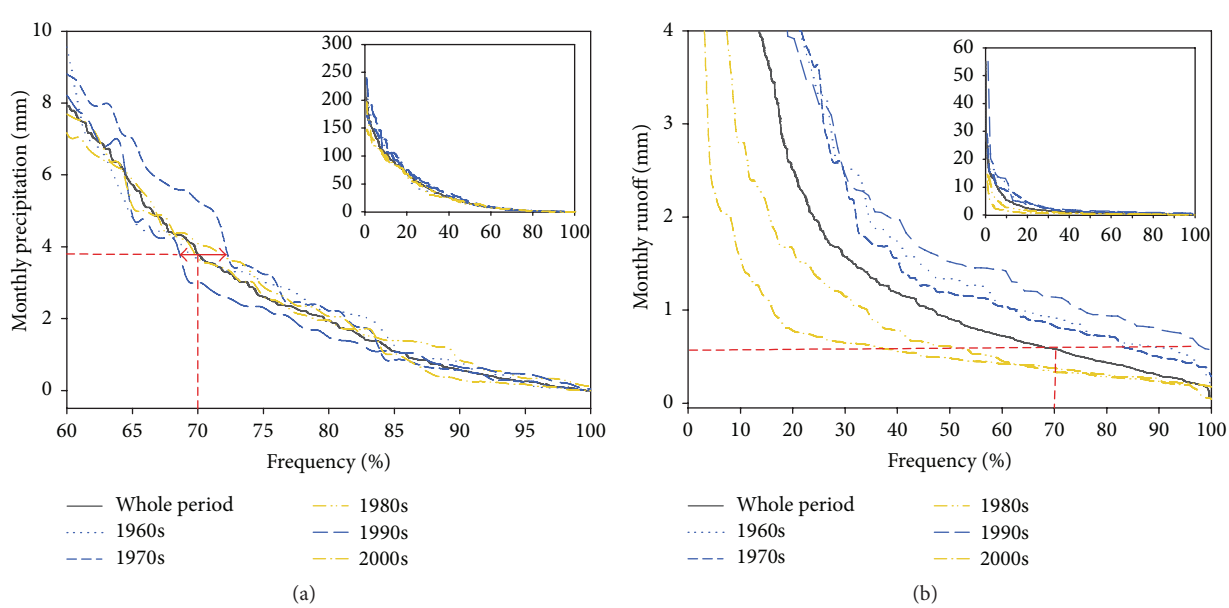

Figure 4: Monthly flow duration curves of precipitation (a) and runoff (b) for each decade. Dull yellow and blue lines represent curves for dry and wet decades, respectively.

Table 2: Mean annual precipitation, runoff, runoff coefficient, baseflow, and BFI of every decadal-year over the Laohahe catchment during the past half-century.

	Precipitation (mm)	Streamflow (mm)	Runoff coefficient	Baseflow (mm)	BFI
1964–1969	414.60	38.34	0.09	10.98	0.29
1970–1979	455.01	35.87	0.08	10.06	0.29
1980–1989	396.31	15.95	0.04	4.89	0.35
1990–1999	473.38	42.98	0.09	12.92	0.32
2000–2009	379.06	9.73	0.03	3.70	0.44

