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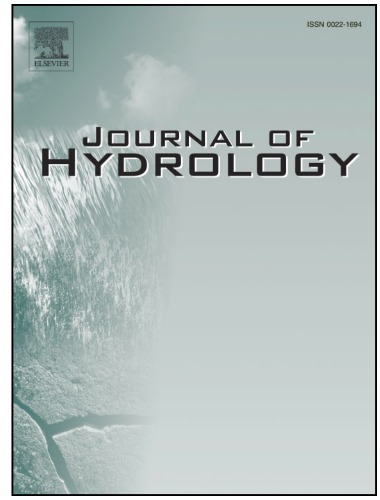

Research papers

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Development of a comprehensive framework for quantifying the impacts of climate change and human activities on river hydrological health variation

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Abstract

Climate change and human activities have together altered the river hydrological regime and consequently threatened the health of river ecosystems. Quantifying the impact of climate change and human activities on river hydrological health regimes is essential for water resource management and river ecology protection. Although previous studies have analysed the hydrologic alterations using some indicators, separating effects of climate change and human activities on river hydrological health is needed for developing adaptive measures to protect the ecosystem of river basins. In this study, a comprehensive assessment framework for quantifying climatic and anthropogenic influences on river hydrological health variation was proposed. The framework consists of the following steps: (1) the reconstruction of natural river streamflow using the variable infiltration capacity (VIC) hydrological model, (2) calculation of river hydrological health through the ecological flow threshold method, and (3) quantification of the impacts of climate change and human activities on river hydrological health using the 'observed–simulated' comparison approach. The semi-arid Laohahe Basin in northern China, which consists of three human-influenced catchments (Taipingzhuang, Chifeng, and Xinglongpo) and one natural catchment (Xiquan), was selected as the case study area. The case study demonstrated that the proposed procedure is efficient in quantifying climatic and anthropogenic influences on river hydrological health. The results revealed that the hydrological health level has significantly declined in the three human-influenced catchments for the human-influenced period (1980–2016), particularly in the 2000s and 2010s, where it degraded much more severely. Whereas, the relatively adequate rainfall in the 1990s maintained the river hydrological health at a good status. The quantitative evaluation showed that human activities were the main driving factors for the hydrological health degradation during the whole human-influenced period, with contributions of 80.8%, 91.9%, and 86.0% for the Taipingzhuang, Chifeng, and Xinglongpo catchments, respectively. Widespread artificial water withdrawal and reservoir operation were the two crucial human activities that caused the degradation of river hydrological health for the studied catchment. The proposed procedure and findings of this study not only help in deeper understanding of the evolutionary characteristics and driving mechanisms of river hydrological health in a changing environment in general, but also provide scientific basis for local water resources management and river ecosystems protection.

Keywords: Ecological flow; Hydrological health; Climate change; Human activities; Impact assessment

1. Introduction

Rivers are one of the most crucial ecosystems in terms of both socioeconomic benefits and natural function, and they play a vital role in the hydrological cycle, as their channels are essential for nutrient cycling and energy flow between diverse ecosystems (Hotchkiss et al., 2015; Zhang et al., 2017; Palmer and Ruhi, 2019). From a systems perspective, rivers have strong anti-interference abilities. However, their self-repairing capacity is inherently limited, which means that when the external interference exceeds their capacity, the riverine ecosystem will irreversibly be degraded and cause many service functions to decline or even disappear (Wohl et al., 2005; Poff, 2018; Belletti et al., 2020). Therefore, it is necessary to maintain river health to ensure the sustainable development of economy and society.

In retrospect, the concept of river health was first proposed in the 1972 Clean Water Act by the USEPA, which means maintaining the chemical, physical, and biological integrity, where integrity refers to a condition in which the natural structure and function of ecosystems is maintained (Karr, 1999). In other words, the original and undisturbed state is the health state of the river, in which the river ecosystem can support and maintain its primary ecological processes (Simpson et al., 1999), and the river health refers to how similar the river is to an undamaged river of the same type, especially regarding its biodiversity and ecosystem functions (Schofield and Davies, 1996). With the increased research, scholars believe that river health should also include the service value of rivers to human society (Meyer, 1997; Johnson et al., 2003). Climate change and human activities, however, significantly affect river health, resulting in the deterioration of water quality, degradation of habitats, and loss of riverine biodiversity (Habersack et al., 2014; Zhao et al., 2019a; Belletti et al., 2020; Cui et al., 2020). Climate change affects the flow of rivers through alterations in rainfall and temperature patterns and intensity, thereby affecting the ecological health of the river. Human activities (such as dam construction, immoderate water consumption, and river cut-off) disturb the natural flow regime and hydrological cycle. Thus, it is urgent to assess the impacts of climate change and human activities on river health.

The generally accepted methods for evaluating river health can be assigned to two groups: biological monitoring and comprehensive indicator methods (Norris and Hawkins, 2000). The majority of scholars are using the comprehensive indicator method because of the integrative perspective with a suit of physical, chemical, and biological variables (Richter et al., 1996; Richter et al., 1997; Poff et al., 2010; Sofi et al., 2020). Generally, in the comprehensive indicator method, the flow and ecological flow satisfaction rate are important indicators because the natural flow regime plays a major role in the structure and function of aquatic ecosystems (Lytle and Poff, 2004; Zhao, et al., 2019a; Sofi et al., 2020; McMillan, 2021). Richter et al. (1996) pioneered the development of the indicators of hydrological alteration (IHA) as well as the range of variability approach (Richter et al., 1997), which can assess the characteristics of flow variation, establishing a link between different hydrological variables and ecological features. Some studies have identified a smaller subset of hydrological indicators to represent the overall change in flow regimes (Gao et al., 2009; Zhang et al., 2015; Zhang et al., 2018), such as ecosurplus and ecodeficit (Vogel et al., 2007) and the most ecologically relevant hydrological indicators (Yang et al., 2008). Ecological flow, containing the quantity and regime of water flows, is of great importance for maintaining the health of river and lake ecosystems, and an extremely low daily flow supplement intensity may cause ineffective ecological restoration measures (Acreman and Dunbar, 2004; Zhao, et al., 2019b). Therefore, a river hydrological health (*H*) assessment method was proposed based on the ecological flow threshold, which better represents the actual demand of river ecosystems for river flow (Ma et al., 2019).

Based on the ecological flow thresholds, the evolutionary characteristics and driving mechanisms of river hydrological health can be analysed. The first step is the accurate calculation of ecological flow. The widely accepted methods for calculating ecological flow can be divided into four main categories: hydrological, hydraulics, habitat, and holistic methods (Boner and Furland, 1982; Mosely, 1982; Nehring and Anderson, 1993; Hughes and Hannart, 2003). In particular, the hydrological method is broadly used because of its ease of obtaining data, simple calculation, and in-depth analysis of the overall hydrological regime of the river. The hydrological methods mainly include the Tennant method (Tennant, 1976), monthly frequency method, and monthly probability density curve method (Zhang et al., 2018). Nowadays, due to environmental changes, the consistency of river flow sequences often undergoes a certain degree of variation, which affects the accuracy of ecological flow calculations (Zhang et al., 2018). Therefore, the use of sub-sequences before hydrological mutation is necessary for accurate calculation. Meanwhile, by comparing the ecological flow with the flow before and after the hydrological mutation, the river hydrological health of the two different periods can be evaluated (Tan et al., 2018). Then further analysis could be carried out to assess the impacts of climate change and human activities on river hydrological health. However, a few recent studies assessed the impacts only from a qualitative perspective (Sellami et al., 2016; Tian et al., 2019; Yu et al., 2020; Mezger et al., 2021). It is essential to develop a quantitative method that separates the impacts of climate change and human activities on river hydrological health. The 'observed–simulated' comparison analysis method is widely used to distinguish the influence of human activities from climate change on streamflow by the reconstruction of natural streamflow (Wang et al., 2020). This method, which simulates near-natural hydrological variables using hydrological models, can avoid the uncertainties caused by naturalised data (e.g. reservoir regulation records and human water withdrawal records), which can be an effective method to quantitatively characterise the impact of environmental changes on river hydrological health. In addition, coupled with existing climate change models simulations, the hydrological model simulation can predict the future river hydrological health variations under changing environment (Zhao et al., 2019a).

Therefore, this study proposed a comprehensive assessment framework for quantifying the impacts of climate change and human activities on river hydrological health variation, which consist of three steps: (1) the reconstruction of river natural streamflow using the variable infiltration capacity (VIC) hydrological model, (2) calculation of river hydrological health through the ecological flow threshold method, and (3) quantification of the impacts of climate change and human activities on river hydrological health using the 'observed–simulated' comparison approach. The semi-arid Laohahe Basin in northern China was selected for the case study because its river streamflow has decreased significantly and streamflow interruption occurred in summer under intense human influence (Jiang et al., 2011; Yong et al., 2013; Liu et al., 2016). The outcomes of this study improve our understanding of the evolutionary characteristics and driving mechanisms of river hydrological health in a changing environment, and also provide scientific basis for practical water resource management and river ecosystems protection in the future.

