


Assessment of ecological instream flow requirements under climate change *Pseudorasbora parva*

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Abstract Climate change alters ecohydrological processes on different temporal and spatial scales. The aim of this study was to estimate ecological instream flow requirements (EIFR) under climate change impacts and to ascertain optimum flow magnitude to maintain the health of river ecosystems. We used the Mann–Kendall test, the River2D Hydrodynamic model, and the frequency-weighted usable area (FWUA) model on an annual scale in the Juma River to investigate changes in EIFRs caused by climate change. Findings indicated that: (1) between 1956 and 2005, annual instream flow in the Juma River exhibited an abrupt downward trend (in 1981); (2) variation in instream flow governed the area of available fish habitat, and degrees of change for low flow threshold values and low and high FWUA threshold almost exclusively occurred in descending sequential order from winter, spring, autumn, and summer; (3) changes in hydrological regimes influenced both the quantity and quality of physical habitat area, contributing greater to quality than to the distribution of area of physical habitat for *Pseudorasbora parva*. Climate change, reflected in the changes in EIFR and the area

of optimum physical habitat, has dramatically influenced ecological structure and function, even in the small river system investigated for this study. Findings indicated that more rational measures should be put into practice to help address climate change.

Keywords Climate change · Frequency-weighted usable area (FWUA) · Ecological instream flow requirements (EIFR) · Hydrodynamic modeling · Juma River

Introduction

Along with other important variables, climate change alters the frequency and intensity of precipitation. This has led to changes in streamflow response, resulting in the degradation of river ecosystems (Poff 2002; IPCC 2007; Liu and Cui 2011; Barranco et al. 2013). Ecological instream flow requirements (EIFRs) (or environmental flow) have been proposed as a means to protect river ecosystems. EIFR is defined as “the quantity of water required to maintain a river ecosystem in its desired state [that is] of particular importance in areas of high natural value” (Acreman and Dunbar 2004; Zhong et al. 2006; Piniewski et al. 2014). EIFRs are determinants of channel morphology, riparian and aquatic flora and fauna, water quality, and stream load transport (Song et al. 2007). Methods used to calculate EIFRs can generally be classified into four types: hydrological, hydraulic ratings, habitat simulations, and holistic methods as well as hybrids or integrations of these methods (Tharme 2003; Huckstorf et al. 2008; Cui et al. 2010; Karimi et al. 2012; Shokoohi and Amini 2014). Methods associated with habitat simulations take into account biological factors in combining hydrological indexes and ecological processes to provide more scientifically based

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and practical results (Daniel and Nassir 1994; Cui et al. 2010; Tian et al. 2012). These include instream flow incremental methodology (IFIM) (Bovee 1982), the physical habitat simulation model (PHABSIM) (Milhous et al. 1989), the Computer Aided Simulation Model for Instream Flow and Riparia (CASiMiR) (Zhao et al. 2008), and the River2D Hydrodynamic model (the fish habitat component of River2D is based on PHABSIM) (Steffler and Blackburn 2002; Wang et al. 2011). Although the applicability of the methods in obtaining EIFR remains an open debate (Peñas et al. 2014), River2D, which links hydrological regimes and fish habitats, has been widely used to define EIFR. Influenced by climate change, ecological structures and functions change along with hydrological regimes (Hamilton 2002; Campos et al. 2013). In this context, it was assumed that EIFR can change along with ecological structure and function. Furthermore, changes in EIFR can reflect changes in ecological structure. Thus, the objectives of this study were: (1) to explore temporal changes in streamflow and precipitation; (2) to calculate optimum EIFR using FWUA; (3) to analyze decreases in FWUA variation resulting from climate change.

Study area and data description

Juma River Basin

The Juma River, a tributary of the Haihe River, China, is approximately 254 km long with four drainage areas, totaling 810 km². Originating from a spring-fed lake in Laiyuan

County, the river flows into the Daqing River, a tributary of the Haihe River. Mean annual precipitation is from 530 to 660 mm, and mean air temperature is 9 °C. Impacted by climate change and anthropogenic activities (e.g., via the construction of reservoirs and the implementation of soil and water conservation projects), streamflow exhibited decreasing trends and even completely dried up in the Haihe River Basin (Yuan et al. 2005; Bao et al. 2012). Chen et al. (2010), using data obtained from the Zijinggwan hydrological station, observed a reduction in streamflow resulting from decreasing trends in precipitation from 1956 to 2005. Gong et al. (2012) similarly found that decreasing trends in precipitation resulted in a reduction of streamflow in the Daqing River Basin. Moreover, the Juma Wild Animal Nature Reserve was instituted to protect the Juma River ecosystem since it is believed to play an important role in maintaining the ecological status of the river system. In this context, understanding changes in EIFR caused by climate change is critical in maintaining the integrity of this aquatic ecosystem (Fig. 1).