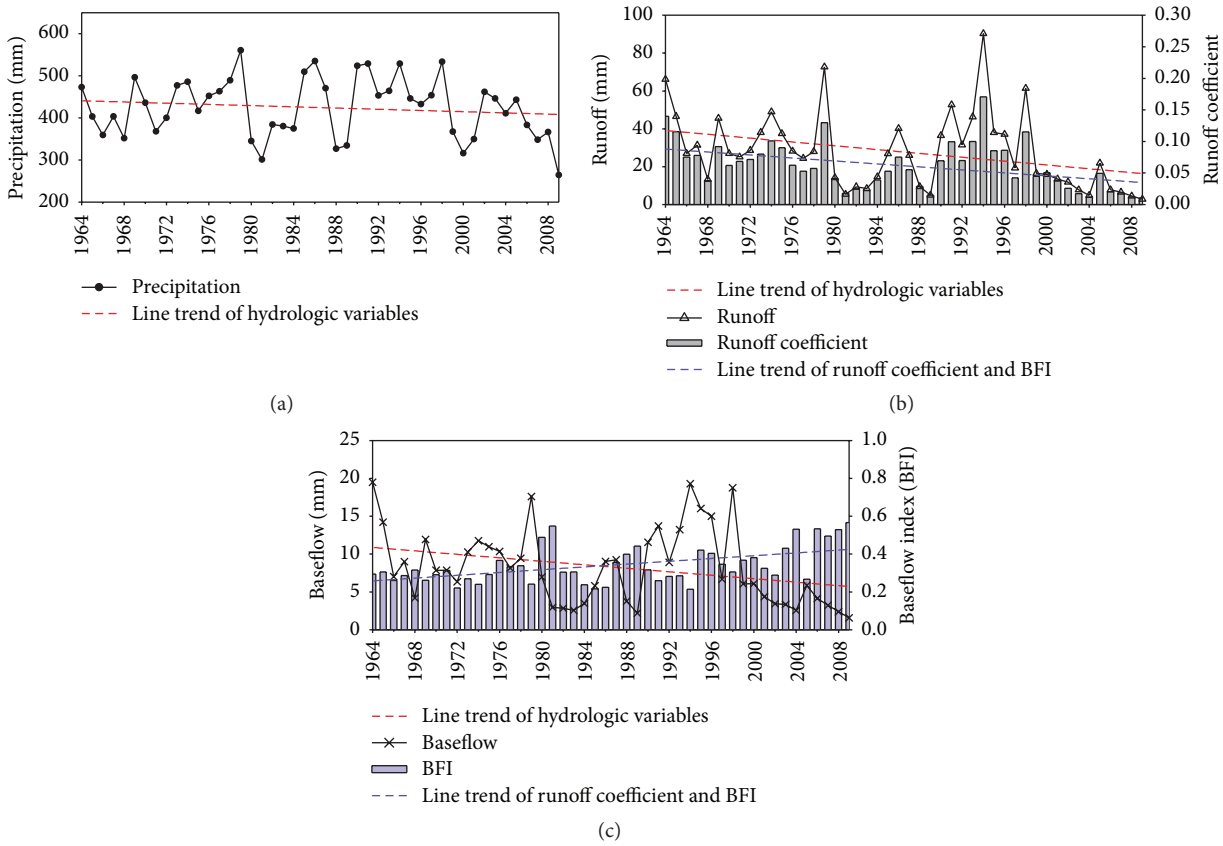

Figure 5: Variations of annual precipitation, runoff, runoff coefficient, baseflow, and baseflow index (BFI) over the Laohahe catchment since 1964. The red dashed line represents linear trend for hydrological variables (precipitation, runoff, and baseflow) and the blue dashed line for runoff coefficient and BFI.

rainfall-runoff relationships. The BFI itself is not a catchment characteristic but it integrates the effect of catchment storage and release properties and is found to have strong positive correlation with hydrological drought duration.

As shown in Figure 5 and Table 2, precipitation (Figure 5(a)) presents a slightly decreasing trend during the past 50 years, accompanied with regularly decadal fluctuation (the 1980s and 2000s are the two driest decades, whereas the 1990s is the wettest decade). Runoff (Figure 5(b)) also shows a descending trend, but in a more rapid rate. This inconsistent pattern between precipitation and runoff is further illustrated by the varied runoff coefficient. Normally, runoff coefficient at this catchment scale varies around 0.09, but in the two driest decades 1980s and 2000s a rather low value (no more than 0.05) is observed, implying the significantly reduced proportion of runoff in precipitation. Meanwhile, runoff components (Figure 5(c)) have also changed and the proportion of baseflow generally increases with an upward trend detected in BFI. This indicates that catchment control like storage and release properties has changed over time, which indirectly influences the development of hydrological drought.