2. Materials and methods

2.1 Study area and data

2.1.1 Laohahe Basin

The Laohahe Basin is located at the junction of the Hebei and Liaoning provinces and the Inner Mongolia Autonomous Region in northeastern China (41°–42.75°N, 117.25°–120°E) (Fig.1). It flows approximately 430 km eastward to the West Liao River, with its origin at Qilaotu Mountain in the northern part of the Yan Shan mountain chain. It covers an area of 18112 km^2, with the Xinglongpo hydrological station (42.32°N, 119.43°E). The basin's elevation ranges from 427 m above mean sea level to over 2000 m a.m.s.l. in the upstream mountainous area, descending from west to east (Yong et al., 2013). The annual precipitation of this basin is 411.7 mm (1964–2016). Summer is the main rainy season, and approximately 88% of the annual precipitation occurs from May to September, which leads to a significant seasonal variation in streamflow (Jiang et al., 2012; Liu et al., 2016; Wang et al., 2020).

Insert Figure 1 about here

In this study, we selected four catchments, including one headwater catchment (Xiquan), two midstream catchments (Taipingzhuang and Chifeng), and the entire catchment. Table 1 lists the geographic and hydrological characteristics of these four catchments. The average annual precipitation of these catchments ranges from 401 to 573 mm, and the average annual streamflow from 21 to 126 mm. The precipitation and runoff show similar characteristics of spatial variation, increasing gradually from the northeast to the southwest.

Insert Table 1 about here

2.1.2 Data

The data used in this study included hydrometeorological, geographic, and socioeconomic data. More details are as follows.

(1) The China Meteorological Data Sharing Service System (http://data.cma.cn/) provided daily meteorological data from 1964 to 2016, including wind speed and maximum and minimum air temperatures measured by ten national standard meteorological stations (Fig.1). Daily precipitation data of 52 rain gauges from 1964 to 2016, daily streamflow series of the same period for the four catchments, and information of the three reservoirs were gathered from the Water Resources Department of the Inner Mongolia Autonomous Region. To drive the VIC hydrological model, the meteorological and precipitation data were interpolated into grid data with a resolution of 0.0625° × 0.0625°, using the inverse distance weighting method. In addition, the daily precipitation and streamflow data were converted to monthly and annual averages.

(2) The geographic datasets consisted of soil type, vegetable type, and digital elevation model (DEM) data. Soil types were obtained from the Food and Agricultural Organization (FAO) dataset. Vegetation types were provided by the University of Maryland's 1-km Global Land Cover Production. The 30-arcsecond global DEM data were available from the U.S. Geological Survey (USGS) website

(https://www.usgs.gov/).

(3) Socioeconomic statistics data were collected as follows: population and gross domestic product (GDP) from the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn); irrigated area and food production from the local statistical bureau.

2.2 Framework for quantifying the impacts of climate change and human activities on hydrological health

As illustrated in Fig.2, the proposed framework can be divided into three main steps for assessing river hydrological health evolution characteristics and quantifying the impact of climate change and human activities on hydrological health variation.

First, it is necessary to test the consistency of the hydrometeorological data. Previous studies in the Laohahe Basin have confirmed a significant decrease in streamflow (Jiang et al., 2011; Yong et al., 2013). Therefore, we implemented a variation analysis of the hydrometeorological series for the selected four basins, focussing on the trend and change point. Numerous methods are available for change-point detection, and we selected the Mann–Kendall (M–K) test (Mann, 1945; Kendall, 1975), Pettitt test (Pettitt, 1979), and precipitation–streamflow double cumulative curve (DCC) method. According to the change point, the whole period can be divided into two parts, i.e., the baseline period ('undisturbed period') and changed period ('disturbed period'). Then, the hydrological and meteorological forcing data in the 'undisturbed period' were used to calibrate the VIC hydrological model (described in Section 2.2.1) with an acquisition of optimal model parameters. Based on these parameters, the meteorological forcing data for the 'disturbed period' were used to drive the model for reconstructing (simulating) natural streamflow series, which was considered to be only affected by climatic factors.

The second step was to establish an assessment of river hydrological health. The most suitable ecological flow was first calculated, and the threshold of ecological flow was determined accordingly. Then, a hydrological health algorithm was constructed, and the level of hydrological health was calculated.

The final step focussed on quantifying the impact of climate change and human activities on hydrological health variation. The total change in the observed hydrological health level between disturbed and undisturbed periods presents the combined effects of climate change and human activities, whereas the change in the simulated hydrological health level between both periods can be considered as solely the effect of climate change (Jiang et al., 2019). Based on the assumption that climatic factors are independent of human activities, we can quantitatively separate the impacts of climate change and human activities.

Insert Figure 2 about here

2.2.1 VIC hydrological model

To simulate the hydrological process, we used the macro-scale semi-distributed VIC model (Liang et al., 1994) developed by the University of Washington, University of California at Berkeley, and Princeton University. The model solves the surface energy and water balance to study the effects of droughts (Luo and Wood, 2007), water resource impacts (Vano et al., 2010), ecologically relevant flow indicators (Wenger et al., 2010; Shrestha et al., 2013), and for various other applications. The model parameters can be commonly classified into two categories. The parameters in the first category can be determined directly from soil type and land cover data, including the saturated soil potential ψ_s (m), soil porosity θ_s (m^3/m^3), saturated hydraulic conductivity k_s (m/s), root depth, and fraction. The other category consists of seven user-calibrated parameters can refer to Liang et al. (1994) and Wang et al. (2020). While optimizing the seven sensitive parameters, three criteria were used to evaluate the model performance (Jiang et al., 2018), that is, the Nash–Sutcliffe efficiency coefficient (NSE), coefficient of correlation, and relative error (BIAS), calculated by the following equations.

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{\mathrm{sim}}(i) - Q_{\mathrm{obs}}(i)\right)^2}{\sum_{i=1}^{n} \left(Q_{\mathrm{obs}}(i) - \overline{Q}_{\mathrm{obs}}\right)^2} \tag{1}$$

$$CC = \frac{\sum_{i=1}^{n} \left(Q_{\mathrm{obs}}(i) - \overline{Q}_{\mathrm{obs}}\right) \cdot \left(Q_{\mathrm{sim}}(i) - \overline{Q}_{\mathrm{sim}}\right)}{\sqrt{\sum_{i=1}^{n} \left(Q_{\mathrm{obs}}(i) - \overline{Q}_{\mathrm{obs}}\right)^2} \sqrt{\sum_{i=1}^{n} \left(Q_{\mathrm{sim}}(i) - \overline{Q}_{\mathrm{sim}}\right)^2}} \tag{2}$$

$$BIAS = \frac{\sum_{i=1}^{n} \left(Q_{\mathrm{sim}}(i) - Q_{\mathrm{obs}}(i)\right)}{\sum_{i=1}^{n} Q_{\mathrm{obs}}(i)} \tag{3}$$

where $Q_{\mathrm{obs}}(i)$ and $Q_{\mathrm{sim}}(i)$ are the observed and simulated runoff (mm/month) at time step *i*, respectively; $\overline{Q}_{\mathrm{obs}}$ and $\overline{Q}_{\mathrm{sim}}$ are the mean observed and simulated runoff values (mm/month), respectively; and *n* is the number of data points.

2.2.2 River hydrological health assessment method

Despite ample research on ecological flow, there is still a lack of universal definitions and standard calculation methods for ecological flow. Several methods currently exist for the measurement of ecological flow criteria, such as the Tennant method (Tennant, 1976), and flow duration curve (Mu et al., 2008), which are susceptible to extreme events and annual distribution inequality (Tan et al., 2018). Therefore, based on the bioadaptability (Wilson and Franklin, 2002) and plasticity (Lai et al., 2010) theory of ecosystems, the river discharge corresponding to the extreme value of the monthly probability density curve is treated as the most suitable ecological discharge for that month in this study. Then, the relevant ecological flow thresholds can be defined. According to Ma et al. (2019), the definitions can be described as follows:

The most suitable ecological flow (Q_0): In the selected flow sequence of the undisturbed period, the flow corresponding to the maximum of the monthly average flow probability density function is the most suitable ecological flow for the month, and the most suitable annual ecological flow process is composed of the most suitable ecological flow per month.

Optimal lower threshold for ecological flow (Q_1): In the selected flow sequence of the undisturbed period, the mean value of the minimum and optimum ecological flow is treated as the lower threshold of the optimal ecological flow. The optimal lower threshold annual ecological flow process is composed of the optimal lower threshold for ecological flow per month.

Optimal upper threshold for ecological flow (Q_2): In the selected flow sequence of the undisturbed period, the mean value of the maximum and optimum ecological flow is treated as the upper threshold of the optimal ecological flow. The optimal upper threshold annual ecological flow process is composed of the optimal upper threshold for ecological flow per month.

Minimum ecological flow (Q_3): In the selected flow sequence of the undisturbed period, the minimum value of the monthly average flow of several years is treated as the minimum ecological flow of that month. The minimum annual ecological flow process is composed of the minimum ecological flow per month.

Maximum ecological flow (Q_4): In the selected flow sequence of the undisturbed period, the maximum value of the monthly average flow over several years is treated as the maximum ecological flow of that month. The maximum annual ecological flow process is composed of the maximum ecological flow per month.

Extremely small ecological flow (Q_5): In the selected flow sequence of the undisturbed period, the minimum daily flow per month for several years is treated as the extremely small ecological flow of that month. The extremely small annual ecological flow process is composed of the extremely small ecological flow per month.