Topographic and hydrological data

Typical inputs of the River2D Hydrodynamic model include bed topography, estimates of initial roughness, discharge at the upper cross section, and water surface elevation at the downstream cross section (Steffler and Blackburn 2002). We assumed that no significant changes in river morphology and channel substrate occurred during the modeling period. Accordingly, we used the Electronic Total Station, a geological mapping tool, to measure the

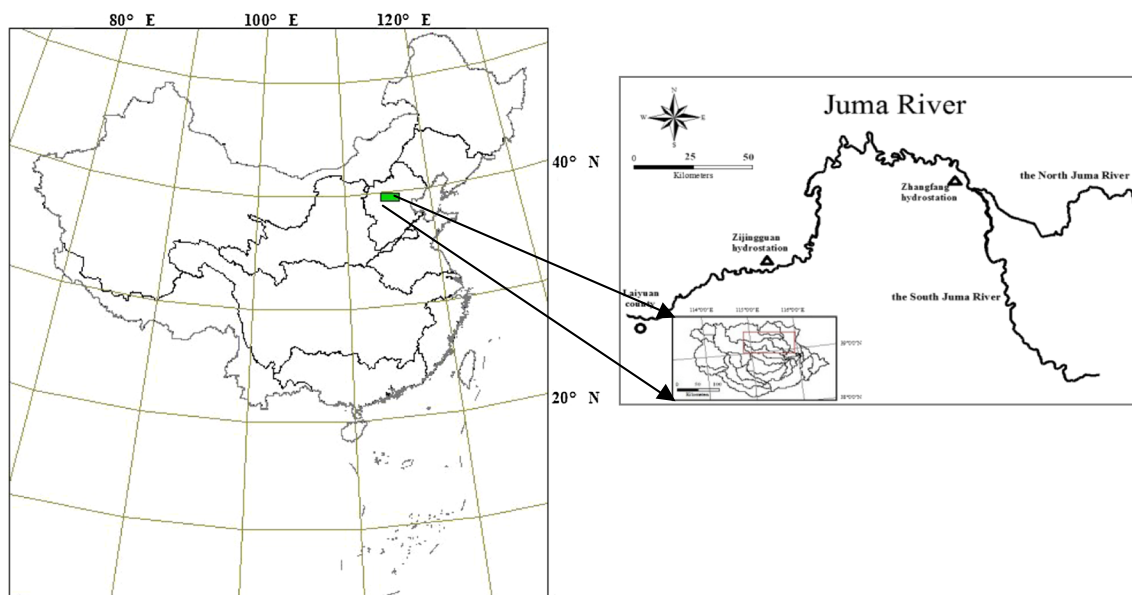


Fig. 1 Map of the study area showing the location of the Juma River and its location in China

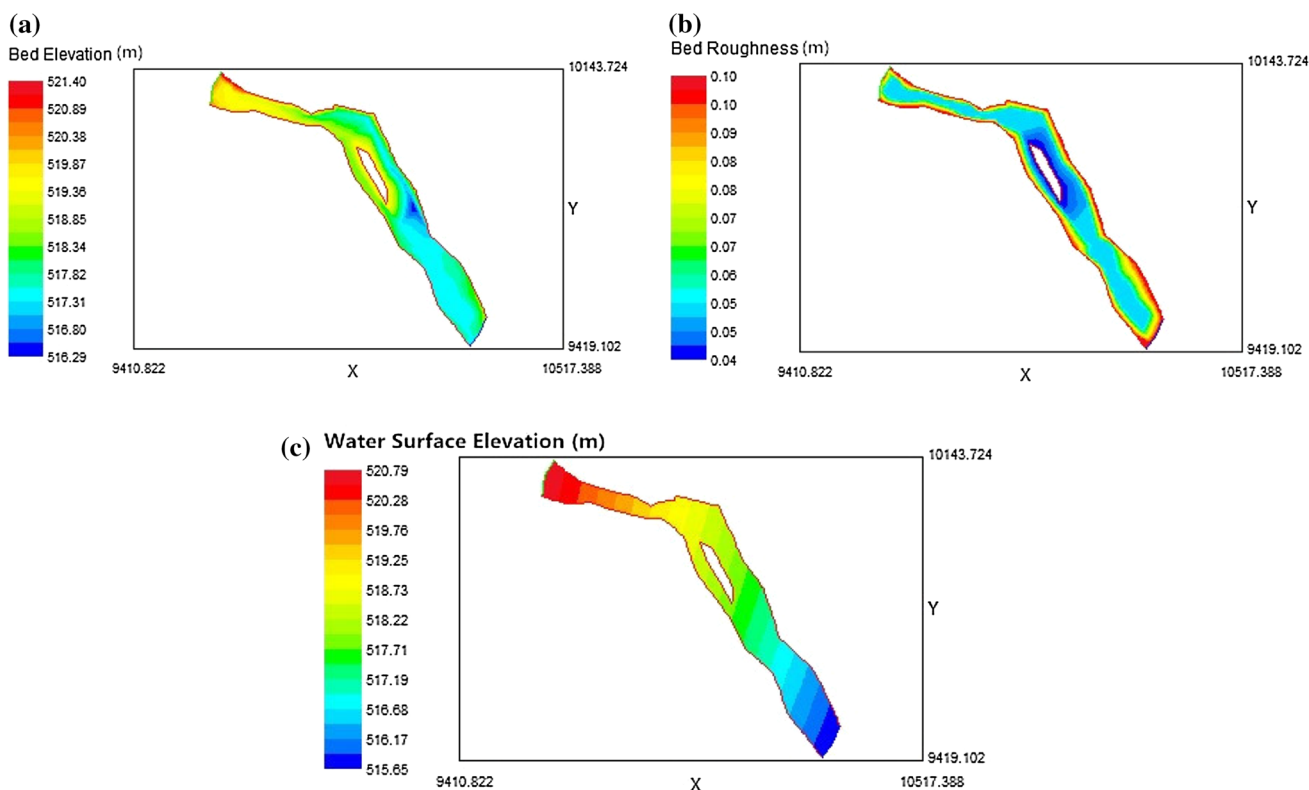


Fig. 2 Modeled river bed elevation (a), roughness (b), and water surface elevation (c) in the study area. X and Y are relative coordinates (m)

relative X coordinate, Y coordinate, and elevation of a 3-km-long river channel using 234 survey points, recording the substrate at each survey point. We collected discharge data from 1951 to 2005 from the Haihe River Water Conservancy Committee and obtained current discharge rates and values from the monitoring instrument used at the Zijingguan hydrological station. We determined water surface elevation using a rod (surveying pole) along the study area. Data were then loaded into the River2D Hydrodynamic model to generate an initial data file of the Juma River (shown in Fig. 2).