Based on the above analysis, we further investigate the runoff changes (i.e., varied response to precipitation and runoff components) with the double cumulative curves method. Figure 6(a) is the double cumulative curve of precipitation and runoff. From this graph we can find two prominent inflection points where the gradient for the cumulative curve of runoff significantly changes compared with that of precipitation, that is, 1979 and 1998. This deviation is

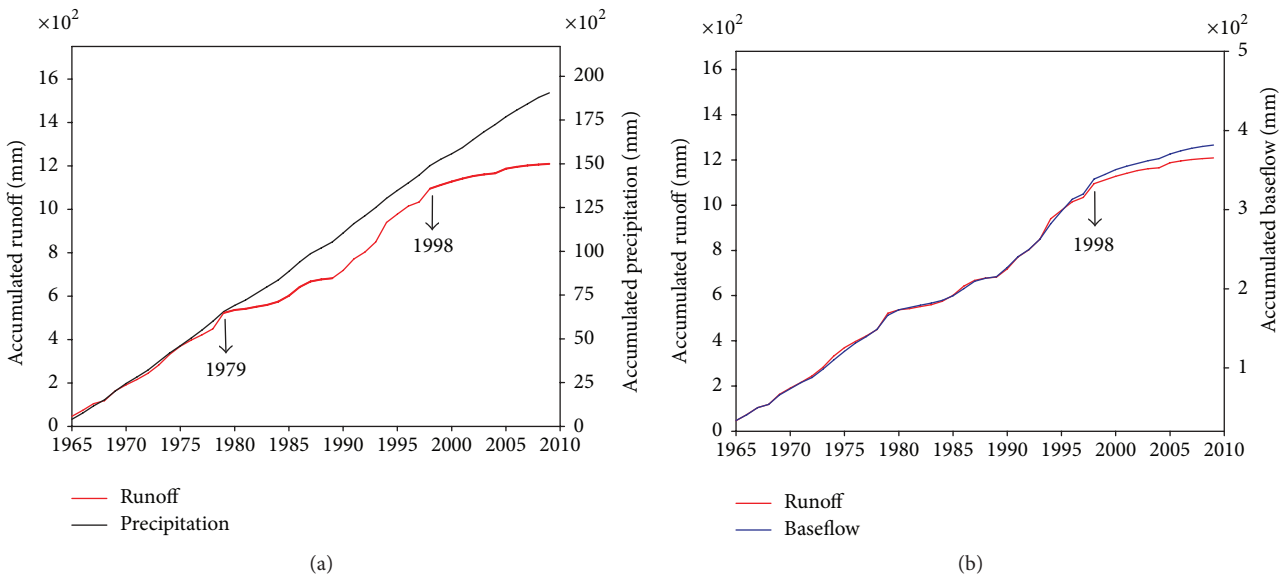

Figure 6: Double cumulative curves of (a) annual precipitation and runoff and (b) annual runoff and baseflow.

quite related to human activities, which lead to sharp decline in runoff [32]. In response to the 1978 land reform policy, most regions in northern China (grain production base) switched their focus to the development of agriculture, and irrigation has become a routine agronomic practice [33]. The Laohahe catchment is one of these cases, as shown in Figure 7; indices like agricultural production (Figure 7(a)) and gross domestic product (GDP, Figure 7(d)) have increased in a staggering speed since 1979. The price paid for the fast-growing agriculture is that more water is consumed and evaporated to meet irrigation demands and livelihood purpose (indicated by a continuous growth in population). The second inflection point which emerged in 1998 implies that reduction in runoff has been aggravated since then. Figure 6(b) shows that, after 1998, runoff decreases more rapidly than baseflow, meaning that consumption from surface water has further increased. During this period, the gross industrial product (GIP) has experienced fast growth (Figure 7(c)), which tremendously contributes to water depletion for the sake of second and third industry development and industrial structure adjustment [11]. In addition, increased reservoir storage capacities during the 2000s might be another reason for surface water reduction. Before 2000s, the Laohahe catchment is mainly regulated by two large reservoirs, namely, the Erdaohezi and Dahushi, with a total regulation capacity of 2.0×10^8 m^3 (a sum of the two reservoirs' storage capacity). In 2003, this regulation capacity has been increased to 5.69×10^8 m^3 with the construction of the San Zuodian reservoir, which potentially brings some pressure to the surface runoff.

