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Fuzzy evaluation and obstacle factors of urban ecological health changes in the Wei River Basin, northwest China

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Abstract

Background Urban ecological health is crucial for the long-term sustainable development of watershed. Accurately evaluating the health level of the ecological environment helps to develop reasonable strategies for ecological environment restoration and resource management. This paper constructed a comprehensive evaluation index system based on the Pressure-State-Response (PSR) framework and evaluated the ecological health of eleven administrative regions in the Wei River Basin (WRB), northwest China in 1980, 2000, and 2020 using an evaluation model established by fuzzy mathematics. Further, obstacle degrees were used to quantify the contribution of pressure, state, and response modules, as well as individual indicators to ecological health.

Results The comprehensive evaluation system constructed based on the PSR framework could effectively reflect the ecological health conditions of different regions in the WRB. During the study period, the ecological health went through a process of first deterioration and then improvement. By 2020, the ecological health of seven administrative regions reached healthy levels. The state module was the main obstacle module of the PSR framework to the ecological health of the most regions. The population density (P1), patch density of construction land (S5), comprehensive elasticity index (S8), soil erosion index (R1), and per capital GDP (R3) were the most crucial individual indicators affecting the ecological health. For different cities, the main obstacle factors varied. In economically developed cities, the limiting effect of P1 was more significant, while in economically underdeveloped cities, the limiting effect of R3 was stronger.

Conclusions In response to the special natural environment and socio-economic conditions of arid and semi-arid areas in the WRB, an ecological health evaluation index system suitable for the characteristics of the basin was constructed. The results indicated that, to improve the levels of urban ecological health, it is necessary to restore the natural ecological environment and control population size while accelerating economic construction. Our results can provide scientific support for the ecological health evaluation and protection of the WRB and even the arid and semi-arid areas in northwest China.

Keywords Wei River Basin, Ecological health, PSR framework, Fuzzy mathematics, Obstacle degree

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Introduction

Ecological environment is the material foundation for human survival and development. In recent decades, a series of global environmental problems such as pollution, resource waste, and ecological damage have received widespread attention (Ma et al. 2017; Marques et al. 2019). Many factors like climate change, population growth, and economic development, may lead to these problems (Wang et al. 2014). For example, from 1985 to 2015, the average annual expansion of global urban area was 9687 km^2, and it was expected to continue to grow in the future (Liu et al. 2020a, b). Urban construction at the cost of sacrificing the environment poses a threat to habitat quality and biodiversity (Grimm et al. 2008). In China, with the development of society and technological progress, the scope and intensity of human impact on the natural environment are constantly increasing, and the resulting regional ecological and environmental problems are also expanding and intensifying (Ouyang et al. 2000). Therefore, understanding the ecological health status and its main constraints is of great significance for effectively coordinating population, resources, environment, and economy under resource constraints, and seeking the optimal comprehensive benefits of ecology, economy, and society (Bryan et al. 2018).

At present, the concept of ecological health has not been fully unified (Tang et al. 2015), but a healthy ecosystem must possess the characteristics as reasonable structure, strong vitality, low external pressure, complete ecological functions, good response to nature and society, stable system, and sustainable state (Peng et al. 2015; Rapport et al. 1999). When facing different human expectations, the assessment results of the same ecosystem may be different. Whether the ecosystem is healthy or not totally depends on the standard value, but "health" is only a relative concept, and there are certain difficulties in defining the standard value (Han and Cao 2021; Shamseldin and Jacquin 2009). Therefore, ecological health assessment is always treated as a fuzzy mathematics problems (Li et al. 2017). The evaluation model established using fuzzy mathematics method is more in line with the actual situation than traditional methods.

Evaluating the health status of the ecological environment requires comprehensive consideration of the coordination between resources, environment, and economy (Jia et al. 2018). At present, assessment index system method was widely used to evaluate the ecological health conditions, because it can comprehensively take into multiple factors and objectively reflect the overall situation of the evaluated watershed (Fan and Fang 2020). There are many frameworks for constructing an evaluation index system, such as the structure–function framework (Ogden et al. 2019), pressure-state-response (PSR) (Jiao et al. 2023) and its extended frameworks, driving force-pressure-state-impact-response (DPSIR) (Chen 2022), and ecosystem vigor-organization-resilience-services (Peng et al. 2015). Among various frameworks, PSR framework is the most comprehensive, effective, and highly recognized framework model for studying environmental issues nowadays (Hazbavi et al. 2019). The application of the PSR model can deeply reflect the interaction between natural ecosystems and socio-economic systems, help people better understand the impact of human activities on the environment and develop effective environmental protection measures (Wilkerson et al. 2018). The focus of the evaluation may vary due to different purposes. For example, it can be used to evaluate the environmental impact of an industrial area, identify pressure sources, environmental status, and response measures, to develop effective environmental protection measures (Chen et al. 2020; Gu et al. 2022). It can also be used to forecast the potential environmental threats to help avoid the impact of disasters on the environment (Sun et al. 2022). What's more, the PSR framework also has good applications at different spatial scales. The existing ecological health assessment research has been conducted at the national (Zhang et al. 2019), provincial (Fan and Fang 2020), municipal (Lai et al. 2022; Li et al. 2022), and regional levels (Sun et al. 2016).

The Wei River Basin (WRB) is an important development zone in the northwest China, playing an important strategic role at the regional and national levels (Song et al. 2015). Since the 1950s, with the rapid development of the economy and society, the urbanization process has accelerated, and the ecological environment has been seriously threatened. The WRB has gradually become an ecologically sensitive area, with frequent problems such as water resource shortage, water quality deterioration, and severe soil erosion (Li et al. 2021). In existing studies, the evaluation of ecological health in the WRB has mostly focused on water pollution (Zhao et al. 2022), or ecological risk assessment at the basin scale based on comprehensive hydrological conditions, natural habitats, biological structures, landscape trends, etc. (Yang et al. 2020). However, the WRB contains many administrative regions, each with differences in geographical location, natural conditions, socio-economic development, population, and other aspects. However, there is currently a relative lack of research on comprehensive evaluation of ecological health in different administrative regions of WRB.

In view of this, the aim of the study is to establish a comprehensive evaluation index system to evaluate the ecological health of urban agglomerations in the WRB. The specific objectives are to: (1) construct a comprehensive evaluation index system that includes population, land use, landscape pattern, ecological service function, natural and socio-economic factors based on the PSR framework in the WRB; (2) establish an evaluation model using fuzzy mathematics, and determine the ecological health status of eleven cities in 1980, 2000, and 2020 according to the principle of maximum membership degree; (3) quantify the contribution rate of different indicators to the ecological health using the obstacle degree method; and (4) discuss the impact of various indicators on ecological health and propose policy suggestions. The research results would provide reference for ecological restoration and future efficient watershed management.

Study area and data

Study area

The WRB is in the southeastern region of the Loess Plateau of China (106°18′–110°37′E, 33°42′–37°20′N), with the drainage area of approximately 13.5×10^4 km^2. The Wei River rises in the Niaoshu Mountain of in Dingxi, Gansu Province, with the total length of 818 km, and finally merges into the Yellow River in Tongguan County, Shaanxi Province. There are many tributaries of the Wei River, feathered and asymmetrically distributed on the north and south bank, with larger tributaries concentrated on the north bank. The upper reaches are mainly loess hilly areas, accounting for over 70% of the area; The northern part of the middle and lower reaches is the Loess Plateau in northern Shaanxi, the central part is the valley alluvial plain area, Guanzhong Plain, and the southern part is the earth rock mountain area of the Qinling Mountains (Zhang et al. 2022). WRB is continental monsoon climate, belonging to the transitional zone between arid and semi-humid regions, with an average annual temperature of 9.8 °C and precipitation of 373–1138 mm. The population distribution in the Guanzhong area is the densest, accounting for over 65% of the total population in the basin, while the population distribution is sparse in the Qinling Mountains and Loess Plateau areas (Ren et al. 2016).

As the largest tributary of the Yellow River, the Wei River flows from west to east through three provinces (districts) of Gansu, Ningxia, and Shaanxi, including 10 regions and 84 counties. The WRB is one of the important water resource economic zones in China, covering major urban and rural areas in the Guanzhong region (Gai et al. 2019). This study selected eleven administrative regions in the WRB, namely Dingxi (DX), Tianshui (TS), Pingliang (PL), Qingyang (QY), Guyuan (GY), Baoji (BJ), Xi'an (XA), Xianyang (XY), Tongchuan (TC), Weinan (WN), and Yan'an (YA) (Fig. 1), to conduct ecological health assessment and obstacle factor analysis. Objectively understanding the changes and influencing factors of urban ecological health can provide a reference for future regional development. It is worth noting that the research object of this study is various administrative regions, rather than referring to "urban" areas with a certain scale and population density, where economic, cultural, political and other activities are concentrated. The administrative region is a second level unit in the national administrative management system, established mainly for the convenience of administrative management and the provision of public services, including urban, rural, and other types of areas.