Materials and methods

The Mann–Kendall test

The nonparametric Mann–Kendall (M–K) test was developed by Mann (1945) and refined by Kendall (1948). It is widely used to determine temporal and spatial trends in hydrological and meteorological time series and can reasonably identify abrupt points of change (Liu et al. 2008; Liang et al. 2011; Yang and Liu 2011). For this study, we used the M–K test with a nominal rejection rate of 5% to detect trends and years of abrupt change in annual

streamflow and precipitation at the Zijingguan hydrological station. Test parameters a_{ij} and d_k are defined as:

$$a_{ij} = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \leq x_j \end{cases} \quad (1 \leq d_j \leq d_i), \tag{1}$$

$$d_k = \sum_{i=1}^k \sum_{j=1}^{i-1} a_{ij} \quad (k = 2, 3, 4, \dots, n), \tag{2}$$

where x_1, x_2, \dots, x_n are the time series, and n is the total number of data in the time series. We calculated the expected value $E(d_k)$ and variance $\text{var}(d_k)$ as follows:

$$E(d_k) = \frac{k(k-1)}{4}, \tag{3}$$

$$\text{var}(d_k) = \frac{k(k-1)(2k+5)}{72} \quad (2 \leq k \leq n). \tag{4}$$

We tested the null hypothesis using $UF(d_k)$, and if the standard normal probability $|UF(d_k)| > u_\alpha$, the null hypothesis was rejected. $UF(d_k)$ constituted the UF curve:

$$UF(d_k) = \frac{d_k - E(d_k)}{\sqrt{\text{var}(d_k)}}. \tag{5}$$

By applying the method to the inverse series, we could obtain the $UB(d_k)$ series as follows:

$$\begin{cases} \text{UB}(d_k) = -\text{UF}'(d_k) \\ k' = n + 1 - k \end{cases} \quad (k = 1, 2, \dots, n). \quad (6)$$

If intersection points of UF and UB were situated between two confidence lines ($\alpha = 0.05$, $\mu_{0.05} = \pm 1.96$), we assumed that an abrupt change took place at that point.

The River2D hydrodynamic model

The River2D Hydrodynamic model is a two-dimensional, depth-averaged finite element model specifically developed to simulate river flow and fish habitat in a given area (Steffler and Blackburn 2002). The model can simulate transient flow of subcritical–supercritical flow and wet–dry flow by applying changes in surface flow to groundwater flow equations expressed in a conservative format, referred to as Saint–Venant equations. They include three equations and represent the conservation of water mass and the two components of the momentum vector, respectively. They are defined as follows: conservation of mass:

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0; \quad (7)$$

Conservation of x -direction momentum:

$$\begin{aligned} \frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(Uq_x) + \frac{\partial}{\partial y}(Vq_x) + \frac{g}{2} \frac{\partial}{\partial x} H^2 \\ = gH(S_{ox} - S_{fx}) + \frac{1}{\rho} \left(\frac{\partial}{\partial x}(H\tau_{xx}) \right) + \frac{1}{\rho} \left(\frac{\partial}{\partial y}(H\tau_{xy}) \right); \end{aligned} \quad (8)$$

Conservation of y -direction momentum:

$$\begin{aligned} \frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}(Uq_y) + \frac{\partial}{\partial y}(Vq_y) + \frac{g}{2} \frac{\partial}{\partial y} H^2 \\ = gH(S_{oy} - S_{fy}) + \frac{1}{\rho} \left(\frac{\partial}{\partial x}(H\tau_{xy}) \right) + \frac{1}{\rho} \left(\frac{\partial}{\partial y}(H\tau_{yy}) \right), \end{aligned} \quad (9)$$

where H is the depth of flow, and U and V are the depth-averaged velocities in x and y coordinate directions, respectively. q_x ($q_x = HU$) and q_y ($q_y = HV$) are the respective discharge intensities, which are related to velocity components; g is the gravitational acceleration; ρ is the water density; S_{ox} and S_{oy} are the bed slopes in x and y directions; S_{fx} and S_{fy} are the corresponding friction slopes; and τ_{ij} is the component of the horizontal turbulent shear stress tensor ($i, j = x, y$).

The River2D Hydrodynamic model is composed of a hydrodynamic model and a fish habitat model. The fish habit module is based on the PHABSIM-weighted useable area (WUA) approach, which is used to determine the optimum flow that can provide the largest physical habitat in rivers. WUA is calculated by summing the product of cell area and its respective combined suitability index

(CSI) value. CSI values are obtained from individual habitat suitability index values for depth, velocity, and channel indexes as follows:

$$\text{WUA} = \sum_{i=1}^n \text{CSI}_i \times A_i, \quad (10)$$

$$\text{CSI}_i = f(V_i)f(D_i)f(C_i), \quad (11)$$

where A_i is the surface area of a cell in partition i ; $f(V_i)$, $f(D_i)$, and $f(C_i)$ are individual habitat suitability index (HSI) values for velocity, depth, and the channel index, respectively, in partition i (shown in Fig. 3).

The River2D Hydrodynamic model has been verified by a number of comparisons with theoretical, experimental, and field results (Ghanem et al. 1995; Waddle et al. 1996; Hayes et al. 2007; Kozarek et al. 2014). It has been widely used in China to determine optimum EIFR and to evaluate ecological consequences of instream flow regulations on the basis of the available physical habitat of specific species (e.g., Jiang et al. 2010; Yang et al. 2010; Tan et al. 2011; Sun et al. 2013).