Extremely large ecological flow (Q_6): In the selected flow sequence of the undisturbed period, the maximum daily flow per month for several years is treated as the extremely large ecological flow of that month. The extremely large annual ecological flow process is composed of the extremely large ecological flow per month.

Different ecological flow thresholds present different states of river health. In addition, compared with low flow, large floods can improve species diversity in rivers, which suggests that excessive flow has a better ecological influence than small flow. Then, the river hydrological health assessment algorithm can be constructed (Ma et al., 2019), as shown in Eq (4).

$$H=\begin{cases}\left(\dfrac{Q}{Q_5}\times 0.5\right)\times 10 & [0,Q_5) \\ \left(\dfrac{Q-Q_5}{Q_3-Q_5}\times 1.5+1\right)\times 10 & [Q_5,Q_3) \\ \left(\dfrac{Q-Q_3}{Q_1-Q_3}\times 2+4\right)\times 10 & [Q_3,Q_1) \\ \left(\dfrac{Q-Q_1}{Q_0-Q_1}\times 1+8\right)\times 10 & [Q_1,Q_0) \\ \left(\dfrac{Q_2-Q}{Q_2-Q_0}\times 1+9\right)\times 10 & [Q_0,Q_2] \\ \left(\dfrac{Q_4-Q}{Q_4-Q_2}\times 2+6\right)\times 10 & (Q_2,Q_4] \\ \left(\dfrac{Q_6-Q}{Q_6-Q_4}\times 1.5+2.5\right)\times 10 & (Q_4,Q_6] \\ \left(\dfrac{1.5\times Q_6-Q}{Q_6}\times 1+0.5\right)\times 10 & (Q_6,1.5Q_6] \\ 5 & (1.5Q_6,\infty)\end{cases} \tag{4}$$

where H denotes the river hydrological health, Q_0 denotes the most suitable ecological flow, Q_1 and Q_2 denote the optimal lower and upper thresholds for ecological flow, Q_3 and Q_4 denote the minimum and maximum ecological flows, and Q_5 and Q_6 denote the extremely small and large ecological flows, respectively. To be consistent with the difference between the minimum flow value of zero and the extremely small ecological flow, Tan et al. (2018) suggest that the upper threshold is taken twice as much as that of the maximum history daily flow, which is the same as the upper threshold of the Tennant method valued 200%. However, Ma et al. (2019) point that it is more practical to set the extremely large ecological flow value as 1.5 times the maximum ecological flow, because the Tennant method generally calculates the annual average flow. In this study, we adopt the Ma's suggestion. When floods exceed this extremely large flow, they are also calculated as 1.5 times the maximum daily flow. In addition, all the data for calculating ecological flows came from the undisturbed period, considering that human activities have affected river health during the changed period.

The proposed assessment method is applicable for different time scales, such as the annual scale, where we only need to change the time scale, and the remaining steps are the same as in the previous analysis.

2.2.3 Quantifying the impacts of climate change and human activities on hydrological health variation

Based on the assessment algorithm, the evolutionary characteristics of river hydrological health can be depicted under the conditions of observed and simulated streamflow. For a small basin, climate change is mainly controlled by external forces; thus, climate change and human activities were regarded as independent variables. Then, the effects of these two variables on river hydrological health can be quantified as follows (Wang et al., 2008; Jiang et al., 2011; Wang et al., 2020):

$$\Delta H_{\mathrm{t}} = \Delta H_{\mathrm{c}} + \Delta H_{\mathrm{h}} = \overline{H}_{2,\mathrm{obs}} - \overline{H}_{1,\mathrm{obs}} \tag{5}$$

$$\Delta H_{\mathrm{c}} = \overline{H}_{2,\mathrm{sim}} - \overline{H}_{1,\mathrm{sim}} \tag{6}$$

$$\Delta H_{\mathrm{h}} = \Delta H_{\mathrm{t}} - \Delta H_{\mathrm{c}} = (\overline{H}_{2,\mathrm{obs}} - \overline{H}_{1,\mathrm{obs}}) - (\overline{H}_{2,\mathrm{sim}} - \overline{H}_{1,\mathrm{sim}}) \tag{7}$$

$$I_{\mathrm{c}} = \frac{\Delta H_{\mathrm{c}}}{|\Delta H_{\mathrm{t}}|} \times 100\% \tag{8}$$

$$I_{\mathrm{h}} = \frac{\Delta H_{\mathrm{h}}}{|\Delta H_{\mathrm{t}}|} \times 100\% \tag{9}$$

where ΔH_{t} and $|\Delta H_{\mathrm{t}}|$ are the total change in hydrological health and its absolute value, respectively; ΔH_{c} and ΔH_{h} represent the change in hydrological health induced by climate change and human activities, respectively; $\overline{H}_{1,\mathrm{obs}}$ and $\overline{H}_{2,\mathrm{obs}}$ denote the observed average annual value of hydrological health for undisturbed and disturbed periods, respectively; $\overline{H}_{1,\mathrm{sim}}$ and $\overline{H}_{2,\mathrm{sim}}$ denote the simulated average annual value of hydrological health for undisturbed and disturbed periods, respectively; I_{c} and I_{h} suggest the relative effects in percentage of climate change and human activities, respectively.

Overall, the main procedure is as follows: (1) divide the undisturbed and disturbed periods, and then reconstruct the natural streamflow series; (2) establish the assessment algorithm and calculate river hydrological health under different streamflow series; and (3) quantify the difference between observed and simulated changes in hydrological health.

3. Results

3.1 Natural streamflow reconstruction

As shown in Table 2, the M–K test results demonstrated that precipitation and potential evapotranspiration (calculated via the Penman–Monteith equation recommended by FAO) series have no significant increasing or decreasing trend for the four catchments, whereas the streamflow series decreased drastically except for the Xiquan catchment (Fig. 3). For the Taipingzhuang, Chifeng, and Xinglongpo catchments, the high values of streamflow appear in the 1960s to 1970s and then start to gradually decline until the late 1980s. But, in the mid-1990s, the Laoha basin seems to enter a relative wet period, and a rebound of the streamflow occurs for the three catchments. In the most recent decade, the annual streamflow are seriously reduced to their historical lowest levels. From the Pettitt test (Table 2) and DCC results (Fig. 3), the first change point of streamflow series occurred in 1979 for the Taipingzhuang, Chifeng, and Xinglongpo catchments. Therefore, we divided the whole period (1964–

2016) into the undisturbed period (1964–1979) and disturbed period (1980–2016).

Insert Figure 3 about here

Insert Table 2 about here

The semi-distributed VIC hydrological model was used to reconstruct the natural streamflow, and the comparison of the reconstructed and observed streamflow series is presented in Fig.4. Then, NSE, CC, and BIAS metrics were calculated and are presented in Table 3. The values of NSE, CC, and BIAS for the Taipingzhuang catchment were 0.90, 0.95, and 1.59% during the calibration period (1964–1974) and 0.82, 0.91, and 5.47% during the validation period (1975–1979), respectively. For the Chifeng catchment, the values of NSE, CC, and BIAS were 0.77, 0.88, 0.6% and 0.71, 0.85, and 11.3% for the calibration and validation periods, respectively. The NSE, CC, and BIAS values for the Xinglongpo catchment during the calibration and validation periods were 0.83 and 0.80, 0.91 and 0.90, and 1.2% and -1.6%, respectively. Overall, these results indicate that the accuracy of the reconstructed streamflow satisfied the requirements of this study.

Insert Figure 4 about here

Insert Table 3 about here

3.2 Calculation of the most suitable ecological flow

When the river flow is the appropriate value of the most suitable ecological flow in each month, it can maintain the health of the river ecosystem and the stability of the population structure of biological species, which is of great significance to the management of river health. To ensure the accuracy of the ecological flow calculation results, we compared the calculation results with other methods. In this study, the nonparametric estimation-kernel density function (KD) was used to fit the monthly flow order. The parametric estimation was also used to fit the monthly flow order (Zhang et al., 2018), which uses the statistical *D* of the Kolmogorov–Smirnov (K–S) method to test the goodness of fit and select the appropriate distribution function. A comparison of the results showed that the generalized extreme value distribution (GEV) was more suitable for the monthly average flow series of the study area. According to (Li et al., 2007), we selected a 50% guarantee rate (Q50) in the monthly frequency calculation method for the most suitable ecological flow calculation. The results of the aforementioned method were also verified by the Tennant method, which is the most widespread hydrological method worldwide (Tharme 2003) and often used to verify the rationality of other ecological flow calculation methods (Li et al., 2014; Pastor et al. 2014). As shown in Figure 5, the monthly ecological flows calculated by the KD method were located between the GEV method and the Q50 method. The lower threshold of the optimum flow calculated by the Tennant method (MAFL) is generally lower than the result of the KD method, while sometimes higher than it of the GEV method. We also carried out a comparison in the annual scale, showed in Table 4. The annual ecological flows fell on the optimum flow range recommended by the Tennant method except for the Xiquan catchment. Meanwhile, the result of the KD method was closer to the optimum flow range in the Xiquan catchment. Therefore, the KD method for calculating the ecological flow used in this study was accurate and reasonable.

Based on the calculation of the most suitable ecological flow (Q_0), the relevant ecological flows (Q_1, Q_2, Q_3, Q_4, Q_5, Q_6) were calculated.. Fig. 6 shows the breakdown of ecological flow according to the threshold definition in Section 2 and the annual distribution of each hydrological station under various hydrological health levels.