Data sources

The datasets used for ecological health assessment included meteorological data, land use data, environmental data, and social economic data. The meteorological

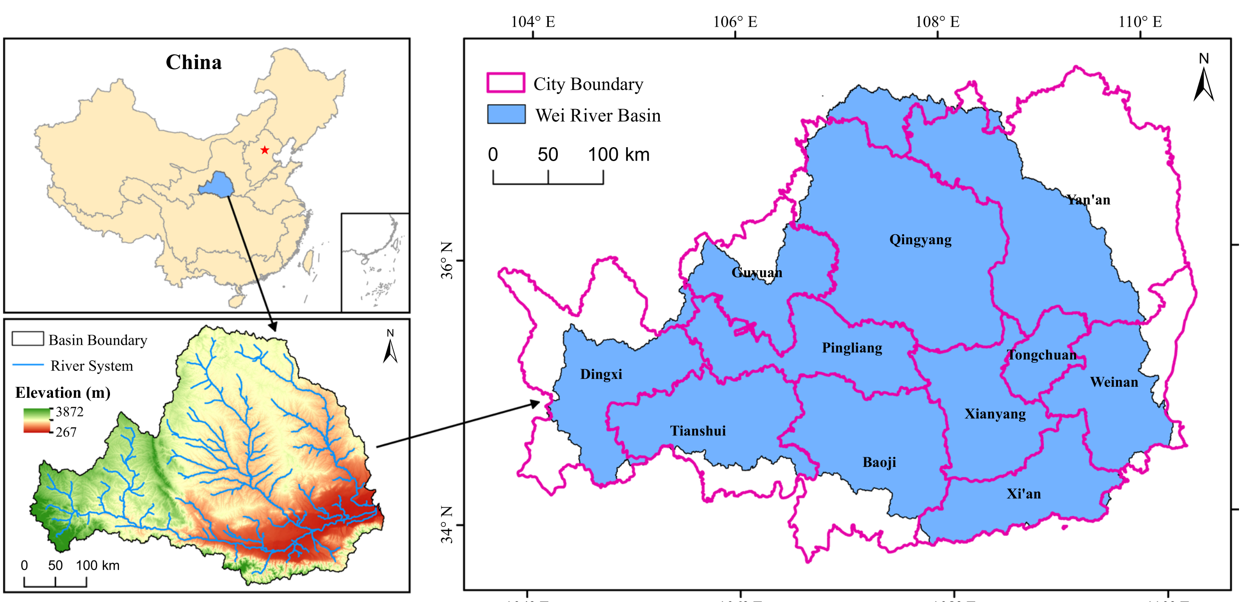

Fig. 1 Geographical location and urban agglomeration distribution of the Wei River Basin

data, including annual average precipitation and temperature), and the spatial distribution of land use/land cover, were sourced from Resource and Environmental Science Data Center, Chinese Academy of Sciences (http://www.resdc.cn), with the resolution of 1 km × 1 km. The spatiotemporal resolution of meteorological data and land use datasets may not be sufficient to capture subtle changes within the study area. For example, rough resolution may not accurately reflect the dynamics of urban heat island effects or local land cover changes. Therefore, when conducting refined research, observation data from local meteorological stations or higher resolution land use datasets should be used to match the local actual situation. This study is based on administrative regions, so the accuracy of the data is required to be low. Meteorological data was used to calculate indicators such as biological first potential productivity and rainfall erosivity. Land use data was basic data to calculate the land pressures, the organization, resilience, service functions, and natural response of the ecosystem. Environmental data are composed of soil and topographical data. Soil data include sand, silt, clay, and soil organic matter content (%), which are from Harmonized World Soil Database (HWSD), with the spatial resolution of 1 km × 1 km. Soil data were acquired to calculate the soil erosion amount. Topographical data here referred to the digital elevation model (DEM) of the study area, which was downloaded from Geospatial Data Cloud Platform of Chinese Academy of Sciences (https://www.gscloud.cn/), with the resolution of 30 m × 30 m, and it was used for slope analysis. Social economic data included population density and per capital GDP of each city, deriving from statistical bulletins of national economy and social development of provinces and cities (https://d.qianzhan.com/), which reflected the population pressure and social response of the research area during the study period. The boundary of administrative division of cities was from the Resource and Environmental Science and Data Center of Chinese Academy of Sciences (http://www.resdc.cn).

Methods

Evaluation index system establishment

PSR framework construction

The PSR framework was developed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) in the 1980s and 1990s to study environmental issues (Walz 2000). It has a very clear causal relationship, including indicators at three levels: pressure, state, and response. Pressure indicators reflect the pressure faced by the ecological environment, such as pollution, resource consumption, land use changes, etc. State indicators indicate the current situation of the ecological environment and reflect the state of the ecosystem under the comprehensive influence of various natural, human, and other factors. In addition to selecting the three aspects of vigor, organization, resilience proposed by Costanza et al. (1998), this study also added an ecological service function to describe the state of the ecosystem together. Response indicators reflect the response of ecological environment to pressures. Human society also responds to environmental changes through environmental, economic, and management strategies to improve environmental quality or prevent environmental degradation, including policy, legal, technological, and socio-economic factors (Wang et al. 2021). Based on the principles of systematicity, independence, differentiation, and quantifiability (Hazbavi et al. 2018), this study selected 11 indicators and constructed an adaptive PSR evaluation index system (Table 1). The indicator type indicates whether the selected indicator belongs to a positive indicator or negative indicator, represented by "+" and "−" respectively.

Acquisition of indicators

In this study, P1, P2, R2, and R3 can be directly obtained by definition or data products, respectively. Landscape pattern indices (S2, S3, S4) and relevant indicators of construction land (S5, S6, S7) were calculated using land use distribution maps in Fragstats 4.2 software. Euclidean nearest neighbor is a commonly used concept in spatial analysis and geographic information systems, used to determine the nearest neighbor point of a given point in Euclidean space. It is widely used in environmental science, land use planning, and infrastructure layout. Perimeter-area fractal dimension is an indicator used to describe the complexity of the shape of a landscape or geographic object. It quantifies the fractal characteristics of an object by analyzing the relationship between its perimeter and area. A higher value usually indicates that the landscape has a more complex edge structure, with a larger proportion between edges and area, which may indicate more edge effects and more complex ecological processes in the landscape (Jia et al. 2019; Jahanmiri and Parker 2022). R1 was calculated based on the revised universal soil loss equation (RUSLE). Chinese scholars have conducted extensive research on the revision of USLE factor calculation methods and the use of equations for soil erosion monitoring and prediction (Chen et al. 2004). In this study, the revised parameter calculation methods were used to calculate various indicators and obtained convincing results (Wu et al. 2023). From slight to severe soil erosion, the soil erosion index was endowed 10, 8, 6, 4, 2, and 0, respectively.

NPP (S1) is constrained by several environmental and climatic factors, with temperature and precipitation having

Table 1 PSR framework for urban ecological health evaluation of Wei River Basin

Module	Element	Indicator	Description	Unit	Type	References
Pressure (P)	Population pressure	Population density	Population per unit area (P1)	Person/km^2	–	(Cheng et al. 2022)
	Land pressure	Land reclamation index	The proportion of arable land to total land area (P2)	%	–	(Liu and Hao 2016)
State (S)	Vigor	Net primary productivity (NPP)	The ability of organisms to absorb external substances and energy to produce organic matter (S1)	g/(m^2·yr)	+	(Vargas et al. 2019)
	Organization	Diversity	Diversity and variability in spatial structure, functional mechanisms, and temporal dynamics of different types of landscapes (S2)	/	+	(Xu et al. 2020)
		Contagion	The degree of aggregation or extension trend of different patch types in the landscape (S3)	/	+	(Xu et al. 2020)
		Evenness	The uneven distribution of patches in the landscape in terms of area (S4)	/	+	(Xu et al. 2020)
		Patch density of construction land	Number of building land patches per unit area (S5)	/	–	(Yu et al. 2020)
		Euclidean nearest neighbor	The closest distance from one patch to another in space (S6)	m	–	(Zhang et al. 2021)
		Perimeter-area fractal dimension	Measuring how the edges of patches change in different proportions to reflect the irregularity of patch shape (S7)	/	–	(Florio et al. 2019)
	Resilience	Comprehensive elasticity index	The ability of an ecosystem to recover after being disturbed (S8)	/	+	(Zhang et al. 2020)
	Service function	Ecosystem service value	The value corresponding to the ability of ecosystems to maintain the natural environment on which humans rely and provide them with various daily necessities (S9)	$\times 10^6$ yuan/ (km^2 ·yr)	+	(Costanza et al. 1998)
Response (R)	Natural response	Soil erosion index	Soil erosion score corresponding to soil loss intensity in the watershed (R1)	/	–	(Cheng et al. 2022)
		Forest coverage rate	Percentage of forest cover area (R2)	%	+	(Fan and Fang 2020)
	Social response	Per capita gross domestic product (GDP)	An important indicator for measuring economic development and people's living standards (R3)	$\times 10^4$ yuan	+	(Zhang et al. 2019)

the greatest impact. This study adopted the Miami model first proposed by Lieth in 1971 to calculate NPP (Sun et al. 2010).

$$NPP_t = \frac{3000}{1 + e^{1.42 - 0.141t}} \quad (1)$$

$$NPP_R = 3000 \times (1 - e^{-0.00065R}) \quad (2)$$

where NPP_t and NPP_R are the NPP values calculated according to temperature and rainfall, the unit is g/(m^2·yr); t is the annual temperature (°C); R is the annual rainfall (mm). The NPP value is the minimum of NPP_t and NPP_R.

The comprehensive elasticity index (S5) of ecosystems can usually be determined by changes in vegetation types. It is calculated as follows:

$$S5 = D_i \sum S_i R_i \tag{3}$$

where S_i is the area of ith land use type; R_i is the comprehensive elasticity index of land use i, with the farmland, forestland, grassland, water area, construction land, and unused land of 0.5, 0.9, 0.7, 0.9, 0.4, and 0, respectively. D_i is the diversity index.