Habitat suitability curves

According to fish species distribution and diversity surveyed by Yang et al. (2013) in the Juma River, the proportion of *Pseudorasbora parva* (*P. parva*) for all species caught was 80.1%. Moreover, by way of survey data collected from twenty field sites upstream and downstream of the river, we found that the local populace most often caught *P. parva* for purposes of cooking. Accordingly, we selected *P. parva* as the target fish in this investigation on the impact of climate change on physical habitat and calculated suitability curves using velocity, water depth, and channel indexes. The channel index is a categorical variable used in habitat simulation models to describe the structural characteristics of stream channels (Bovee 1986), which we obtained according to channel substrates for *P. parva*. These values were interpolated from a separate channel index file to computational notes. We obtained relevant habitat preference curves by combining literature research, field investigations, and data from particular species/life stages (Parasiewicz et al. 2012; Xu et al. 2012; Zeng 2012; Wang et al. 2013) (shown in Fig. 3). The optimum range of velocity, water depth, and channel indexes were from 1.0 to 1.5 m/s, from 1.0 to 1.75 m, and from 1.0 to 6.0, respectively.

WUA modification

We calculated $f(V_i)$, $f(D_i)$, and $f(C_i)$ on the basis of the frequency of fish appearing at different velocities, water depths, and channel indexes, and this was based on the

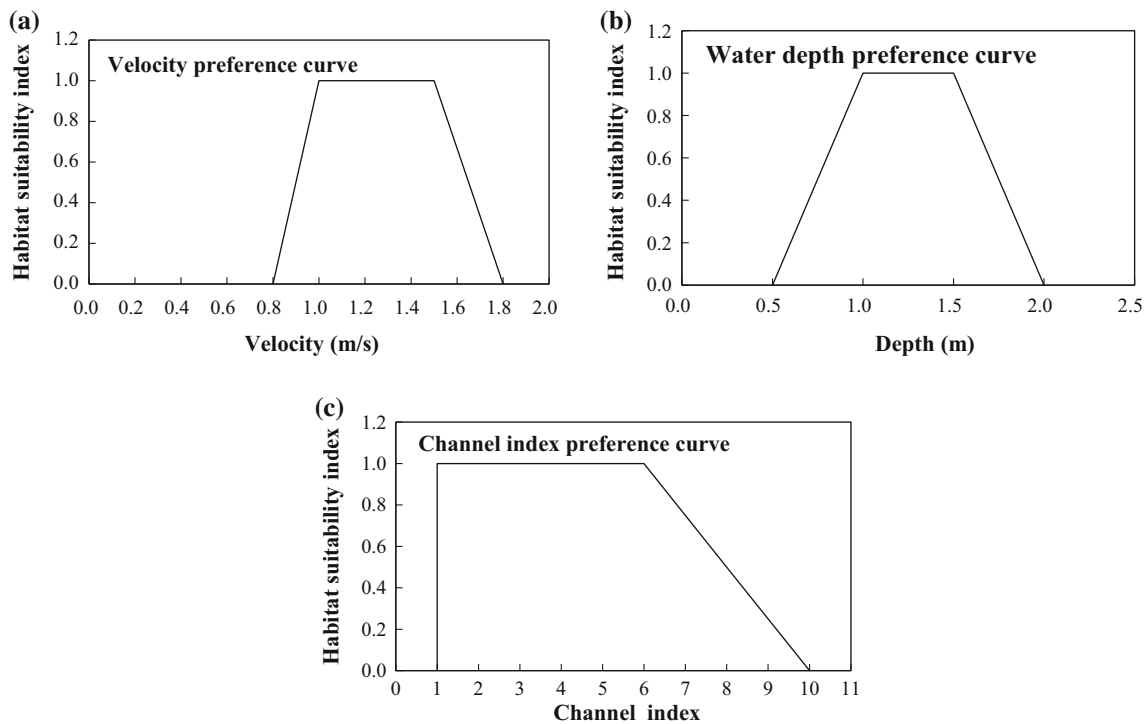


Fig. 3 Velocity (a), water depth (b), and channel index (c) preference curves for *Pseudorasbora parva* in the Juma River, China

hypothesis that $f(V_i)$, $f(D_i)$, and $f(C_i)$ had the same influence as the suitability index did. In addition, values of $f(V_i)$, $f(D_i)$, and $f(C_i)$ were all between 0 and 1. Therefore, if we added an adjusting factor to CSIs and assumed that they had the same influence on final results, such as $f(V_i)$, $f(D_i)$, and $f(C_i)$ would, modifications of WUA could be considered reasonable. Thus, we conducted a “weight” by adding all CSIs calculated from different guaranteed hydrological frequencies and a value of their corresponding discharge frequencies (namely $f(F_i)$) to obtain an optimum dynamic equilibrium between EIFR and the available habitat area. To be more specific, each WUA calculated from a different guaranteed hydrological frequency was multiplied by its corresponding frequency factor. This is referred to as the frequency-weighted usable area (FWUA) method. WUA modifications were conducted as follows:

$$FWUA = \sum_{i=1} f(F_i) \times CSI_i \times A_i = \sum_{i=1} f(F_i) \times WUA. \tag{12}$$

Furthermore, Leclerc et al. (1995) divided the quality of the physical habitat of fish into different grades in accordance with CSIs: extremely low: $0 < CSI < .1$; low: $0.1 < CSI < 0.4$; moderate: $0.4 < CSI < 0.7$; and high: $0.7 < CSI < 1.0$. We adopted this standard to analyze

variety in the quality of the physical habitat of fish during normal periods and periods of change during different seasons. In order to validate the accuracy of the modified WUA method (FWUA), we compared our EIFR results to those obtained using other methods, such as the range of variability approach (RVA) method (Richter et al. 1996), the monthly frequency calculation method (MFC) (Yang et al. 2003), and the Tennant method (Tennant 1976).