As a matter of fact, human activities carried out at this catchment are not limited to the above-mentioned aspects. Other forms such as abstraction from groundwater, land cover and land use change, and livestock breeding all influence runoff patterns in a direct or indirect way. Accordingly, the naturalized process of hydrological drought is disturbed and develops in a more complicated mode. From the perspective of water resources management, our traditional drought mitigation solutions should be adjusted so as to adapt to droughts driven by different causes. This once again shows the significance of making the distinction between naturalized drought and human-induced drought.

4.3. Separating Naturalized and Human-Induced Hydrological Drought. According to the above analysis on the changes of catchment characteristics, the temporal span is divided into two parts, that is, the baseline (undisturbed) period from 1964 to 1979 during which catchment conditions are relatively natural and minor human activities are negligible and the changed (disturbed) period from 1980 to 2010. Following the separating framework described in Section 3.2, we first calibrate the hydrological VIC model using hydrometeorological forcing during the baseline period. Specifically, the VIC model is run at a daily temporal and $0.0625^\circ \times 0.0625^\circ$ spatial resolution. Calibration contains a relative long time, 1964–1974, which aims to ensure an appropriate sample size with both wet and dry years involved and further improves the representativeness of parameters. Accordingly, the remaining five years (1975–1979) belong to the validation period. Figure 8(a) is the monthly simulation results during the baseline period. Overall, a satisfying model performance is found for both calibration and validation periods. Values of NSCE and BIAS are 0.85 and 4.2% for the calibration period and 0.80 and 1.8% for the validation period, respectively, suggesting that VIC is capable of capturing natural variability of the observed hydrograph (e.g., water amounts, peak magnitude, and recession).

With the calibrated model, we reconstructed the streamflow series using hydrometeorological forcing during the changed period (1980–2009). As shown in Figure 8(b), the difference between observed and simulated (reconstructed) series mainly reflects the anthropogenic effects on runoff, combined with minor simulation errors.

Table 3: Drought characteristics (using the 70-percentile monthly threshold) for the observed and simulated runoff during 1980–2009.

Changed period	Number of droughts	Duration (month)		Deficit (mm)	
		Mean	Max	Mean	Max
Observed	27	7.5	29	−3.12	−15.47
Simulated	32	4	6	−1.12	−1.86