As for S8, it is equal to the value corresponding to the ability of ecosystems to maintain the natural environment on which humans rely for survival and provide various necessities of life. Economists and ecologists have conducted many studies on the estimation of the value of ecosystem services. In this study, we applied the method proposed by Xie et al. (2008) to estimate the value of S8. It was an ecosystem service value evaluation system based on expert knowledge that can more accurately reflect the production-consumption-value realization process of ecosystem services in China. In this method, ecosystem services mainly include supply services, regulation services, support services, cultural services, etc. (Xie et al. 2008). The average ecosystem service value of farmland, forestland, grassland, water area, construction land, and unused land per unit area were 1.22, 8.17, 2.66, 15.8, 1.15, and 0.22, respectively. The total ecosystem service value was equal to the sum of the values of different land use types.

Determination of evaluation index weights

Indicator weight refers to the importance relationship of each indicator under the same objective constraint. The entropy method was applied to assign weights to ecological health evaluation indicators, and the main steps are as follows:

(1) Data standardization processing. Due to differences in the dimensions, magnitude, and positive or negative orientations of each indicator, it is necessary to standardize the initial data. The standardization method is as follows:

For positive indicators:

$$X'_{\mathrm{ij}} = \frac{X_{ij} - \min X_j}{\max X_j - \min X_j} \tag{4}$$

For negative indicators:

$$X'_{\mathrm{ij}} = \frac{\max X_j - X_{ij}}{\max X_j - \min X_j} \tag{5}$$

(2) Calculate the proportion of the jth indicator value in the ith year:

$$Y_{\mathrm{ij}} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}} \tag{6}$$

(3) Calculation of indicator information entropy:

$$\mathrm{e}_j = -k \sum_{i=1}^{m} \left(Y_{ij} \times \ln Y_{ij} \right) \tag{7}$$

In the formula, $\mathrm{k} = \frac{1}{\ln m}$, then $0 \le \mathrm{e}_j \le 1$, when $Y_{\mathrm{ij}}=0$, let $Y_{\mathrm{ij}} \times \ln Y_{ij} = 0$.

(4) Calculation of information entropy redundancy:

$$\mathrm{d}_j = 1 - e_j \tag{8}$$

(5) Determination of indicator weights:

$$\omega_{\mathrm{i}} = \frac{d_j}{\sum_{j=m}^{n} d_j} \tag{9}$$

In the formula, $X_{\mathrm{ij}}\prime$ and X_{ij} are the standardized and original values of the jth single indicator in the ith year, respectively, while $\max X_j$ and $\min X_j$ are the maximum and minimum values of the jth single indicator in all years. m is the number of evaluation years, and n is the number of indicators. The weight results of each indicator determined through AHP in this study were shown in Table S1. P2 of the the pressure module, S2, S4, and S8 of the state module, and R3 of the response module had higher weights, indicating that these indicators have a greater impact on ecological health.

Urban ecological health evaluation model

This study used the evaluation model based on fuzzy mathematical method to determine the ecological health levels of each city. The model quantifies some unclear and non-quantitative factors by applying the principle of fuzzy relationship synthesis, and uses the membership degree in fuzzy mathematics to describe the evaluation level (Zahabi and Kaber 2019). It provides a systematic for a similar representation of complex or poorly defined problems using linguistic variables, in which the transition from one member to another is gradual rather than sudden, and is consistent with human reasoning processes. Using fuzzy models for soft classification can make a single indicator value belong to multiple health levels with different membership degrees, thus better reflecting the actual characteristics of the indicator and comprehensive assessment results (Cheng et al. 2022). In this study, ecological health level is divided into five classes, namely "Morbidity" (I), "Unhealthy" (II), "Sub-healthy" (III), "Healthy" (IV), and "Very healthy" (V). The ecological health evaluation model developed by fuzzy mathematical method is as follows:

$$H = W \times R \quad (10)$$

where H is the diagnosis result of ecological health; W is the weight matrix of pressure, state, and response to ecological health, $W = (\omega_1, \omega_2, \omega_3)$; R is the membership matrix of each ecological health assessment element to health standards at all levels:

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} \end{bmatrix} \quad (11)$$

where R_{ij} is the degree of membership of the ith element to the jth level standard:

$$R_{ij} = \left(\omega_{i1} \ \ \omega_{i2} \cdots \omega_{ik} \right) \begin{bmatrix} r_{1j} \\ r_{2j} \\ \vdots \\ r_{kj} \end{bmatrix} \quad (12)$$

where k is the number of indicators included in each rating indicator; ω_{ik} is the weight of the kth indicator in the ith element; r_{kj} is the relative membership degree of the kth indicator to the jth health level standard. In fuzzy sets, relative membership is usually used to determine the health status of ecosystems.

Relative membership is to compare the advantages and disadvantages of different decisions in the limited universe and has nothing to do with decisions outside the universe. It can reduce or even eliminate the defects of subjective arbitrariness (Chen and Zhao 1993). In this study, we follow the principle of maximum membership to judge the ecological health levels. For positive indicators, the calculation formula is as follows (taking the ith indicator X_i as an example, where S_{ij} is the jth level health standards for the ith indicator), while the calculation for negative indicators is similar, with only the sign is reversed.

(1) when the ith indicator X_i is less than its corresponding first level standard value (Morbidity), its relative membership degree to "morbidity" is 1, while to other health levels is 0. That is, when $X_i < S_{ij}$:

$$r_{i,1} = 1, r_{i,2} = r_{i,3} = r_{i,4} = r_{i,5} = 0 \quad (13)$$

(2) when the ith indicator X_i is between its corresponding j level and $j+1$ level standard values, its relative membership degree to the j-level health grade is $1 - \frac{X_i - S_{i,j}}{X_i + S_{i,j}}$, to the $j+1$ level health level is $\frac{X_i - S_{i,j}}{X_i + S_{i,j}}$, and to other health levels is 0. That is, when $S_{i,j} \leq X_i \leq S_{i,j+1}$:

$$r_{i,j} = \frac{X_i - S_{i,j}}{S_{i,j+1} - S_{i,j}}, r_{i,j} = 1 - r_{i,j+1}, j = 1, 2, 3, 4 \quad (14)$$

(3) when the ith indicator X_i is greater than its corresponding fifth level (very healthy) standard value, its membership degree to the fifth level health level is 1, while to other health levels is 0. That is, when $X_i > S_{ij}$:

$$r_{i,5} = 1, r_{i,1} = r_{i,2} = r_{i,3} = r_{i,4} = 0 \quad (15)$$

The flowchart of research methodology to evaluate the ecological health status of administrative regions is shown in Fig. 2. It includes the following steps: assessment class set, criterion set, weights set, membership function, fuzzy combination, fuzzy relation matrix and fuzzy evaluation matrix.

Evaluation criteria for indicators

To conduct comprehensive quantitative analysis and evaluation of ecological health, it is necessary to establish

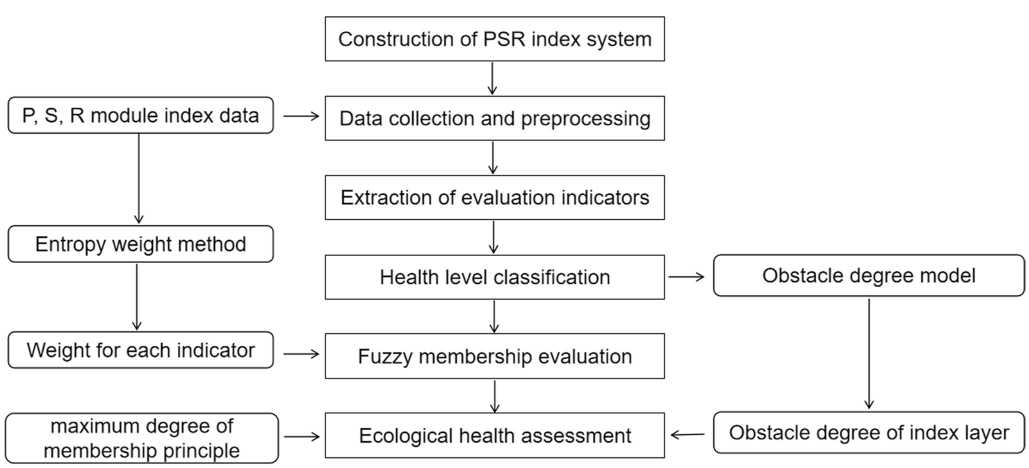

Fig. 2 Flowchart of research methodology to evaluate the ecological health status of the WRB based on PSR framework

comparable quantitative indicators for evaluating the health of indicator factors and determine the threshold range of the indicators. The methods for determining the threshold range of indicators are not unified (Jakobsson et al. 2021). Some indicators are based on relevant national or international standards, such as soil erosion classification standards, while others are classified using sorting and statistical methods or natural breakpoint method in Arcgis10.2 software. The results of quantifying and grading various indicators based on the actual situation of the WRB are shown in Table S2.