Results and discussion

Temporal trends in streamflow and precipitation

The M–K test showed that annual streamflow at the Zijingguan hydrological station exhibited an abrupt downward trend in 1981 ($\alpha = 0.05$) (Fig. 4a). Therefore, annual streamflow at the Zijingguan hydrological station can be divided into two separate periods: a normal period (1956–1980) and a period of change (1981–2005).

As shown in Fig. 4, we detected significant decreasing trends ($P < 0.05$) in annual streamflow and precipitation with an average slope of $-0.09 \times 10^8 \text{ m}^3 \text{ a}^{-2}$ and -2.20 mm a^{-2} , respectively. During the normal period, average annual streamflow was $3.1 \times 10^8 \text{ m}^3 \text{ a}^{-1}$, while

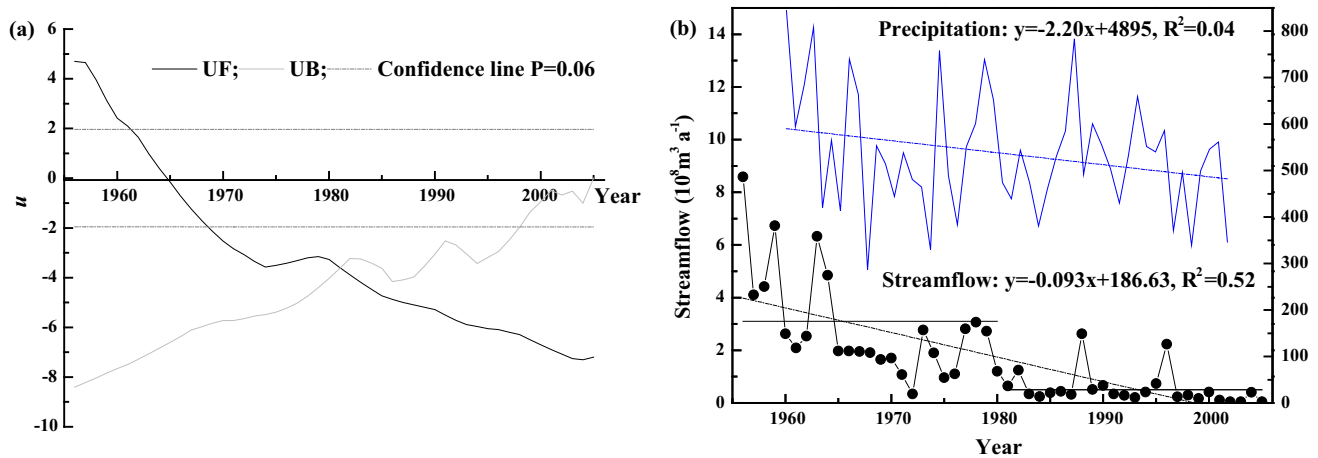
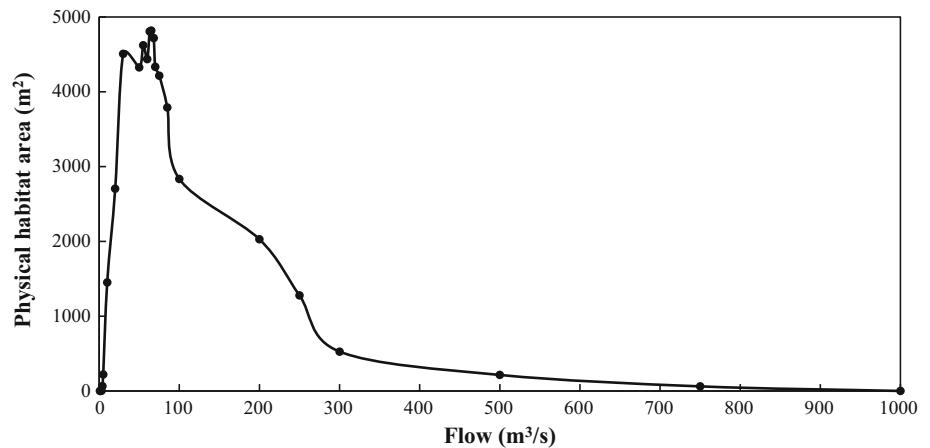


Fig. 4 Abrupt changes in annual flow series revealed by the Mann–Kendall test (a), and temporal trends in annual streamflow and precipitation taken from the Zijinguan hydrological station between 1956 and 2005 (b)

Fig. 5 Variation in the area of physical habitat of different flows



during the period of change average annual streamflow decreased to $0.5 \times 10^8 \text{ m}^3 \text{ a}^{-1}$. Annual precipitation was 564.3 and 340.4 mm a^{-1} during the normal period and period of change, respectively. Streamflow showed decreasing trends in precipitation (with a 0.78 Pearson product-moment correlation coefficient).