Insert Figure 5 about here

Insert Figure 6 about here

Insert Table 4 about here

3.3 Assessment of river hydrological health

We calculated the river hydrological health of each catchment using the assessment method established in Section 2. As Fig. 7 illustrates, the observed hydrological health during the undisturbed period was better than that during the disturbed period for the three human-impacted catchments. Before 1980, the river hydrological health level was generally higher than 80, whereas it was lower than 50 after 1980, except from 1990 to 1999. The hydrological health of the simulated streamflow exhibited good consistency and was in a better state at the monthly scale (e.g. June–October) with a level of over 90. Furthermore, we calculated the health degree at the annual scale and the average value during different periods. As shown in Table 5, the averages of the hydrological health levels were 89.4, 88.8, and 91.0 for the Taipingzhuang, Chifeng, and Xinglongpo catchments, respectively, from 1964 to 1979. However, the averages were 45.9, 51.1, and 50.0 for the Taipingzhuang, Chifeng, and Xinglongpo catchments, respectively, for the human-influenced period (1980–2016), which indicated an evident decline.

Especially in the 2010s, the means of hydrological health were 11.5, 2.1 and 8.8 respectively, suggesting a significant variation of flow regimes.

Insert Figure 7 about here

Insert Table 5 about here

3.4 Quantifying the impacts of climate change and human activities on river hydrological health

Considering the hydrological health calculation results from the observed and simulated series, the impacts of climate change and human activities can be quantitatively separated based on the framework described in Section 2. In addition, we calculated the relative contributions of climate change and human activities over different decades during the disturbed period to further assess decadal variations. The results of the quantitative estimation are shown in Table 5 and Fig.8. For the entire disturbed period, the impact of human activities on hydrological health variation is conspicuously greater than that of climate change. The contributions of human activities were 80.8%, 91.9% and 86.0% for the Taipingzhuang, Chifeng, and Xinglongpo catchments, respectively, whereas the percentages of climate change contribution on health variation were only 19.2%, 8.1%, and 14.0%, respectively.

For the different decades during the disturbed period, the contribution of human activities to hydrological health variation shows an increasing trend, except in the 1990s. Considering the whole basin (Xinglongpo catchment) as an example, the percentages of human activities were 73.5%, 0.6%, 87.3%, and 97.5%, respectively, from the 1980s to the 2010s. Although the percentage of human activities was low in the 1990s, it still showed a slight variation, with a decrease of 3.6. A previous study showed that precipitation was abundant during the period of 1990–1999, and less water was drawn from river channels for industrial production and agricultural irrigation (Yong et al., 2013; Wang et al., 2020). Consequently, hydrological health remained at a high level in the 1990s. The Taipingzhuang and Chifeng catchments showed similar characteristics to the Xinglongpo catchment. These results illustrate that in the human-influenced period, especially in the 2000s and 2010s, human activities drastically influenced hydrological health, which is of great importance to aquatic ecosystems.

Insert Figure 8 about here

4. Discussions

4.1 Rationality analysis of river hydrological health assessment

In this study, we adopted a hydrological health assessment method based on the ecological flow threshold. Using dimensionless mathematical formulas, seven different levels of ecological flow were coupled into a system to assess river hydrological health. Q_0 is the most suitable ecological flow, and the rationality of the calculation results is proved in Section 3.2. Q_1 and Q_2 denote the optimal lower and upper thresholds for ecological flow, respectively. Previous studies have often used the most suitable ecological flow plus or minus the standard deviation and the frequency range of the hydrological sequence with a specific ratio to obtain the above two thresholds (Shi et al., 2014; Zhang et al., 2018). However, these methods can easily make the optimal limits of suitable ecological flow exceed the maximum and minimum ecological flow. The method adopted in this study treat the mean value of the minimum (maximum) and optimum ecological flow as the lower (upper) threshold of the optimal ecological flow, which can resolve the mentioned problem. Moreover, the method considers the influence of extreme flow on the upper and lower limits of the suitable flow interval. Q_3 and Q_4 denote the minimum and maximum ecological flows, respectively. These two values are the minimum and maximum values of each month in the selected monthly average flow sequence. When the aquatic organisms have safely experienced such a minimum (maximum) flow under natural conditions and the ecosystem has not been severely damaged to the extent that it is irreversible, it means that the aquatic ecosystem can adapt to such flow conditions. When the flow exceeds these two thresholds, it indicates that the river ecosystem has been severely damaged. Q_5 and Q_6 denote the extremely small and extremely large ecological flows, respectively, and their values are the minimum and maximum daily flows of each month in the selected daily flow sequence. Such extreme events have great impacts on river ecosystems and may lead to the extinction of some species causing irreversible ecological disasters; however, the probability of their occurrence is small. Therefore, these flows were assigned to a smaller subsection.

In the study area, the Xiquan catchment is located in the headwaters of the Laohahe Basin, which is less disturbed by human activities and has no significant changing trend in runoff (Table 2). Hence, it was selected as a reference basin to evaluate the rationality of the above hydrological health assessment method by calculating the hydrological health under the condition of observed and simulated flow sequences. As shown in Fig. 7, the monthly scale hydrological health sequence distribution in the Xiquan catchment is relatively consistent, with a good overall health level and no evident variation. In the other three catchments, the observed hydrological health sequence showed a significant change with a change point in 1979, which was consistent with the characteristics of runoff change. In addition, the observed and simulated hydrological health indexes in the Xiquan catchment were 91.27 and 96.05 in the baseline period, respectively, whereas those in the changed period were 91.65 and 96.27. Compared to the hydrological health changes of the other three human-influenced basins (Fig. 8), it is considered that the hydrological health of the Xiquan catchment had no significant change. In summary, we suggest that the application of a river hydrological health assessment based on the ecological flow threshold in the Laohahe Basin is reasonable.

4.2 Impact of human activities on river hydrological health

The results in Section 3.4 show that climate change and human activities have significant impacts on the hydrological health of the Laohahe Basin, among which human activities are the main influencing factor, with contributions of more than 80%, especially in the Chifeng catchment, with a contribution of more than 90%.

In the Laohahe Basin, agriculture, stock raising, and the mining industry are the three main activities in production (Jiang et al., 2011). Large-scale agricultural irrigation reduces the flow of the river. Meanwhile, with economic development and population growth, urban water supply and industrial water use are also increasing, which exacerbates the decrease in water in the river, thereby affecting its hydrological health. Fig. 9(a) shows that since 1980, socioeconomic data in the study area have increased significantly. The scale of agricultural production has been continuously expanding, with grain crops (mainly wheat, corn, rice, and soybean) accounting for approximately 70%, and grain output has increased by approximately 4 million tonnes. Large-scale agricultural planting requires sufficient water to meet the irrigation demand. Particularly in March to May every year, when crops are in the critical sowing period, large amounts of water resources are consumed, making the hydrological health of rivers at a low level in the middle and lower reaches. The GDP of the research area shows a trend of exponential growth, especially after 2000, where the growth rate is evident. Simultaneously, the population of the region peaked in 2000 and remained relatively high. Correspondingly, the hydrological health of the whole basin is seriously degraded. Especially in the Chifeng catchment, the river health is maintained at a relatively high level only in summer (June–August), which is mainly because the largest city in the study area is located in this catchment.

Fig. 9(b) shows an intuitive display of water withdrawal over the last decade. The percentage of water withdrawal from natural river runoff showed an increasing trend and reached a peak in 2010, beyond 75%. Since then, the percentage remained high. This is consistent with the results of the hydrological health regime in our study, which revealed a more serious deterioration of hydrological health and a higher contribution of human activities in the 2010s. The excessive development of water resources has caused streamflow cut-off, resulting in severe river ecosystem degradation. This seriously restricts the sustainable development of the basin and attracts government attention. Hence, the Ministry of Water Resources of the People's Republic of China proposed a new initiative to use West Liao River water resources as its capacity permits for water resources management and water environment restoration of the basin (Tang et al., 2019). The outcomes of this study will provide scientific guidance for this new initiative and promote the protection of local river ecosystems.

Insert Figure 9 about here

Reservoir regulation is another human activity that obstructs flow regimes and consequently affects river hydrological health. As shown in Fig. 1, there are three large reservoirs in the basin, namely Sanzuodian Reservoir (total storage capacity: 3.69×10^8 m^3), Erdaohezi Reservoir (total storage capacity: 0.8×10^8 m^3), and Dahushi Reservoir (total storage capacity: 1.2×10^8 m^3). The principle of reservoir regulations in the basin generally follows the maintenance of storage in winter and spring and the release of water in summer and autumn to meet the needs of agricultural irrigation (Yong et al., 2013; Ren et al., 2014), thereby exacerbating hydrological health degradation. The reservoir drainage is generally lower than the natural inflow; however, the precipitation in the basin is mostly concentrated from June to September. Therefore, from June to September every year, a certain amount of flow can still be ensured in the channel, thereby maintaining the hydrological health at a relatively high level (Fig. 7).

The impact of climate change on hydrological health is mainly manifested by the changes in precipitation. The hydrological health of the basin remained at a relatively high level in the 1990s compared with the 1980s and the 2000s, with more precipitation and increased intra-channel flow (Yong et al., 2013).