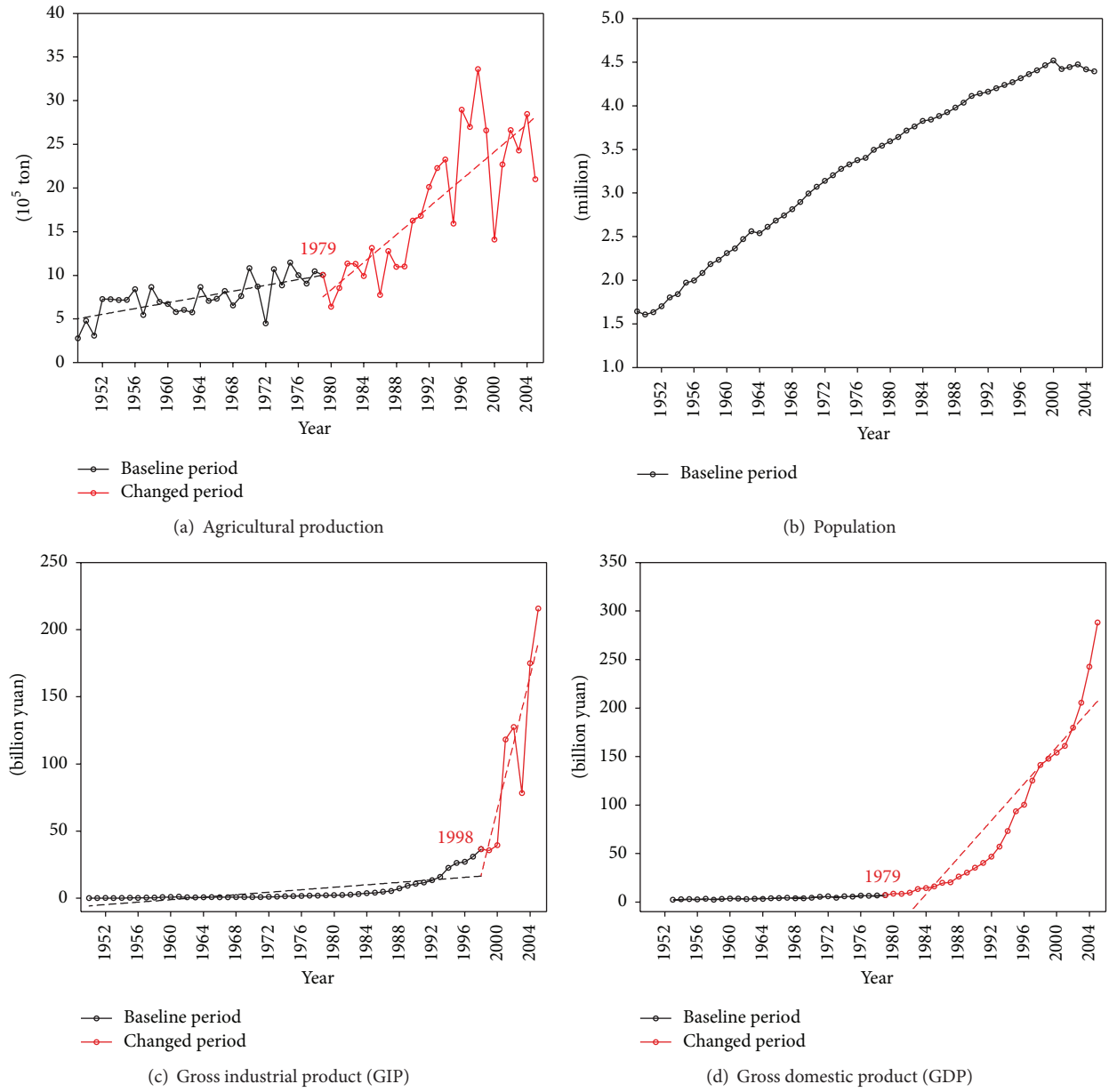

Figure 7: Time series of (a) agricultural products, (b) population, (c) gross industrial product (GIP), and (d) gross domestic product (GDP) in Chifeng, the main city within the Laohahe catchment, from 1949 to 2005.

Figure 9 presents the evolution of hydrological droughts separately identified from observed and simulated streamflow series. Obviously, the upper panel (Figure 9(a)) representing droughts caused by combined effects of natural condition and human disturbances shows a more severe dry pattern than the naturalized condition displayed in the middle panel (Figure 9(b)). Table 3 lists their specific differences in statistics of drought characteristics. Although in the naturalized circumstance five more drought events are observed, drought duration and deficit volume are amplified two to four times and three to eight times, respectively, when human disturbances are involved. This means that the severity of human-induced drought far exceeds that of droughts in naturalized situations. Figure 9(c) is the temporal difference