Optimum EIFR calculated by FWUA

The area of physical habitat for *P. parva* (Fig. 5) reached a maximum of 4816.8 m^2 when instream flow was $65 \text{ m}^3/\text{s}$. Moreover, the optimum range of flow was from 30 to $75 \text{ m}^3/\text{s}$ and the area of physical habitat for *P. parva* was $>4000 \text{ m}^2$ during this period. Furthermore, the area of physical habitat decreased rapidly when flow exceeded $85 \text{ m}^3/\text{s}$, and the area of physical habitat for *P. parva*

decreased to zero when flow reached $850 \text{ m}^3/\text{s}$. The traditional approach typically used for areas of physical habitat omits the influence of climate change as well as changes that occur during different seasons. For example, when climate change was taking into account, the maximum high flow threshold for different guaranteed hydrological frequencies was only $66.0 \text{ m}^3/\text{s}$.

As shown in Table 1, the extent of maximum habitat had typically occurred during flow exceedance frequencies of 75% with the exception of the spring and winter seasons that fell within the period of change, which exhibited maximum habitat values during exceedance frequencies of 50%. Therefore, the area of optimum physical habitat can be elicited as shown in Table 2. Results showed that the area of optimum physical habitat dramatically decreased in winter and spring with autumn and summer following in

Table 1 Variation in area of physical habitat for different hydrological frequencies during different seasons

Frequency	Season	Low (m ²)			High (m ²)		
		Normal period	Period of change	Alteration (%)	Normal period	Period of change	Alteration (%)
25%	Spring	48.4	0.0	100.0	715.7	165.9	76.8
	Summer	593.5	0.0	100.0	1955.7	1540.5	21.2
	Autumn	48.7	19.5	60.0	1496.1	886.4	40.8
	Winter	3.2	0.0	100.0	743.7	21.4	97.1
50%	Spring	148.0	8.4	94.3	1205.4	286.1	76.3
	Summer	1293.8	1120.9	13.4	3282.7	2799.8	14.7
	Autumn	741.1	222.5	70.0	2961.8	1516.9	48.8
75%	Spring	112.1	0.0	100.0	946.8	27.2	98.0
	Summer	851.2	63.5	92.5	1373.2	249.3	81.8
	Autumn	2681.6	2942.0	-9.7	4562.5	3359.8	26.4
	Winter	2174.8	1839.5	15.4	2970.7	1926.1	35.2
	Winter	550.5	5.6	99.7	1015.7	12.5	99.3

Table 2 Area of optimum physical habitat (AOPH) during different seasons for the normal period and the period of change

Season	Optimal AOPH (m ²)	
	Normal period	Period of change
Spring	851.2–1373.2	63.5–286.1
Summer	2681.6–4562.5	2942.0–3359.8
Autumn	2174.8–2970.7	1839.5–1926.1
Winter	550.5–1015.7	5.6–27.2

Table 3 Ecological instream flow requirements (EIFR) during the normal period calculated by means of different methods

Season	EIFR (10 ⁸ m ³)			Evaluated by the Tennant method
	FWUA	RVA	MFC	
Spring	0.68–0.91	0.47–0.84	0.51–1.06	Excellent
Summer	1.76–3.91	0.93–2.70	0.83–3.70	Outstanding
Autumn	1.38–1.87	0.12–1.28	0.36–1.49	Excellent
Winter	0.29–0.73	0.09–1.07	0.48–1.32	Good

descending order. The loss of the optimum area of physical habitat in winter and spring could be key factors in reducing *P. parva* populations.

As shown in Table 3, we calculated EIFR during the normal period from FWUA and compared it to results from the RVA, MFC, and Tennant methods. The range of EIFR calculated using FWUA was consistent with the other three methods. FWUA was highly reliable and was more conducive to the maintenance of the ecological health of rivers as well as the protection of instream biological habitats.

FWUA variation under climate change

Figure 6 shows that variations in optimum minimum and maximum flow and FWUA exhibited the same trends during both normal periods and periods of change. During the normal period (1956–1980), high flow threshold and FWUA values all occurred in the following descending order: summer, autumn, winter, and spring, while during the period of change (1981–2005), low flow threshold and FWUA values all occurred in the following descending order: summer, autumn, spring, and winter.

Variation in low flow threshold values and low and high FWUA threshold values during both the normal period and the period of change showed that the degree of change in winter was highest with a value change greater than 76.5% for instream flow and greater than 97.1% for FWUA. It was followed in descending order by spring, autumn, and summer. The high flow threshold by itself showed that winter also experienced the highest changes in flow. Conversely, changes in high flow threshold values in summer exceeded those in spring, reaching 46.2%. At the same time, low flow threshold values during the period of change were greater than during the normal period for summer.

Variation in the quality and distribution of FWUA

Figure 7 provides the four physical habitat grades for all seasons. For the normal period, the four grades during spring, autumn, and winter showed little proportional differences, whereas in summer, physical habitat quality was mostly in the moderate to high levels. During the period of change, moderate and high levels of physical