4.3 Advantages of the new framework

In this study, we proposed a framework based on ecological flow, which was used to assess hydrological health and its evolution characteristics, then quantitatively analyse the attribution of the evolution. The framework can reflect not only the inter-annual evolution characteristics of hydrological health, but also the intra-annual distribution characteristics of hydrological health. For example, after the year 2000, the hydrological health of each sub-catchment showed persistent low intra- and inter-annual values from March to May and from September to November (Figure 8(b), (c) and (d)). These persistent low values may cause great damage to the river ecosystem. As described in section 4.2, these durations are highly likely to result from regular human activity. Therefore, compared with the traditional IHA method (Haghighi and Kløve, 2013; Haghighi et al., 2014), which can only reflect the inter-annual changes of hydrological regime, this framework can provide a better scientific basis for protecting the ecological health of rivers. In addition, there are autocorrelation and information redundancy among the 33 variables of IHA (Smakhtin and Shilpakar, 2006), which makes it difficult to operate and manage in water resource management practice (Clausen and Biggs, 2000; Cheng et al., 2018). However, based on biological adaptability and taking ecological flow as the evaluation, the method of assessing river hydrological health is simple and scientific. We have also used the framework to assess the contribution of climate change and human activities on hydrological health changes over time in order to better understand the evolution of hydrological regimes and their causes in the changing environment.

In summary, the proposed framework can be easily utilized to study the changes of river hydrological health and the effect of climate change and human activities, as well as the method introduced by Cui et al. (2020). Meanwhile, our framework is convenient to regulate water resources without damaging river hydrological health because of the less variables. Moreover, considering the timeliness of ecological flow and the spatial adaptability of ecological components with multiscale and multiobjective, the method can infer the general hydrologic health of the river section by using the instantaneous flow of the monitored section, so as to infer the ecosystem health of the river. At the same time, the use of short-term inflow forecasts and economic and social water demand forecasts can assess hydrological health within a certain period of time, so as to provide a scientific basis for the rational allocation of water resources and the restoration of river ecosystems.

4.4 Uncertainties and limitations

Although the approach proposed in this study was successfully applied to assess the evolutionary characteristics of river hydrological health and to quantify the impacts of climate change and human activities on river hydrological health, it still has some uncertainties and limitations.

The approach proposed in this study is based on the VIC hydrological model. When a hydrological model is used, uncertainty is inevitable. The model structure, parameter values, and input data quality are all sources of model uncertainty, which influence the reliability of the simulated streamflow. Despite these limitations, previous studies have shown that the VIC model is capable of representing most water resource indicators and 32 ecologically relevant indicators of IHA (Wenger et al., 2010; Shrestha et al., 2013). Meanwhile, as Table 3 and Fig. 4(a) show, the NSE, BIAS, and CC values of the Xiquan catchment were 0.78, 9.19%, and 0.91 in the calibration period (1965–1974), 0.79, –5.8%, and 0.92 during the validation period (1975–1979), and 0.77, –0.14%, and 0.88 in the simulation period (1980–2016), respectively. These results suggest that the model performance during the disturbed period is acceptable for the following assessment of natural river hydrological health. In future studies, we can compare the simulation results of multiple hydrological models and use optimization method to reduce uncertainties (Jiang et al., 2019; Cui et al., 2020).

Another limitation of our proposed framework is that there is no quantitative separation of the effects of different human activity patterns on river hydrological health, such as land use and land cover changes, human withdrawals, and reservoir regulations. Under different conditions, the influence of human activities on runoff is not always consistent. For example, in the humid Dongjiang River Basin in China, the regulation of high and low flows of reservoirs will lead to an increase in ecological surplus (Zhang et al., 2015). However, a reservoir significantly increased the ecological deficit in the semi-humid and semi-arid Yellow River Basin (Zhang et al., 2018). In the semi-arid Laohahe Basin, the influence of land use and land cover change on runoff is less than that of rainfall, and the amount of artificial water withdrawal will be more than 50% of the natural runoff in a normal year (Liu et al., 2009; Jiang et al., 2012). Therefore, further analysis is required as the data becomes available to better understand the effects of different types of human activities on river hydrological health.

5. Conclusions

In this study, we proposed a comprehensive assessment framework for quantifying the impacts of climate change and human activities on river hydrological health variation, which combines the river natural streamflow reconstruction using VIC hydrological model, the river hydrological health calculation through the ecological flow threshold method, and the quantification of the impacts of climate change and human activities using the 'observed–simulated' comparison approach. The framework was applied to the semi-arid Laohahe Basin in northern China. The main findings can be summarized as follows:

(1) The method based on ecological flow thresholds can effectively assess the river hydrological health, and the proposed framework can be effectively utilized to quantify the impacts of climate change and human activities on the hydrological health by using the 'observed–simulated' comparison approach.

(2) In the Laohahe Basin, the river hydrological health degraded significantly during the human-influenced period (1980-2016), particularly in the 2000s and 2010s, where it degraded much more severely. While in the 1990s, the hydrological health maintained a good status because of the increasing rainfall.

(3) For the entire human-influenced period, the contributions of human activities to hydrological health degeneration were 80.8%, 91.9%, and 86.0% for the Taipingzhuang, Chifeng, and Xinglongpo catchments, respectively. Widespread artificial water withdrawal and reservoir operation were the two crucial human

activities that caused the degradation of river hydrological health for the studied catchment.

The findings of this study help to understand the evolutionary characteristics and driving mechanisms of river hydrological health in a changing environment, which will be helpful for local water resources management and river ecosystems protection. Although the Laohahe Basin was selected as a case study in this study, the proposed approach can be applied to other regions as well. Future studies should focus on constructing a comprehensive framework that separates the impacts of different kinds of human activities (land use change, reservoir regulations, and human water withdrawal) on river hydrological health, which will provide valuable information for adapting different types of human activity responses according to river hydrological health.

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Table 1 Basic information of the hydrological stations over the study area.

Hydrological station	Area (km^2)	River	Longitude (E°)	Latitude (N°)	Mean annual precipitation (mm)	Mean annual streamflow (mm)	Data period
Xiquan	419	Heili River	118.53	41.42	572.88	126.45	1964–2016
Taipingzhuang	7720	Laoha River	119.25	42.20	438.53	26.57	1964–2016
Chifeng	8678	Yingjin River	118.95	42.28	401.00	21.06	1964–2016
Xinglongpo	18112	Laoha River	119.43	42.32	411.74	24.48	1964–2016

Table 2 Results of M–K trend analyses and Pettitt change-point tests of annual precipitation, potential evapotranspiration (PET), and streamflow for the four selected basins for the period 1964–2016.

Hydrological station	MK trend test (year)						Pettitt test for change-point (year)		
	Precipitation		PET		Streamflow		Precipitation	PET	Streamflow
	Z value	Trend	Z value	Trend	Z value	Trend			
Xiquan	-1.57	↓	-1.20	↓	-0.41	↓	—	—	—
Taipingzhuang	-0.58	↓	0.31	↑	-5.07	↓	—	—	1979
Chifeng	-0.97	↓	-0.64	↓	-5.16	↓	—	—	1979
Xinglongpo	-0.81	↓	-0.70	↓	-5.04	↓	—	—	1979

Notes: '↓' and '↑' indicate downward and upward trends, respectively.

Table 3 Performance of streamflow (mm/month) simulation for the four catchments using the VIC model.

Catchment	Calibration period			Validation period			Disturbed (simulation) period		
	E_{NSE}	E_{CC}	E_{BIAS} (%)	E_{NSE}	E_{CC}	E_{BIAS} (%)	E_{NSE}	E_{CC}	E_{BIAS} (%)
Xiquan	0.78	0.91	9.19	0.79	0.92	-5.8	0.77	0.88	-0.14
Taipingzhuang	0.90	0.95	1.59	0.82	0.91	5.47	—	—	—
Chifeng	0.77	0.88	0.6	0.71	0.85	11.3	—	—	—
Xinglongpo	0.83	0.91	1.2	0.80	0.90	-1.6	—	—	—

Table 4 Comparison of the ecological flow calculation result

Catchment	Most suitable ecological flow			
	KD	GEV	Q_{50}	Tennant
Xiquan	0.96	0.85	1.3	1.01—1.68
Taipingzhuang	8.84	7.48	9.49	6.12—10.21
Chifeng	5.88	4.01	6.33	4.91—8.18
Xinglongpo	14.73	12.39	16.85	11.59—19.32

Table 5 Mean annual H of each basin and the change from the base period in the period of 1964–2016.