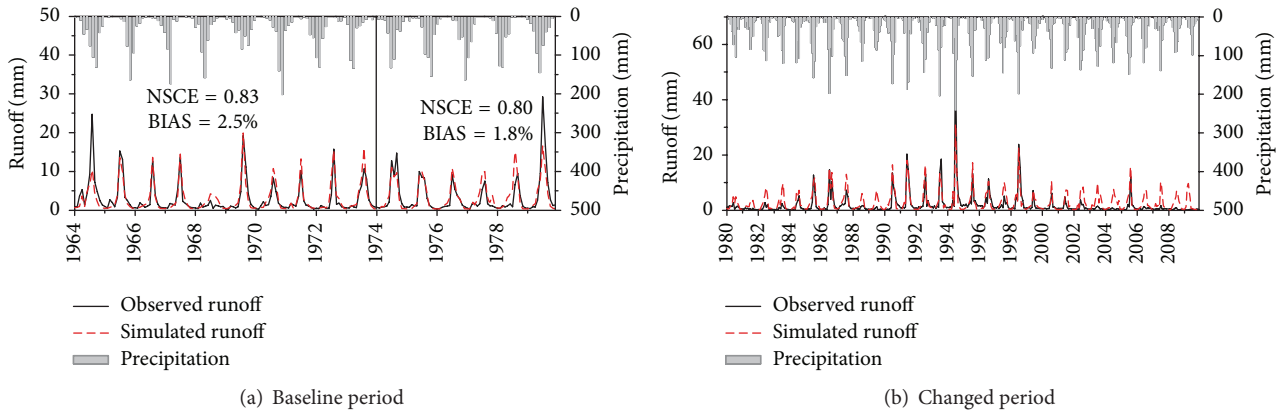

Figure 8: VIC simulated monthly runoff at the Xinglongpo hydrologic station for (a) the baseline period 1964–1979 and (b) changed period 1980–2009.