Diagnosis of the obstacle factors

Ecological health is a complex issue, and the degree of impact of various factors on "health" varies. Obstacle analysis method is a technique used to identify and quantify the main obstacles that affect the achievement of goals in a multi-indicator comprehensive evaluation system. This method reveals which indicators have the greatest impact on the overall evaluation results by calculating the obstacles of each evaluation indicator, thereby providing decision-makers with directions for improvement measures. To determine the main obstacle factors affecting ecological health, three indicators, namely factor contribution degree (*F*), indicator deviation degree (*I*), and obstacle degree (*h*, *H*), were used to diagnose, and analyze the obstacles to ecological health (Yao et al. 2015), which provides reference for efficient environmental management (Zhang et al. 2019).

$$I_j = 1 - X'_{ij} \tag{16}$$

$$h_j = \frac{I_j \times F_j}{\sum_{j=1}^{n}(F_j \times I_j)} \times 100\% \tag{17}$$

$$H_j = \sum h_{ij} \tag{18}$$

where X'_{ij} represents the standardized values of individual indicator i under each module j; I_j represents the gap between each individual indicator and the development goals, *i.e.* the difference between the standardized values of each individual indicator and 100%; F_j represents the degree of impact of each individual indicator on the ecological health, that is, the weight of each individual indicator on the overall goal; h and H represent the magnitude of the impact of each individual indicator and each assessment module (P, S, R) on ecological health, respectively, which are the goals and results of diagnosing ecological health barriers.

The standardized values of individual indicator X_{ij} was calculated as follows to eliminate the differences in units and magnitudes of individual indicators (Liu and Hao 2016):

For positive indicators:

$$X'_{ij} = \frac{(X_{ij} - minX_j)}{(maxX_j - minX_{ij})} \tag{19}$$

For negative indicators:

$$X'_{ij} = \frac{(maxX_j - X_{ij})}{(maxX_j - minX_{ij})} \tag{20}$$

where X_{ij} represents the original values of individual indicator i under j module; $maxX_j$ and $minX_j$ represent the maximum and minimum individual indicator value of the ith indicator. The increase of positive indicators or the decrease of inverse indicators will promote the improvement of ecological health, while the decrease of positive indicators or the increase of inverse indicators will reduce the ecological health (Fan and Fang 2020).

Results

Evaluation grades for the pressure, state, and response

Figure 3 depicted health levels of pressure, state, and response modules of different cities in 1980, 2000, and 2020. For pressure module, it showed that cities in the south and east of the WRB faced greater pressure than those in the north and west (Fig. 3a–c). In 1980 and 2020, except for DX, YA, GY, and BJ, the pressure modules in all other administrative regions were at an "Unhealthy" and "Morbidity" level, with a total of seven. In 2000, nine administrative regions were at an "Unhealthy" or "Morbidity" level, indicating that in 2000 the health level of the pressure modules in each administrative region was the lowest. During the research period, the pressure modules in WN and XY remained at a "Morbidity" level, while GY remained at a "Very healthy" level. Overall, the health level of pressure module has improved. The health level of the pressure module has gone through a process of first deteriorating and then improving, with the number of administrative regions under "Very healthy" going through a process of first decreasing and then increasing, from three in 1980 (GY, DX, and YA) to one in 2000 (GY) and two in 2020 (DX and GY). With the growth of population and economic development, better developed cities such as XA, WN, and TC are facing greater population and land pressure, while slower developing cities such as DX and TS are facing less pressure.

For state module, all administrative regions were classified as "Sub-healthy" level or above (Fig. 3d–f). During the research period, except for TS, PL, TC, XY, BJ and XA in 1980 and PL, TC, BJ, and XA WN in 2000, DX, PL, TC, XY, WN, BJ and XA in 2020 being "Healthy" and "Very healthy" levels, all other administrative regions

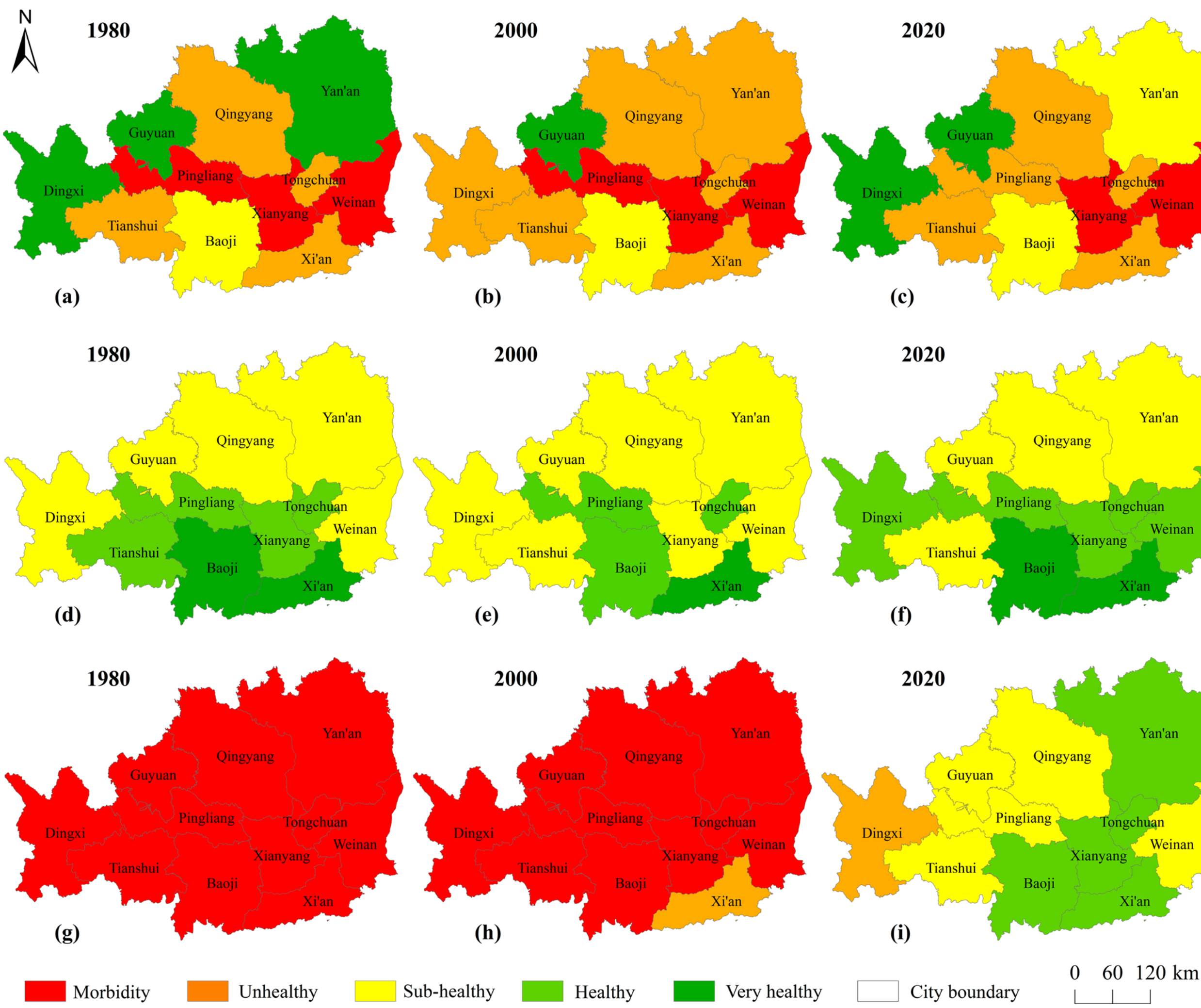

Fig. 3 Ecological health assessment results of pressure (**a**–**c**), state (**d**–**f**), and response (**g**–**i**) of different cities

were at the "Sub-healthy" level. It was obvious that the health level of the state module has gone through a process of first deteriorating and then improving. The number of administrative regions with a "Healthy" level or above decreased from six in 1980 to four in 2000, and increased to seven in 2020. The health status of the state module was closely related to the natural conditions, and the improvement of the state level indicated that vegetation restoration measures in the watershed have significant effects.

For response module, in 1980 and 2000, all cities were in "Morbidity" or "Unhealthy" level, while in 2020, the health level has been improved in all administrative regions, with YA, XY, TC, BJ, and XA being upgraded to "Healthy" levels, GY, PL, TS, and QY to "Sub-healthy" levels (Fig. 3g–i). Compared to 1980 and 2000, the health level of the response module in 2020 significantly improved. There are two levels of response, natural and social response, indicating that administrative regions have achieved significant results in economic development or ecological restoration.

Comprehensive evaluation of ecological health

The ecological health assessment results of administrative regions in the WRB in 1980, 2000 and 2020 are shown in Fig. 4, and the relative membership degrees to different health levels are shown in Table 2. Overall, the ecological health of various administrative regions in the WRB has gone through a process of relative improvement, deterioration, and then improvement. According to the principle of maximum membership, in 1980, the number of administrative regions classified as "Healthy" or "Very healthy" was six, namely TS, PL, TC, XY, BJ, and XA, while all other administrative regions were at a "Sub-healthy" level. In 2000, the ecological health level of XY decreased to a "Sub-healthy" level, and that of

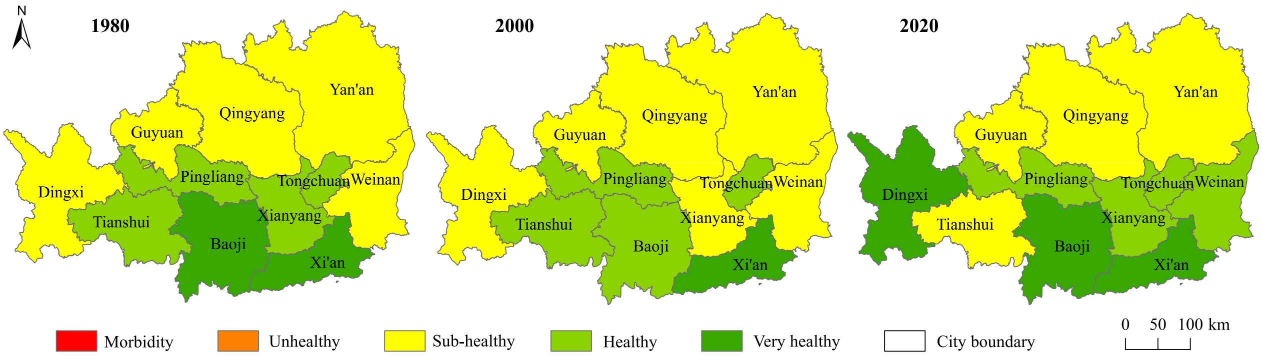

Fig. 4 Comprehensive evaluation results of urban ecological health in different years