Catchment	1964–1979		1980–1989		1990–1999		2000–2009		2010–2016		1980–2016	
		ΔH_t		ΔH_t		ΔH_t		ΔH_t		ΔH_t		ΔH_t
Xiquan	91.3	—	89.5	-1.8	93.8	2.5	87.2	-4.0	96.3	5.0	91.7	0.4
Taipingzhuang	89.4	—	49.4	-40.1	81.9	-7.6	33.0	-56.5	11.5	-77.9	45.9	-43.5
Chifeng	88.8	—	67.6	-21.3	90.0	1.2	30.0	-58.8	2.1	-86.8	51.1	-37.7
Xinglongpo	91.0	—	56.5	-34.4	87.4	-3.6	34.8	-56.2	8.8	-82.2	50.0	-41.0

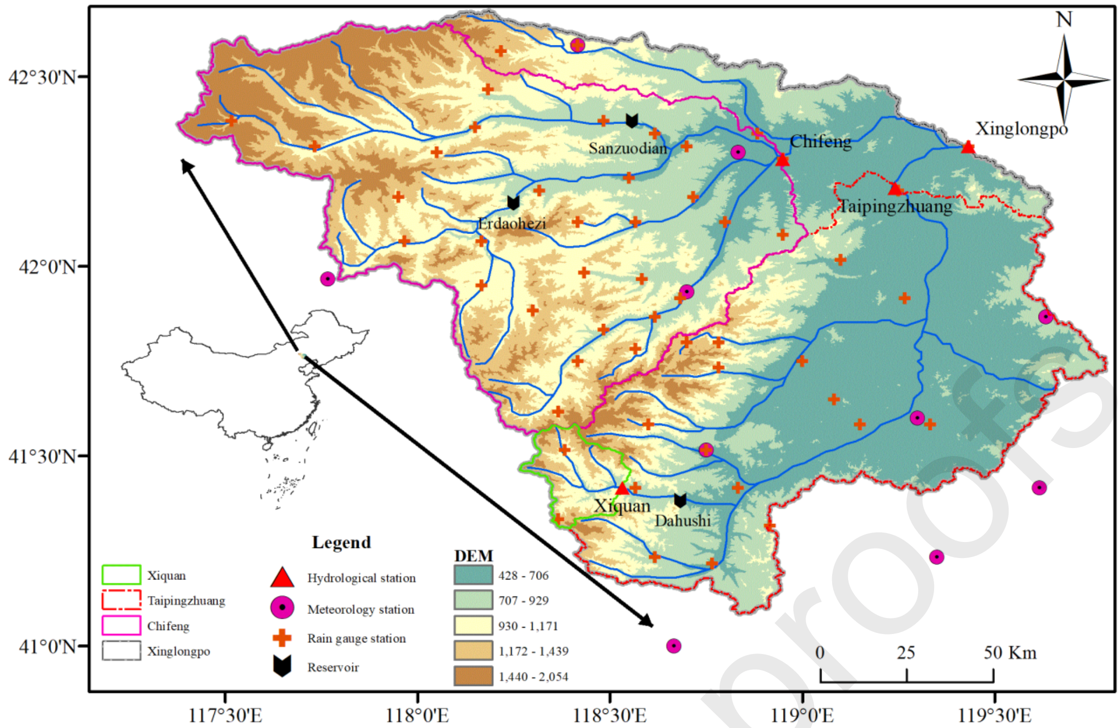

Fig. 1. Location of the study areas and distribution of the hydrological, meteorological, and rain gauge stations.

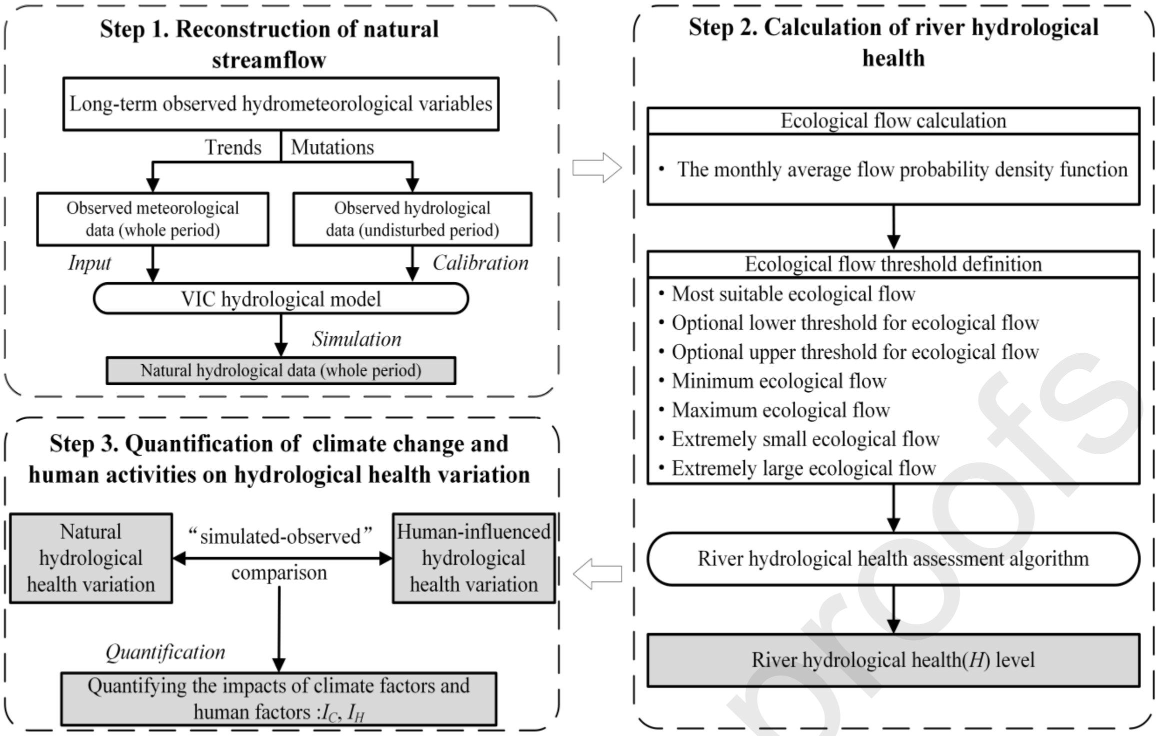

Fig.2. Proposed comprehensive assessment framework for calculating hydrological health and quantifying the impacts of climate change and human activities on hydrological health.

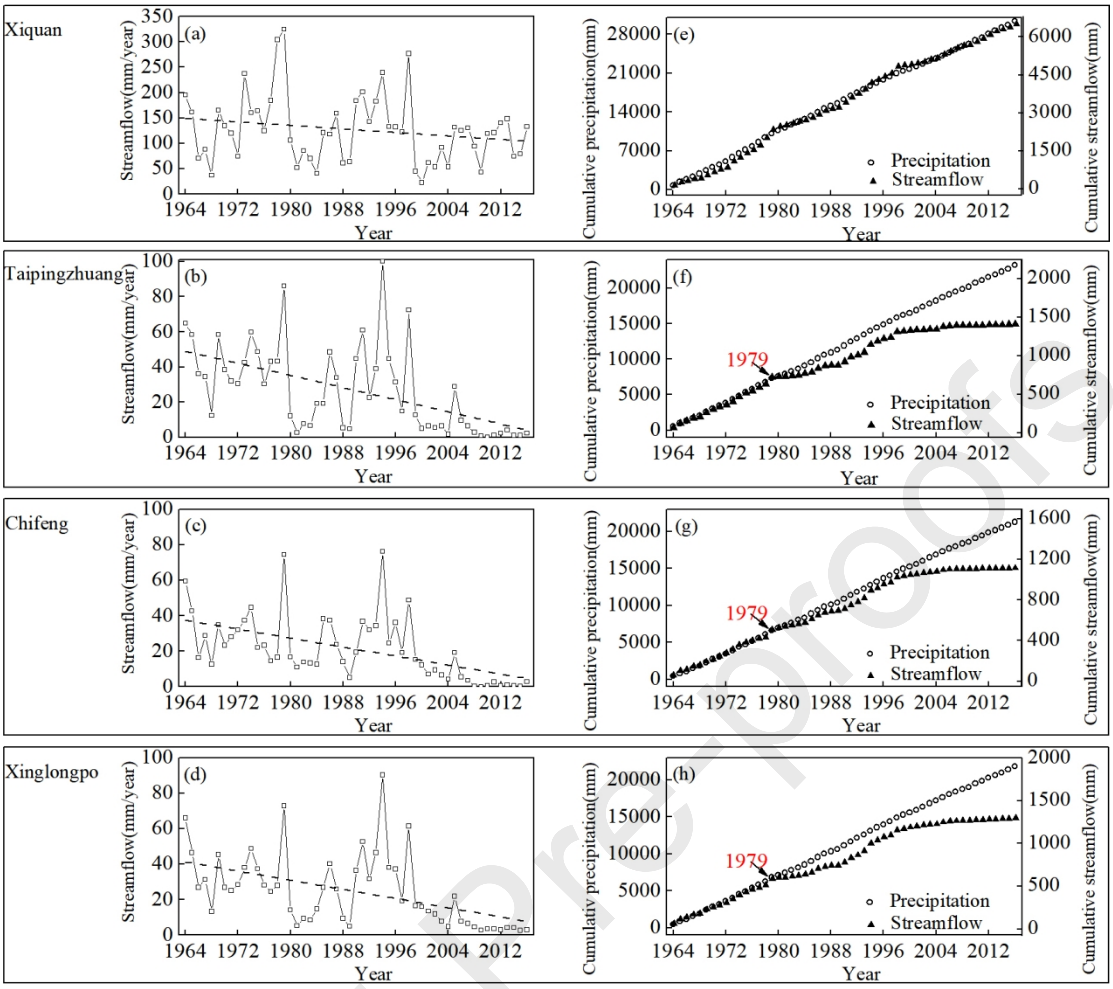

Fig. 3. The time series variations of annual streamflow (a-d) and the double cumulative curves of annual precipitation and streamflow (e-f) for the four selected study catchments.