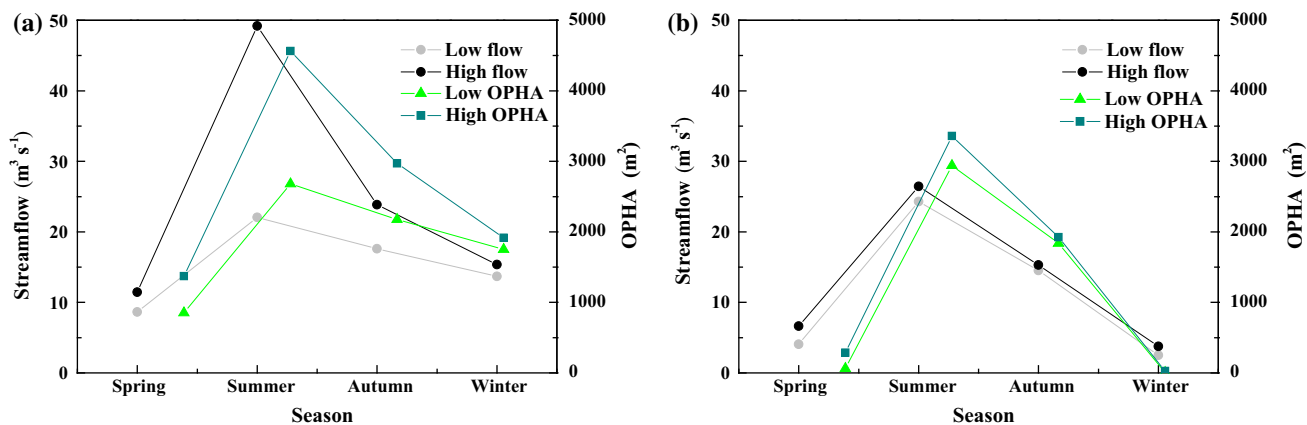
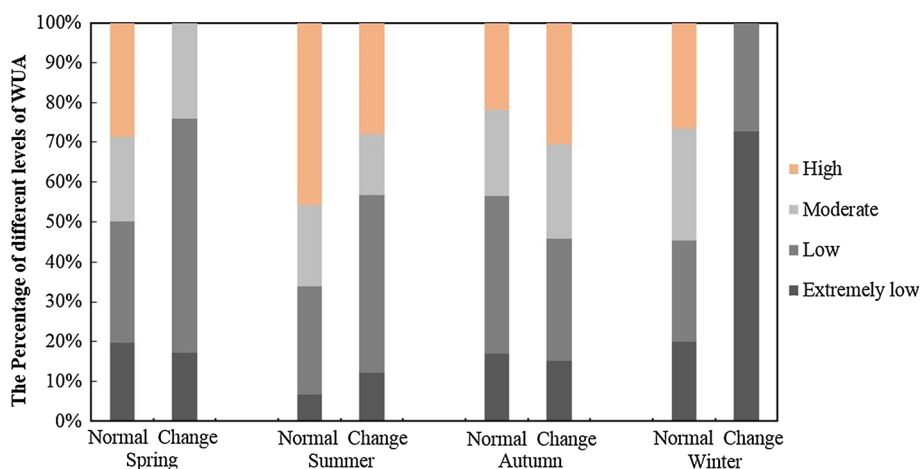


Fig. 6 Variation in low and high thresholds of flow and the area of optimum physical habitat (AOPH) for the normal period (a) and the period of change (b) during different seasons

Fig. 7 Variation in the quality of fish habitat for the normal period and the period of change during different seasons



habitat quality in spring and winter ceased altogether, and low and extremely low quality levels accounted for the majority of the habitat. In summer, high levels decreased and low levels increased proportionally. Conversely, moderate and high levels in autumn increased and low and extremely low levels decreased proportionally. Given that the quality of moderate and high physical habitats only changed slightly during the summer and autumn compared to that of winter and spring, the overall degree of change in FWUA for fish habitat during the summer and autumn was not significant when habitat area did not change during the four seasons.

The available habitat for *P. parva* (Fig. 8) was mainly located in the eastern middle reaches of the Juma River during both the normal period and the period of change. Differences were mainly in the extent and degree of CSIs. This means that there was only a slight impact on the distribution of *P. parva* FWUA (Fig. 8), while there

was a significant impact on quality of *P. parva* FWUA (Fig. 7).

Influenced by climate change, streamflow exhibited significant decreasing trends ($P < 0.05$) with a reduction in precipitation (that also showed significant decreasing trends; $P < 0.05$) in the Juma River Basin (Fig. 4), which is consistent with results from Chen et al. (2010), Ji et al. (2010), Xu (2011), and Gong et al. (2012). As shown in Fig. 6, climate change greatly reduced the frequency of high flow while increasing the frequency of low flow during summer. A reduction in streamflow could occur by means of associated biological changes, such as growth, breeding and the migration of fish species, the growth rate of vegetation as well as some chemical alterations in water temperature, oxygen content, and photosynthesis (Richter et al. 1996; Ruiz et al. 2013). Alterations in hydrological regimes [e.g., the reduction in frequency of high flow and increases in frequency of low flow in summer (Fig. 6)]