Table 2 Relative membership degrees of urban ecological health evaluation in different years

City	Year	Morbidity (I)	Unhealthy (II)	Sub-healthy (III)	Healthy (IV)	Very healthy (V)	Comprehensive evaluation grade
DX	1980	0.0341	0.0340	0.1137	0.0619	0.0554	III
	2000	0.0341	0.0342	0.1098	0.0677	0.0533	III
	2020	0.0173	0.0391	0.0756	0.0784	0.0886	V
PL	1980	0.0313	0.0507	0.0816	0.1200	0.0480	IV
	2000	0.0312	0.0536	0.0914	0.1088	0.0464	IV
	2020	0.0107	0.0609	0.0652	0.1028	0.0918	IV
QY	1980	0.0353	0.0511	0.1013	0.0477	0.0635	III
	2000	0.0353	0.0608	0.0911	0.0481	0.0636	III
	2020	0.0126	0.0376	0.1169	0.0473	0.0847	III
TS	1980	0.0198	0.0148	0.1060	0.1242	0.0431	IV
	2000	0.0199	0.0150	0.1164	0.1181	0.0388	IV
	2020	0.0029	0.0203	0.1044	0.0879	0.0910	III
GY	1980	0.0197	0.0699	0.1567	0.056	0.0341	III
	2000	0.0190	0.0798	0.1455	0.0618	0.0304	III
	2020	0.0027	0.0241	0.1650	0.0976	0.0471	III
BJ	1980	0.0170	0.0086	0.0791	0.0703	0.1270	V
	2000	0.0156	0.0113	0.0763	0.1188	0.0800	IV
	2020	0	0.0075	0.0764	0.0884	0.1296	V
TC	1980	0.0228	0.0237	0.0664	0.0904	0.0826	IV
	2000	0.0228	0.0209	0.0683	0.0924	0.0879	IV
	2020	0.0007	0.0162	0.0526	0.1309	0.0918	IV
WN	1980	0.0428	0.0181	0.1214	0.0886	0.0070	III
	2000	0.0428	0.0143	0.1415	0.0723	0.0065	III
	2020	0.0222	0.0122	0.1073	0.1298	0.0064	IV
XA	1980	0.0197	0.0164	0.0762	0.0939	0.1157	V
	2000	0.0092	0.0269	0.0749	0.1040	0.1069	V
	2020	0.0073	0.0077	0.0775	0.0690	0.1605	V
XY	1980	0.0403	0.0161	0.1141	0.1152	0.0086	IV
	2000	0.0403	0.0171	0.1249	0.1034	0.0085	III
	2020	0.0139	0.0162	0.0705	0.1722	0.0215	IV
YA	1980	0.0324	0.0212	0.1204	0.0280	0.0811	III
	2000	0.0209	0.0360	0.1263	0.0197	0.0801	III
	2020	0.0059	0.0189	0.0953	0.0705	0.0927	III

BJ decreased to "Healthy" level, while the health levels of other administrative regions remain unchanged. In 2020, the number of administrative regions classified as "Healthy" or "Very healthy" increased to seven, namely DX, PL, TC, WN, XY, BJ, and XA, other cities were at "Sub-healthy" level. In terms of space, the ecological health status of cities in the north of the watershed was worse than that in the south, which was related to the economic development and natural conditions of different regions.

Obstacle degrees of indicators

Obstacle degrees of pressure, state, and response module

The obstacle degrees of pressure, state and response modules to ecological health varied in different administrative regions and years (Fig. 5). The state module dominated in the ecological health assessment in most of the administrative regions. Except for the response as the main obstacle factor to the ecological health of PL in 1980 and the pressure as the main obstacle factor to YA, WN, PL, and DX in 2020, the main obstacle factor to the ecological health of other administrative regions in 1980, 2000, and 2020 was the state module. This was because there were many indicators in the state module, and this module accounts for a large proportion of the weight, so it has a greater impact on the results of ecological health assessment.

Obstacle degrees of individual indicators

The obstacle degrees of all individual factors to the ecological health are shown in Fig. 6. The top five individual indicators and their obstacle degrees to different administrative regions in the WRB from 1980 to 2020 are shown in Table 3. For a single city, the top five indicators that affected its ecological health level in different years were basically the same, but there are differences in some cities in 2020. For individual indicator, in the pressure module, both population pressure (P1) and land pressure (P2) posed significant obstacles to ecological health of the administrative regions. In the state module, the obstacle degrees of patch density of construction land (S5), comprehensive elasticity index (S8), and ecosystem service value (S9) were relatively high. In the response module, soil erosion index (R1) and per capita GDP (R3) posed significant obstacles to ecological health. Overall, the indicators in the state module have the highest number of obstacles to ecological health in the top five, which was consistent with the results in Fig. 5. Compared to 1980 and 2000, the number of obstacles to ecological health in 2020 was relatively small, but the degree of obstacles was relatively high. For different cities, due to differences in socio-economic development status and basic ecological environment conditions, single indicator had different obstacle degrees to ecological health. For example, in 2020, population pressure (P1), patch density of construction land (S5), and soil erosion index (R1) became the single indicators that most affect ecological health.

Discussion

Factors affecting urban ecological health

The impact of economic development on ecological health

Based on the constructed PSR framework and individual obstacle degree analysis, the indicators related to socioeconomic and having high obstacle degrees to ecological health were P1 and S3 indicators. In economically developed cities like XA, the obstacle degree of R3 to ecological health was relatively low, while the obstacle degree of P1 was high. However, in economically underdeveloped

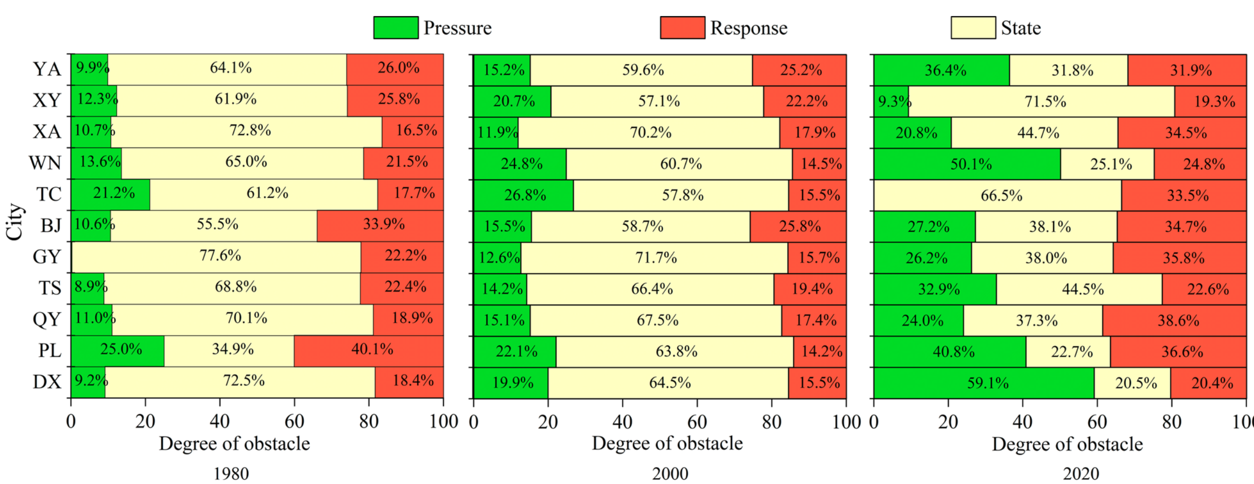

Fig. 5 Obstacle degrees contributed by pressure, state, and response modules in 1980, 2000, and 2020. Obstacle degrees less than 5% did not display