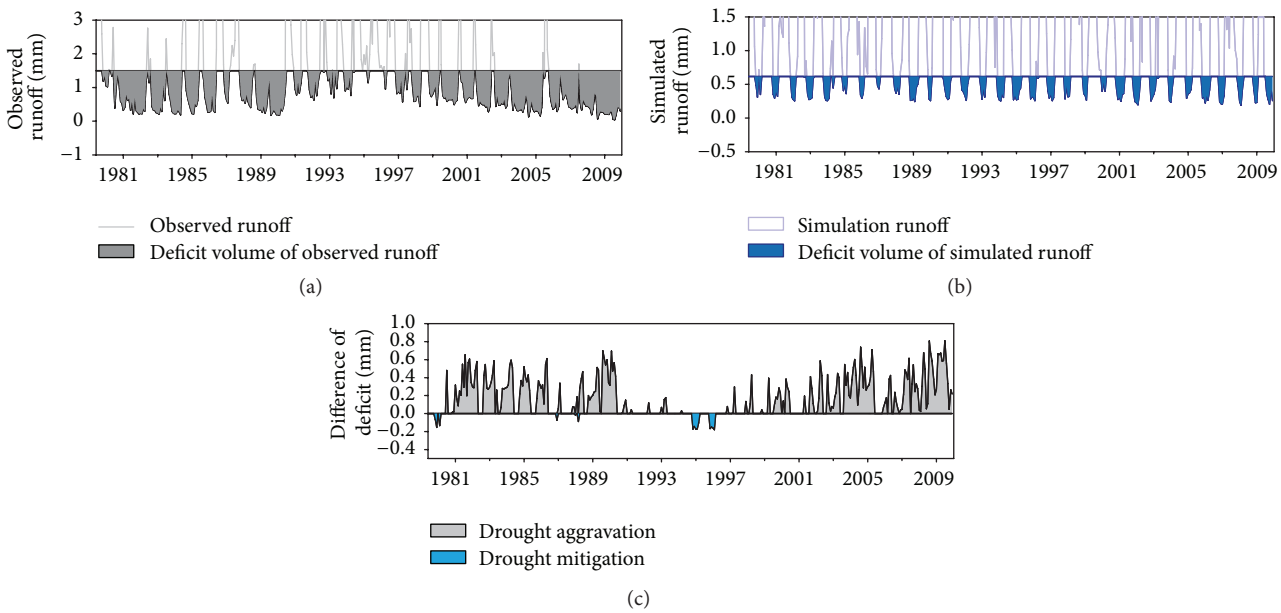

Figure 9: Identified hydrological droughts (with 70-percentile threshold derived from the baseline period) during 1980–2009 from (a) observed runoff and (b) simulated runoff series, and (c) is the difference between observed and simulated runoff series representing the net effect of human activities on drought.

between observed and simulated droughts, which reflects the net impact of human activities. The positive values (light grey area) represent a negative role of aggravating drought, whereas the negative values (light blue area) imply a positive effect of drought mitigation. We can find that, during the whole changed period, human activities are more inclined to play a negative role. In particular in the two dry decades 1980s and 2000s, human activities have induced several consecutive drought events with rather long durations, such as droughts from November 1980 to April 1982 (18 months) and from August 2007 to December 2009 (29 months). In contrast, the influence is rather moderate during the wet decade 1990s; even in 1994 and 1995, a positive effect is observed. The abnormal human activity behaviors in these two years may be related to the interannual regulation roles of reservoirs. Figure 10 shows the monthly variations of precipitation and runoff during the past 46 years (only low flow seasons are displayed, from the recession month (September) in this year to May of next year). We can see that precipitation in 1994 and 1995 is generally the lowest; however, corresponding runoff is extremely high. We speculate that the drainage from reservoirs could be one contributing factor. Due to lack of reservoir records, this unusual phenomenon needs to be further analyzed in the future.

In addition, since the whole separation framework of hydrological droughts largely depends on hydrological model simulations, accurate model performance in capturing the characteristics of hydrograph is essential for the separation results between naturalized and human-induced droughts. As many other hydrological simulations, minor biases (errors