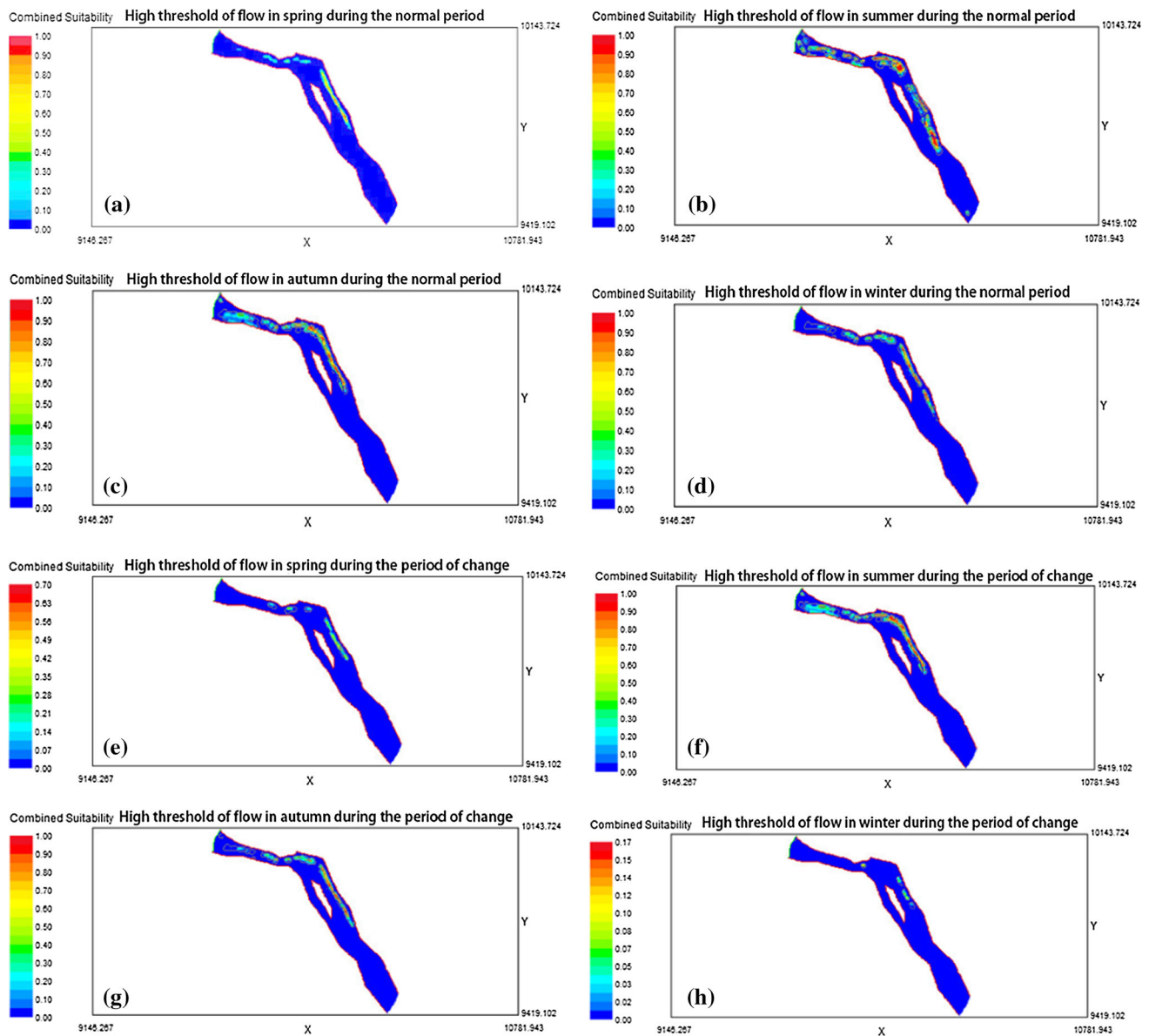


Fig. 8 Combined suitability index (CSI) of the high flow threshold for the normal period and the period of change during spring (a, e), summer (b, f), autumn (c, g), and winter (d, h)

could directly influence hydrological processes and riverine ecosystems (Gibson et al. 2005; Yang et al. 2012; Yan et al. 2013; Dindaroğlu et al. 2015). As shown in Fig. 6, low and high pulses exhibited similar decreasing trends, which also led to decreases in area of low and high optimum physical habitat between the normal period and the period of change and resulted in decreases in quantity and quality for the entire habitat area for *P. parva* in the Juma River (Fig. 7). As a result of the complex interactions between flow regimes and ecological systems (Ryberg et al. 2012; Karimi et al. 2012), changes in seasonal

streamflow between the normal period and the period of change dramatically altered the available habitat of *P. parva* (see Fig. 6, Table 2). Due to the assumption that no significant changes in river morphology and channel substrate occurred, we set the channel index as the steady state during the study period, which is consistent with other studies (e.g., Steffler and Blackburn 2002; Clark et al. 2008; Lee et al. 2010). In fact, changes in hydrological regimes can alter river morphology and channel substrate and result in changes to optimum physical habitat. Considering that changes in hydrological regimes were mainly

affected by climate, we used the modified WUA method to calculate optimum physical habitat area and EIFR in the Juma River Basin. Compared to the RVA, MFC, and the Tennant methods, FWUA obtained results consistent with the other methods (Table 3), which indicated that EIFR derived from FWUA is a creditable approach. Furthermore, climate change altered hydrological regimes and affected available habitat (Abbaspour et al. 2012), even for the small river area investigated in this study. Alterations in ecological structure and function that result from changes in hydrological regimes can strengthen and amplify their influencing factors on larger scales. More suitable water management practices should therefore be put into place to maintain natural hydrological regimes (Karimi et al. 2012; Shokoohi and Amini 2014), which could help address the impact of climate change on riverine ecosystems.

Conclusion

EIFR plays an important role in maintaining the balance of river ecosystems and promoting the harmonious and sustainable development of local economies. Using the M–K test, the River2D Hydrodynamic model, and FWUA, we investigated EIFR response to climate change. Several conclusions can be drawn from our results:

1. Impacted by climate change, annual streamflow in the Juma River showed a significant decreasing trend. Specifically, annual streamflow exhibited a downward trend from an abrupt change that occurred in 1981. We used this abrupt change to partition the study period (1956–2005) into a normal period and a period of change;
2. The area of optimum physical habitat for *P. parva* and instream flow both exhibited significant alteration to climate change. The degrees of change in area of optimum physical habitat and flow magnitude were magnified in winter and followed in descending order by spring, autumn, and summer. The quality of optimum physical habitat was severely degraded; however, the area distribution of optimum physical habitat changed little under climate change;
3. Changes in EIFR and area of optimum physical habitat showed that hydrological regimes impact ecological structures and functions, even in a small river system, and therefore rational measurements of such values should be put into practice to adapt to climate change in small river systems, which could help to maintain their ecological integrity on a large basin scale.

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