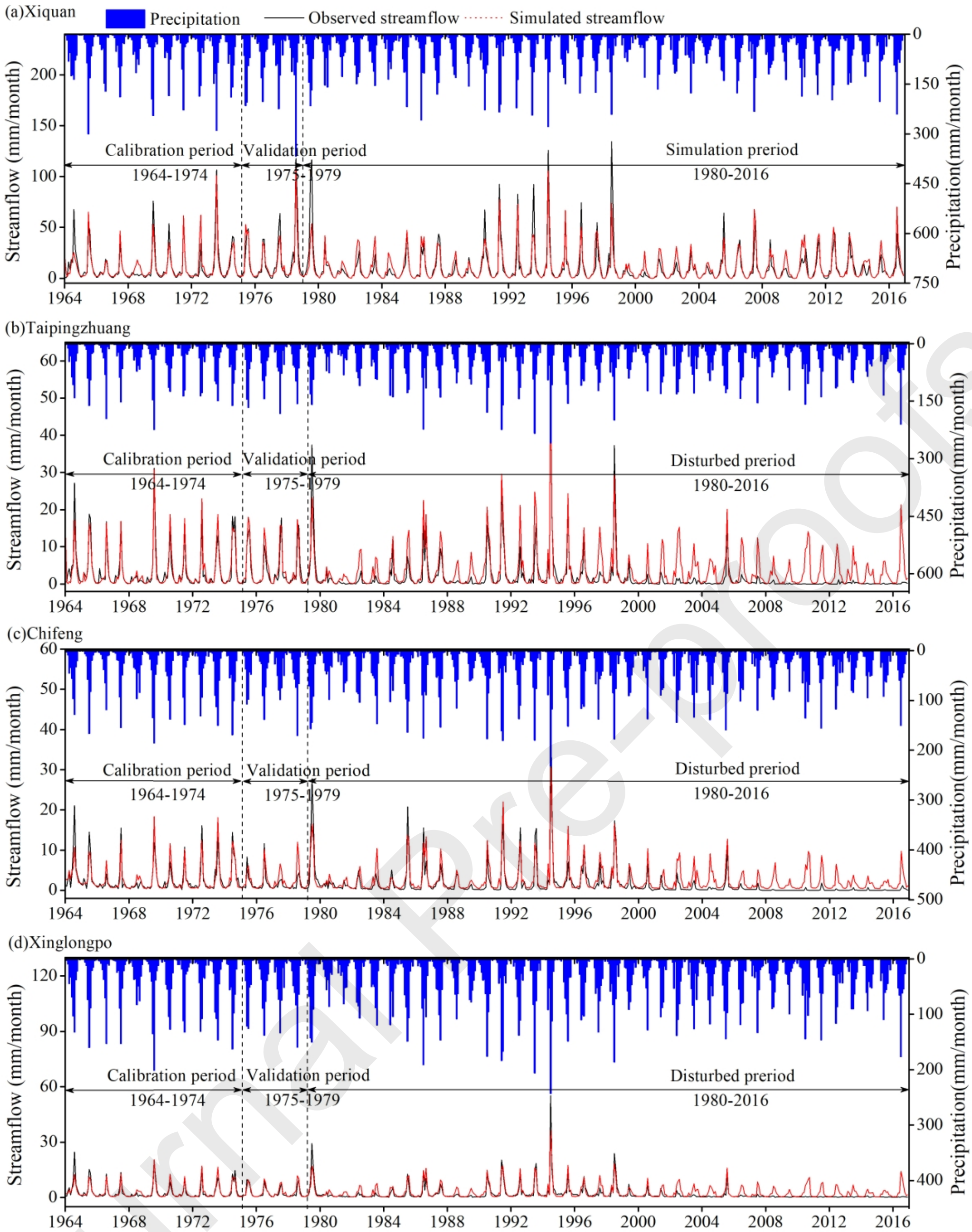

Fig. 4. Comparisons of VIC-simulated and observed monthly streamflow for the four selected study catchments.

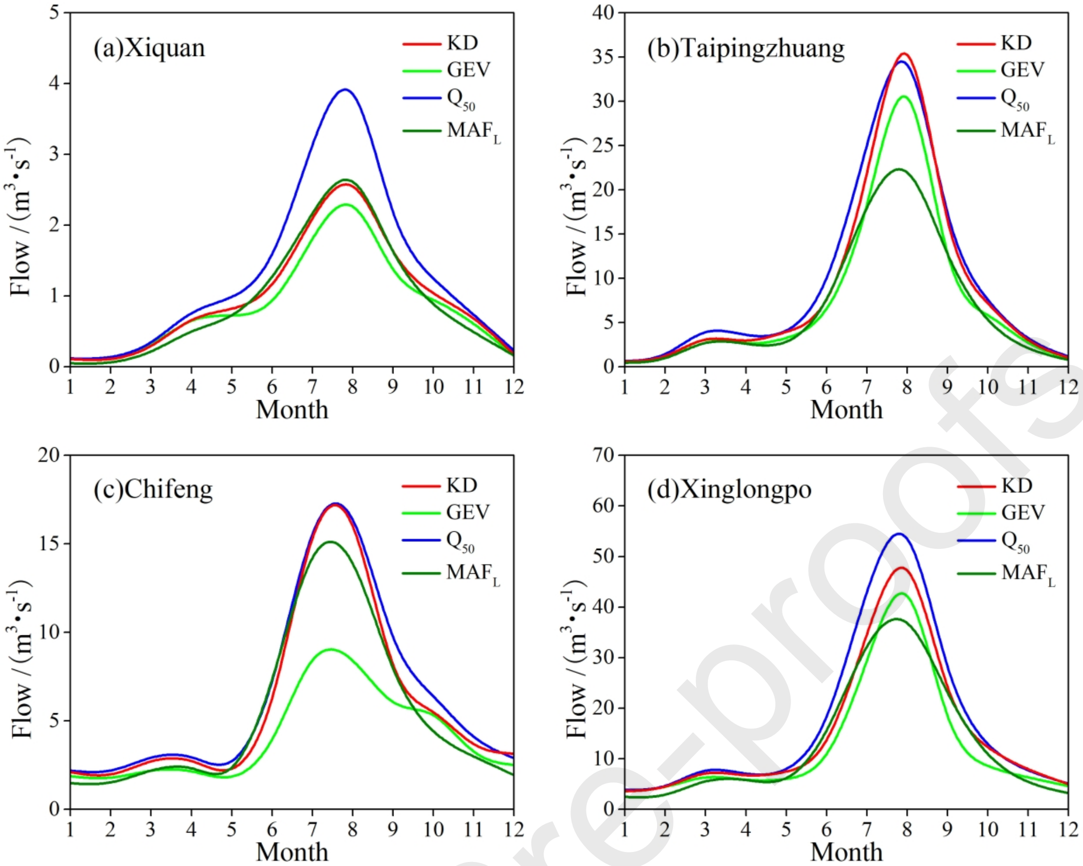

Fig. 5. Comparisons of the most suitable ecological flow for the four selected study catchments.

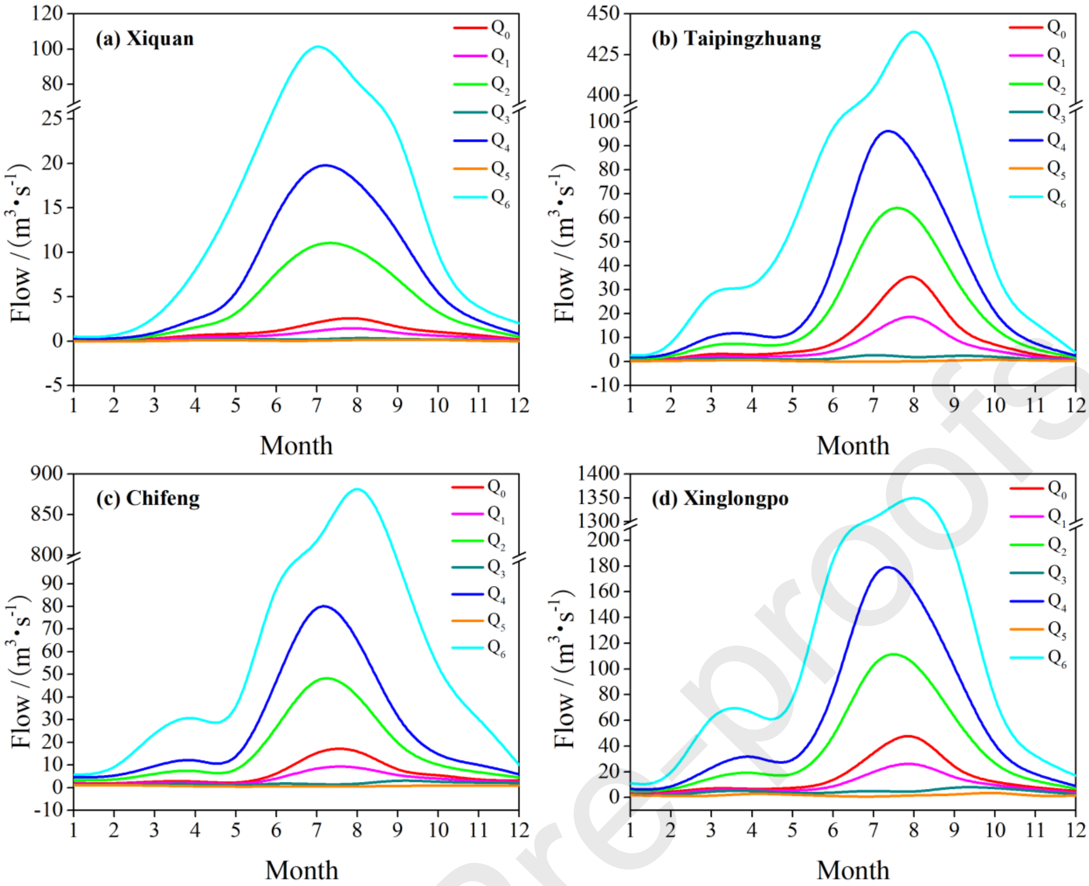

Fig. 6. Calculation results of ecological flow for the four selected study catchments.