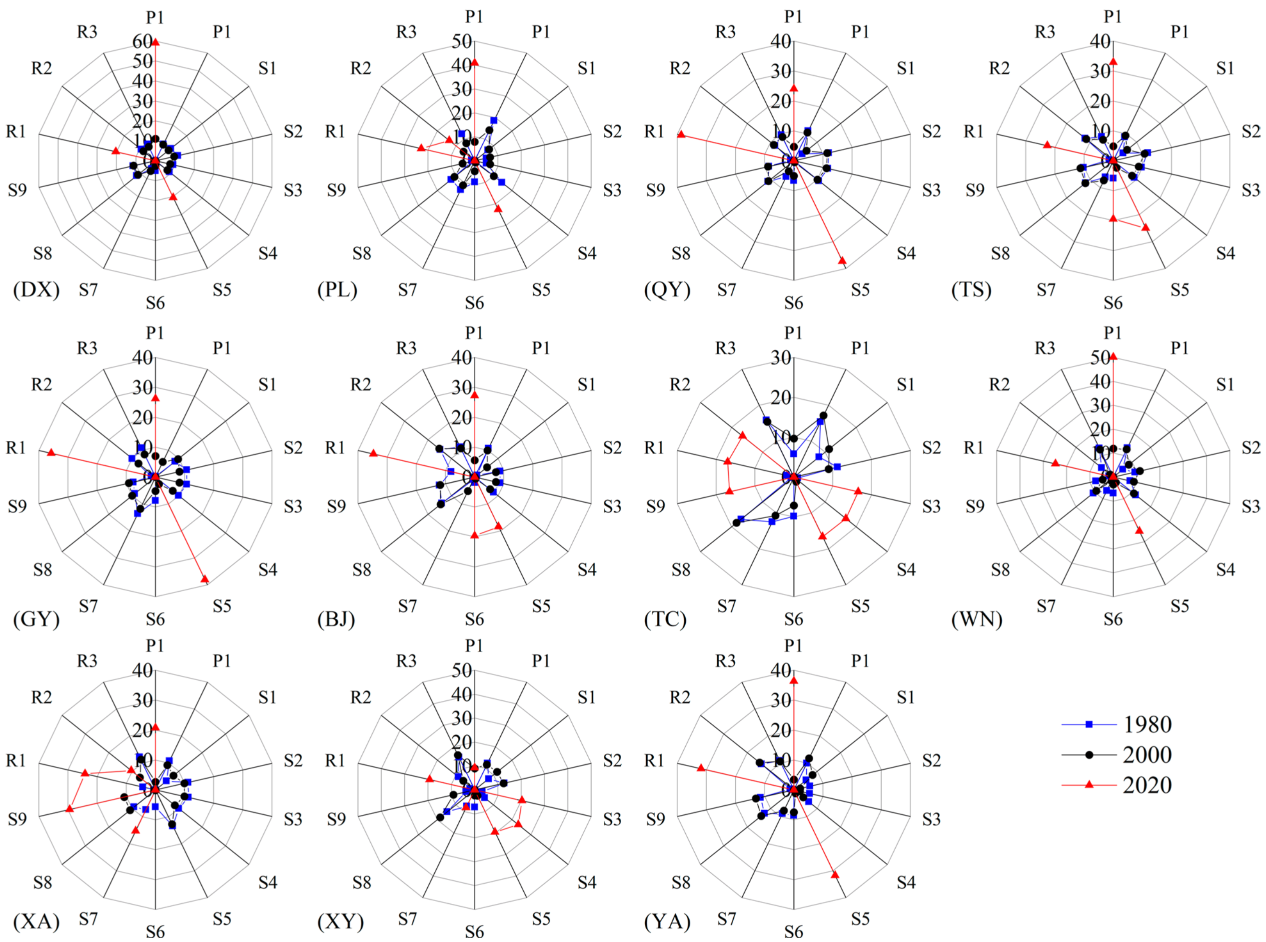

Fig. 6 Obstacle degrees contributed by single indicator of different cities in 1980, 2000, and 2020

areas, such as DX and TS in Gansu Province, the situation was the opposite. This is because with the economic development and population growth, the social response had reached a high level, but along with the fact that the increasing rate of resources demand, the pressure facing cities is gradually increasing, and excessive exploitation of resources leads to resource depletion, ultimately disrupting ecological balance, which was consistent with the results of Liu et al. (2020c). What's more, population growth may also lead to environmental pollution and ecosystem degradation, affecting biodiversity and ecological service functions. Wang et al. (2019) found that during the urban development process, a large amount of industrial and agricultural waste was generated, causing huge damage to the environment. Zhu and Li (2014) pointed out that many urbanization efforts were achieved at the cost of damaging the environment, such as removing lots of surface vegetation, which worsened the ecological health status. Our results were consistent with Zhang et al. (2019), who found that ecological deficit often existed in economically developed regions, such as the eastern regions of China. Cheng et al. (2022) also concluded that developed urban areas often had low security due to strong socio-economic pressure. Generally, the comprehensive ecological security of China's land resources showed a lower level in the northwest.

Dai and Khan (2022) thought that city was a unified spiral composite system of "socio-economic-environment", and how to effectively protect the ecological environment while achieving economic and social development is an important value of urban ecological security research. To improve the ecological environment, China has implemented a series of major measures. The 13th Five-Year Plan (2016–2020) have to some extent alleviated the pressure on urban resources and land, and promoted high-quality development of cities by adjusting the scale of cities according to resource and environmental carrying capacity, implementing green planning, design, and construction standards (Zhang et al. 2019). In this study, seven administrative regions reached a "Healthy" or higher ecological health grades in 2020, indicating that the combination of ecological and economic measures

Table 3 Obstacle degrees of top five indicators to urban ecological health

City	Year	Pressure		State									Response		
		P1	**P2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**R1**	**R2**	**R3**
DX	1980			9.80	11.49						12.06	11.55			9.21
	2000	10.99	8.93		9.62						11.26	11.26			
	2020	59.09						20.51					20.40		
PL	1980		18.64				14.55			13.41	12.61				12.41
	2000		14.19				10.27			11.31	10.84				8.14
	2020	40.79						22.66					22.92	13.63	
QY	1980		11.04		11.94	11.64	10.72				11.12				
	2000		10.48		11.47	11.19	10.11				10.87				
	2020	24.04						37.33					38.63		
TS	1980				11.86		9.01				11.87	10.26		12.02	
	2000		9.36		10.69						11.98	11.26		11.62	
	2020	32.87						25.05	19.46				22.62		
GY	1980				10.70	10.72				13.61				9.93	10.79
	2000			9.66						11.76	10.02	9.14			8.43
	2020	26.18						38.04					35.78		
BJ	1980		10.61								14.07	12.10		14.76	11.13
	2000		9.87								14.60	11.84		15.21	10.61
	2020	27.23						18.40	19.65				34.71		
TC	1980		15.40		11.20					12.47	16.94				15.85
	2000		17.12	11.30						10.70	18.38				15.39
	2020						16.66	16.65				16.58	17.06	16.48	
WN	1980		13.56		9.35		12.02				10.77				13.37
	2000	11.90	12.90		11.43		10.95								12.72
	2020	50.07						25.14					21.49		
XA	1980		10.71		11.24	11.25		13.38							12.20
	2000					9.90		12.75			10.91	10.69			11.23
	2020	20.75								15.27		29.46	24.17	10.35	
XY	1980		12.29		12.74					14.70				8.69	15.12
	2000		11.73	12.03	12.43						18.43				16.14
	2020	9.25				20.30	23.34	19.56					19.28		
YA	1980		9.86								12.58	11.47		13.87	10.84
	2000		11.70								13.98	13.00		14.65	10.57
	2020	36.36						31.76					31.86		

has significantly improved the urban ecological health of the WRB.

The impact of land use on ecological health

The impact of indicators closely related to land use/land cover conditions on ecosystem health also cannot be ignored, such as P2, S2, S3, S4, S5, S6, and R2. During the research period, the land use in the WRB has undergone significant changes. The area of forest land, grassland, and construction land in each administrative region showed an increasing trend, while the area of cultivated land decreased (Figs. 7 and 8). The growth of construction land area indicates that the WRB has undergone rapid urbanization and industrialization processes. With population growth and economic development, the demand for housing, infrastructure, and industrial land has increased, leading to the conversion of existing farmland into construction land. The area of water and unused land has increased and decreased. WN has the largest area of water and unused land, while TC has the smallest area of water and unused land. Among different administrative regions, YA has the largest reduction in farmland and the largest increase in forest and grassland areas. Compared to 1980, arable land has decreased by about 19.29%, while forest and grassland have increased by 9.79% and 7.22%. The construction land area in

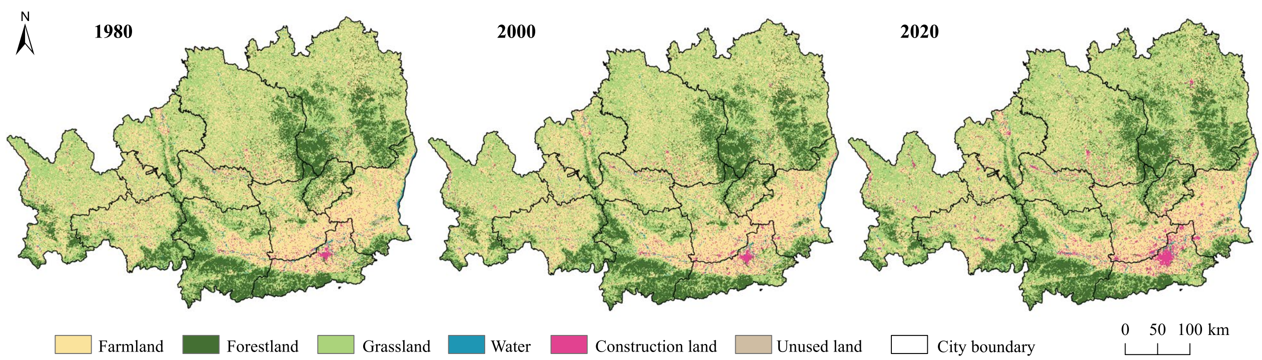

Fig. 7 The land use distribution of different administrative regions in the Wei River Basin in 1980, 2000, and 2020

WN, XA, and XY regions has increased the most significantly, with increases of 62.25%, 80.41%, and 83.16%, respectively. The development of the economy and the construction of infrastructure have promoted social reactions, while vegetation restoration has promoted the improvement of state modules. Compared with 1980 to 2000, the speed of land use change was faster from 2000 to 2020. This explains why in 2020, compared to 2000 and 1980, the degree of obstacles to urban ecological health in the state module decreased, while the degree of obstacles in the pressure and response module increased.