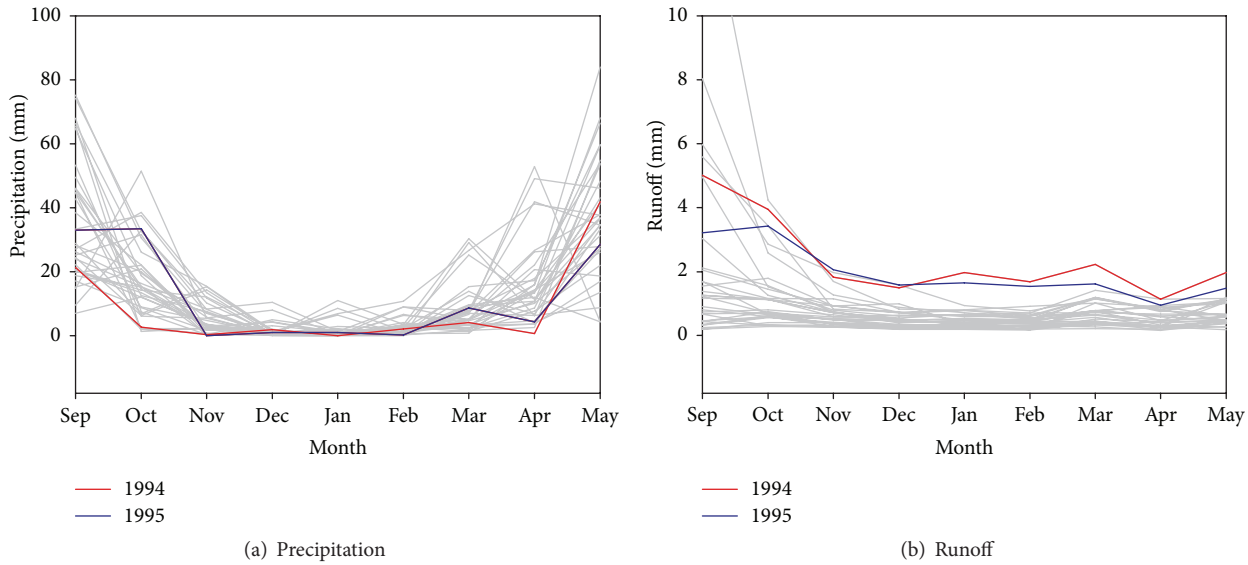

Figure 10: Monthly variations of (a) precipitation and (b) runoff during the past 46 years. The red and blue lines represent variables in 1994 and 1995, respectively, and the grey lines represent variables in other 44 years.

not more than 2.5%, equivalent to approximately 0.9 mm in streamflow) in produced water amounts are observed during the baseline period, with overestimations in peak streamflow contributing to most of the errors (Figure 8). Since droughts recognized by the fixed threshold are more likely to happen in low flow seasons, this systematic positive deviation in flood peak would not influence our separated results in any significant way as long as the errors for the low flow section are effectively controlled. In a more direct way, we compared the differences between observations and hydrological model simulations identified streamflow deficit volume during the baseline period to analyze the propagated bias in droughts. Results show that, among the 73 months which experience hydrological droughts during the baseline period, the difference between the two datasets on average is 0.01 mm/month, with maximum absolute value no more than 0.05 mm/month. This magnitude in general is rather small compared with the streamflow deficit volume of human-induced droughts, where an order of 0.2–0.8 mm/month is found for most of the drought events (Figure 9(c)). In other words, minor errors derived from model simulations though exist; they will not influence the dominant contribution of human activities substantially, especially for the two driest decades 1980s and 2000s. According to the above findings, we could conclude that, with the participation of human activities, hydrological drought in the Laohahe catchment has been further aggravated and become more severe.

5. Summary and Conclusions

In this paper, a case study over the Laohahe catchment is conducted, which serves as a representative example of the evolution of hydrological drought in the context of changing environments. The common understanding of the hydrological drought development is mainly governed by climate and catchment control. However, for catchments like our studied one which is intensively disturbed by human activities, the causes for hydrological drought become rather complicated and the effects from human activities should be considered.

The comparison between meteorological droughts and hydrological droughts occurring in the Laohahe catchment during 1964–2009 shows an interesting pattern; that is, meteorological droughts occur regularly in every decade, but for hydrological droughts, significant decadal differences are observed: the 1980s and 2000s suffer extremely severe hydrological droughts whereas, for the 1990s, almost no droughts occur. This striking contrast is far beyond the scope of naturalized drought process dominated by climate and catchment control, indicating the potential impact of human disturbances on hydrological drought.

The long-term series of runoff related variables are further analyzed and changes in runoff are confirmed according to several indices, that is, inconsistent trend between precipitation and runoff, varied runoff coefficient, and BFI among decades, which commonly reflect the varied responses of runoff to precipitation and runoff components. Then, the double cumulative curves method is employed to detect the changed points, which further divides the whole period into two parts, that is, the undisturbed period (1964–1979) and disturbed period (1980–2009). Meanwhile, four socioeconomic indices are also analyzed which imply increased water consumption in the changed period.

Based on the divided periods, a separating framework is introduced to distinguish between naturalized drought and human-induced drought during the changed period. From the comparison between their drought characteristics, it can be found that the drought duration and deficit volume of naturalized drought are amplified two to four times and three to eight times, respectively, when human activities are involved.

This reflects the considerable impact of human activities on hydrological drought. Generally, human activities are more inclined to play a negative role which aggravates droughts. In particular in the two dry decades 1980s and 2000s, human activities have induced several consecutive drought events with rather long durations (up to 29 months). With a comprehensive analysis on the individual roles of natural condition and human activities on hydrological drought, this study is promising to provide some theoretical support for future drought mitigation and water resources management.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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