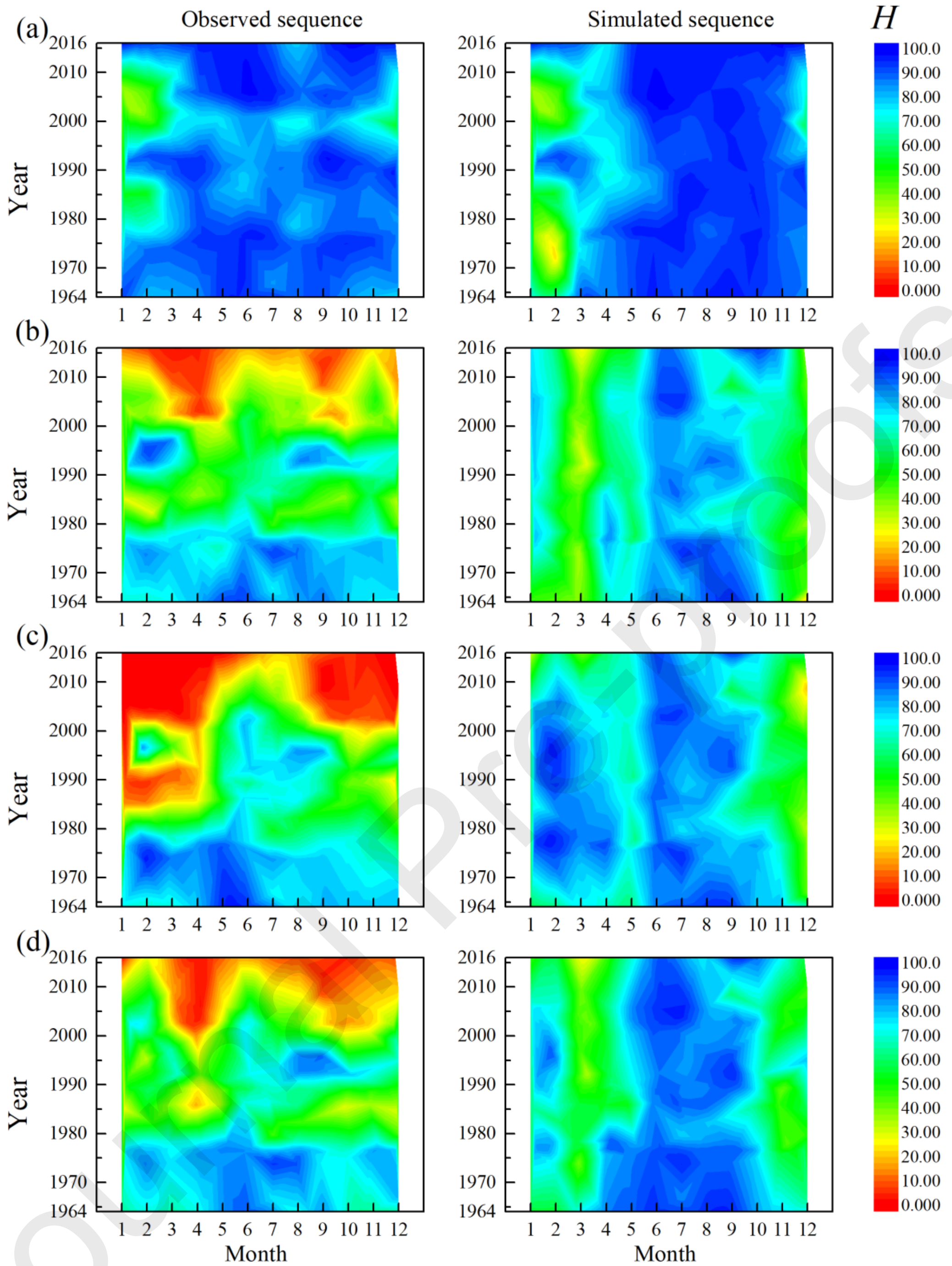

Fig. 7. Comparison of the river hydrological health (H) based on observed and VIC-simulated monthly runoff from 1964 to 2016 for the four selected study catchments.

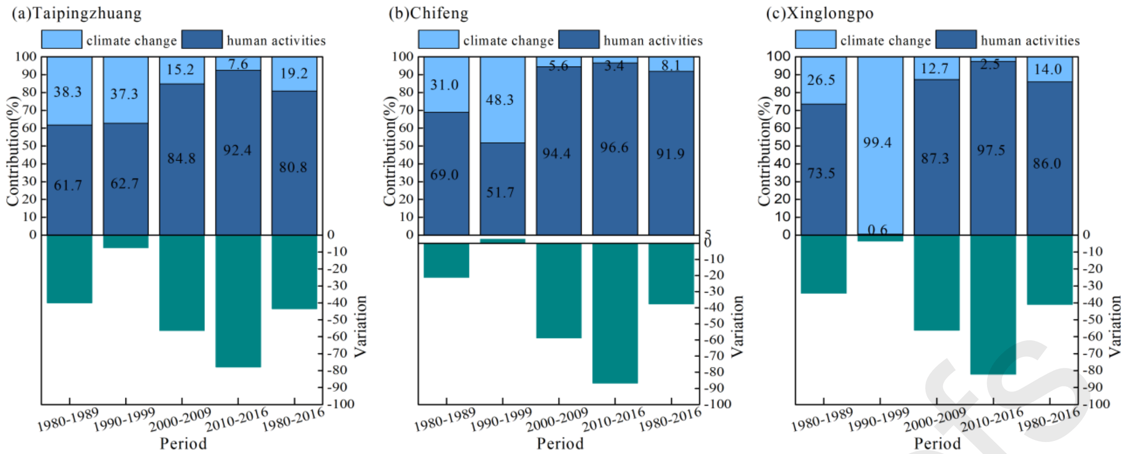

Fig. 8. Contribution rates of climate change and human activities to river hydrological health (*H*) decline in different periods for the three human-influenced catchments. The variation is the decline of *H* in different periods compare with the base period.

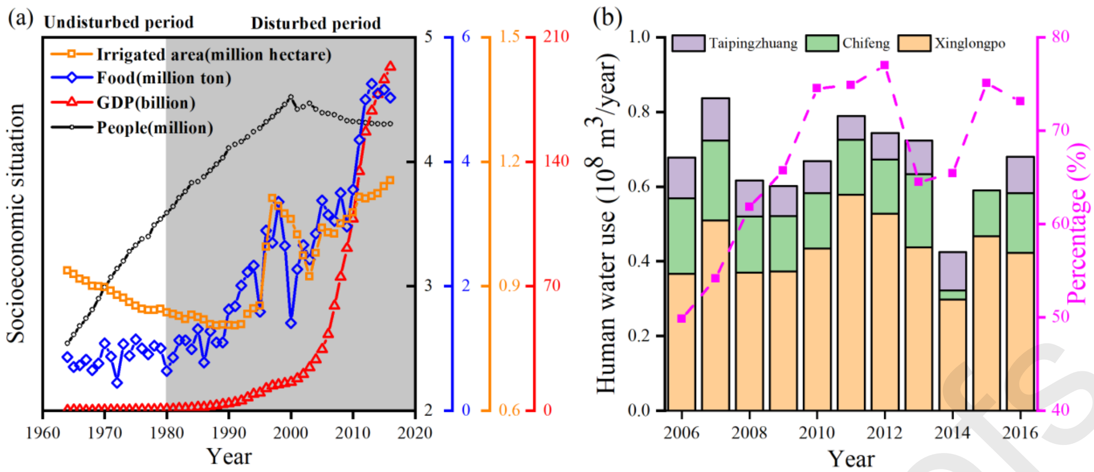

Fig. 9. Changes in socioeconomic situation and human water use data for the study area.

Highlight

- A comprehensive framework for quantifying the climatic and anthropogenic influences on river hydrological health is proposed.
- Human activities significantly aggravate the degradation of river hydrological health for the studied catchment.
- Widespread artificial water withdrawal and reservoir operation are the two crucial human activities
- Adequate rainfall maintains the river hydrological health at a good status in the 1990s.

CRediT Author Statement

Shanhu Jiang: Conceptualization, Methodology, Project administration. **Le Zhou**: Data curation, Writing-Original draft preparation, Software. **Liliang Ren**: Methodology, Funding acquisition. **Menghao Wang**: Writing-Original draft preparation. **Chong-Yu Xu**: Writing-Reviewing and Editing. **Fei Yuan:** Methodology. **Yi Liu:** Methodology. **Xiaoli Yang:** Methodology. **Yu Ding:** Writing-Original draft preparation.