Administrative regions with a large proportion of agricultural land had poor ecological health status due to high population and land pressure. For example, XY, WN, and BJ located in the Guanzhong Plain area, were greatly affected by the P2 index. Cities that were greatly affected by state module often have characterized by dry climate and sparse vegetation, such as PL, QY, and TS in Gansu Province, TC and YA in Shaanxi Province. Most of these places are in the Loess Plateau region, with crisscrossing gullies, fragmented terrain, and severe soil erosion (Jiang et al. 2018). The natural conditions were initially at a relatively low level, resulting in weaker primary vegetation productivity and ecosystem service functions. Coupled with underdeveloped economy and the inappropriate land use planning and sustainable development measures, the state and response level for ecological health in these places was consequently constrained (Li et al. 2012). To protect the ecological environment and improve land quality, the Grain for Green Project was carried out first in Sichuan, Shaanxi, and Gansu provinces, and has been implemented nationwide since 2000 (Mu et al. 2007). However, since various vegetation restoration measures have only just begun, and the ecological environment was still at a poor level, resulting in poor performance of state assessment for ecological health in 2000. By 2020, the increase in vegetation coverage has improved the ecological environment and enhanced the resilience to pressure (Qiu et al. 2022). Therefore, after 2000, the obstacle degree of indicators in state module which restricted by land use types decreased, which led to the ascended levels of comprehensive urban ecological health.

In addition, the indicator of proximity to water bodies is an important factor affecting ecological health. Although the Wei River flows through these administrative regions, its distance from the water system varies, resulting in differences in the ecological health status of each administrative region. Firstly, water systems are an important source of water resources, and their proximity directly affects the availability and supply efficiency of water resources. Regions closer to the water system may have easier access to sufficient water resources, which is beneficial for maintaining regional ecological balance and supporting biodiversity. Secondly, water systems play an important role in regulating climate and maintaining hydrological balance. Regions closer to the water system may benefit from more stable climate conditions and better flood prevention and control capabilities. Thirdly, the health status of the water system directly affects the water quality in the surrounding areas. Areas closer to water systems need to pay more attention to water quality protection and pollution control to prevent pollutants from causing damage to water systems and ecosystems. Fourthly, water systems have a significant impact on the socio-economic development of surrounding areas, such as agricultural irrigation, industrial water use, and tourism development. Regions closer to the water system may have more advantages in economic development, but at the same time, it is necessary to balance development and ecological protection.

Suggestions for future urban development

Based on the comprehensive evaluation index system and obstacle diagnose, we identified the primary obstacle factors to ecological health. To provide theoretical

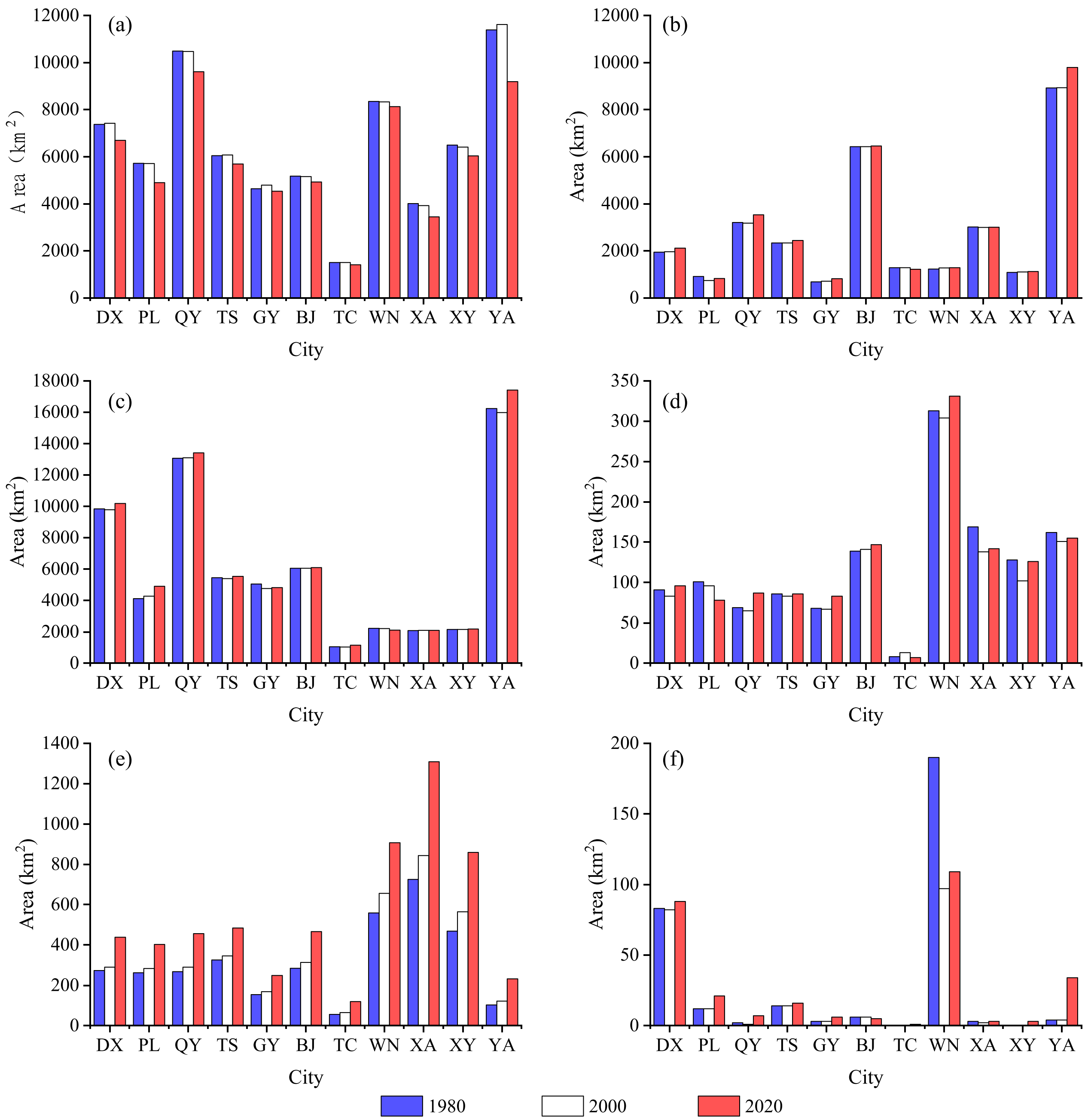

Fig. 8 Area changes of different land use types of various administrative regions in 1980, 2000, and 2020. **a**–**f** represent cultivated land, forest land, grassland, water area, construction land, and unused land, respectively

references for the realization of efficient, coordinated, and sustainable development of society-economy-ecology, we proposed corresponding improvement suggestions for cities dominated by different obstacle factors. Cities dominated by pressure often have the characteristics of high population density and frequent economic activities. Thus, to improve the level of ecological health, the number of populations should be controlled within a reasonable range, or be transferred to adjacent cities with less pressure designedly. This can alleviate high pressure while improving the response level of nearby cities with the development of economy (Cheng et al. 2022). For example, the establishment and development of Xixian New Area, a core area of the Guanzhong-Tianshui Economic Zone, has helped Xi'an's industries and population spread to Xianyang, optimizing industrial structure and urban functional zoning. For land pressure, it is essential to reasonably plan land resources and accelerate the construction of high standard farmlands.

Indicators of the state module were largely influenced by the vegetation coverage and the proportion of construction land. The state module dominated cities often characterized by adverse natural environment, leading to low carrying capacity and resilience, such as YA and GY. Therefore, the ecological restoration measures such as Grain for Green Project and afforestation should be implemented persistently and the quality of afforestation should be improved through reasonable allocation, and restoring some cultivated lands and overgrazed grasslands to forests and grasslands to improve soil and water conservation capabilities and increase biodiversity. After completing the restoration of existing farmland to forests, the government (county or township) shall organize the continued afforestation of barren mountains, deserts, and wasteland suitable for forests. In addition, the ecological environment in densely populated urban areas, such as XY and XA, can be effectively improved by increasing urban green spaces, optimizing urban planning, establishing a sound environmental monitoring network, and promoting green buildings.

Response is divided into natural response and social response. Improvement measures in terms of natural response can refer to that of state dominated cities, while social response is mainly reflected in economic development. Through breaking the boundaries of administrative divisions, promoting resource sharing and connectivity, exploring and improving benefit sharing and assistance mechanisms, promoting the "enclave economy", and achieving coordinated development between developed regions and surrounding regions are effective strategies to promote the capability of social response.

In addition to targeted improvements to ecological health under the leadership of different modules, the following measures also contribute to the restoration and improvement of ecological health. The soil and water conservation projects, such as constructing terraces, dams, sedimentation tanks, should be implemented continuously to reduce soil erosion and protect and improve water quality. The supervision of industrial emissions, agricultural fertilizer and pesticide use, urban sewage should be strengthened to reduce the impact of pollutants on the ecosystem. The sustainable agricultural models such as organic agriculture and ecological agriculture should be promoted to reduce the use of chemical fertilizers and pesticides, and improve the ecological friendliness of agricultural production. An ecological compensation mechanism should be established to provide economic compensation to areas or groups that provide ecological services, to encourage all parties to participate in ecological protection. In urban planning, the integrating green spaces should be taken into to promote green building standards and enhance the service function of urban ecosystems. Finally, policies and measures should be developed to address climate change, including reducing greenhouse gas emissions and enhancing the adaptability of ecosystems. Through these comprehensive measures, the ecological health can be effectively improved and maintained, and the goal of harmonious coexistence between humans and nature can be achieved.

Advantages and disadvantages of the research

In response to the special natural environment and socio-economic conditions of arid and semi-arid areas in the WRB, an ecological health evaluation index system was constructed to suit for the characteristics of the watershed from three dimensions: pressure, state, and response. This can provide scientific support for the ecological health evaluation and protection of the WRB and even the arid and semi-arid areas in northwest China. In the evaluation process, the ecological health was treated as a fuzzy issue. The assessment model established by fuzzy mathematics was more in line with the actual situation than the traditional assessment method and weaken the defects of subjective arbitrariness. Moreover, the results can help to see the distance between the final ecological health rating and its adjacent health levels, which will guide the future planning of watershed. In terms of evaluation indicators, we selected the most critical indicators for each module to structure the evaluation system for the sake of efficiency, simplicity, and comprehensiveness and obtained consistent evaluation results with similar studies. At the same time, the obstacle analysis method was used to quantify the direction and degree of the impact of various ecological environments and socioeconomic factors on the ecological health of the WRB at different time periods, which provided a new perspective for understanding and predicting changes of the ecological health in the WRB, and provided scientific basis and methodological support for formulating effective ecological restoration measures and promoting sustainable development strategies of the social economy.

Certainly, there are also some uncertainties in our research, mainly manifested in the following aspects. First, in the fuzzy mathematical evaluation model, the relative membership degree was sometimes very sensitive to the increase or decrease of the number of evaluated objects, which may affect the stability of the ranking results (Cheng et al. 2022). What's more, the WRB has a vast terrain, and there are significant differences in the topography and landforms of different sub-basins. Using a single evaluation system may not accurately reflect the actual ecological health status of the basin, and social and economic data are mostly based on administrative regions, making it difficult to expand to natural watersheds. In order to improve the accuracy and applicability of evaluation, future research should consider using more refined geographical units, such as using grid based methods or conducting ecological health assessments based on small watersheds, which can capture the spatial distribution differences of ecological health in more detail, thereby providing more accurate data support for ecological protection and management. This also provides a train of thought and method for ecological health assessment in other watersheds around the world.

Conclusions

Based on the PSR framework, this study constructed a comprehensive evaluation index system for ecological health, and used the fuzzy comprehensive assessment model to analyze the ecological health status of eleven administrative regions in the WRB in 1980, 2000 and 2020. Then, the obstacle model was applied to quantify the obstacle degrees of pressure, state, and response modules, as well as individual indicators on urban ecological health. The main conclusions are as follows:

(1) The comprehensive evaluation index system constructed based on the PSR framework could reflect the status of urban ecological health in the WRB. During the study period, the urban ecological health in the WRB went through a process of first deterioration and then improvement. The number of administrative regions in "Healthy" status decreased from six in 1980 to five in 2000. By 2020, the ecological health level of seven administrative regions has reached the "Healthy" or "Very healthy" levels.

(2) Obstacle analysis showed that state module of the PSR framework was the main obstacle to urban ecological health, and dominated in most of the selected administrative regions. Population pressure (P1), patch density of construction land (S5), comprehensive elasticity index (S8), soil erosion index (R1), and per capita GDP (R3) were the top five individual indicators affecting urban ecological health.

(3) The dominated obstacle modules or indicators for ecological health varied in different regions and periods. For economically developed cities, population pressure was often the main obstacle for urban ecological health, while in economically underdeveloped regions, the social response was the main obstacle. To improve the levels of urban ecological health, it is necessary to restore the natural ecological environment and control population size while accelerating economic construction.

Our findings could provide a scientific foundation for safeguarding ecological health in WRB and provide methodological references for subsequent related researches.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-024-00529-1.

Supplementary Material 1.

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The annual spatial interpolation dataset of meteorological elements and the multi-period land use remote sensing monitoring dataset in China used here are downloaded at http://www.resdc.cn/DOI.

Author contributions

CW and PG conceived the research. PG and XM supervised the research. CW and XF conducted the method learning. CW, JZ and RX conducted the data analysis. CW drafted and revised the manuscript. All authors contributed to the writing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used in the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

Bryan BA, Gao L, Ye Y, Sun X, Connor JD, Crossman ND, Stafford-Smith M, Wu J, He C, Yu D, Liu Z, Li A, Huang Q, Ren H, Deng X, Zheng H, Niu J, Han G, Hou X (2018) China's response to a national land-system sustainability emergency. Nature 559(7713):193–204. https://doi.org/10.1038/s41586-018-0280-2

Chen WX (2022) A multi-scale assessment of ecosystem health based on the Pressure-State-Response framework: a case in the Middle Reaches of the Yangtze River Urban Agglomerations, China. Environ Sci Pollut R 29(19):29202–29219. https://doi.org/10.1007/s11356-021-17768-w

Chen SY, Zhao YQ (1993) Fuzzy optimum selecting theory and model. Math Appl 1:1–6 (in Chinese)

Chen YM, Liu GB, Zheng FL, Zhang W (2004) Proceeding and application on soil erosion model of rusle. Res Soil Water Conserv 11(4):80–83 (in Chinese)
Chen C, Wang K, Feng M (2020) Research on China's industrial green development based on the pressure-state-response model. J Sci Ind Res 79(6):541–546
Cheng H, Zhu L, Meng J (2022) Fuzzy evaluation of the ecological security of land resources in mainland China based on the Pressure-State-Response framework. Sci Total Environ 804:150053. https://doi.org/10.1016/j.scitotenv.2021.150053
Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1998) The value of the world's ecosystem services and natural capital. Ecol Econ 25(1):3–15. https://doi.org/10.1016/s0921-8009(98)00020-2
Dai J, Khan YA (2022) Ecological environment pressure state and response system for coupling coordinate development: an application on China data. Environ Sci Pollut R 30(10):25682–25690. https://doi.org/10.1007/s11356-022-23900-1
Fan YP, Fang CL (2020) Evolution process and obstacle factors of ecological security in western China, a case study of Qinghai province. Ecol Indic 117:106659. https://doi.org/10.1016/j.ecolind.2020.106659
Florio BJ, Fawell PD, Small M (2019) The use of the perimeter-area method to calculate the fractal dimension of aggregates. Powder Technol 343:551–559. https://doi.org/10.1016/j.powtec.2018.11.030
Gai LT, Nunes JP, Baartman JEM, Zhang HM, Wang F, de Roo A, Ritsema CJ, Geissen V (2019) Assessing the impact of human interventions on floods and low flows in the Wei River Basin in China using the LISFLOOD model. Sci Total Environ 653:1077–1094. https://doi.org/10.1016/j.scitotenv.2018.10.379
Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu JG, Bai XM, Briggs JM (2008) Global change and the ecology of cities. Science 319(5864):756–760. https://doi.org/10.1126/science.1150195
Gu DL, Guo JH, Fan YR, Zuo QT, Yu L (2022) Evaluating water-energy-food system of Yellow River basin based on type-2 fuzzy sets and Pressure-State-Response model. Agr Water Manage 267:107607. https://doi.org/10.1016/j.agwat.2022.107607
Han X, Cao T (2021) Study on ecological environment quality evaluation of the energy consumption pollution treatment in industrial parks. Environ Sci Pollut R 28(22):28038–28057. https://doi.org/10.1007/s11356-020-10147-x
Hazbavi Z, Baartman JEM, Nunes JP, Keesstra SD, Sadeghi SH (2018) Changeability of reliability, resilience and vulnerability indicators with respect to drought patterns. Ecol Indic 87:196–208. https://doi.org/10.1016/j.ecolind.2017.12.054
Hazbavi Z, Sadeghi SH, Gholamalifard M, Davudirad AA (2019) Watershed health assessment using the pressure–state–response (PSR) framework. Land Degrad Dev 31(1):3–19. https://doi.org/10.1002/ldr.3420
Jahanmiri F, Parker DC (2022) An overview of fractal geometry applied to urban planning. Land 11(4):475. https://doi.org/10.3390/land11040475
Jakobsson S, Evju M, Framstad E, Imbert A, Lyngstad A (2021) Introducing the index-based ecological condition assessment framework (IBECA). Ecol Indic 124:107252. https://doi.org/10.1016/j.ecolind.2020.107252
Jia Z, Cai Y, Chen Y, Zeng W (2018) Regionalization of water environmental carrying capacity for supporting the sustainable water resources management and development in China. Resour Conserv Recy 134:282–293. https://doi.org/10.1016/j.resconrec.2018.03.030
Jia YQ, Tang LN, Xu M, Yang XY (2019) Landscape pattern indices for evaluating urban spatial morphology—a case study of Chinese cities. Ecol Indic 99:27–37. https://doi.org/10.1016/j.ecolind.2018.12.007
Jiang C, Zhang H, Zhang Z, Wang D (2018) Model-based assessment soil loss by wind and water erosion in China's Loess Plateau: dynamic change, conservation effectiveness, and strategies for sustainable restoration. Glob Planet Change 172:396–413. https://doi.org/10.1016/j.gloplacha.2018.11.002
Jiao LD, Wang L, Lu H, Fan YW, Zhang Y, Wu Y (2023) An assessment model for urban resilience based on the pressure-state-response framework and BP-GA neural network. Urban Clim 49:101543. https://doi.org/10.1016/j.uclim.2023.101543
Lai SH, Sha JM, Eladawy A, Li XM, Wang JL, Kurbanov E, Lin ZJ, Wu LB, Han R, Su YC (2022) Evaluation of ecological security and ecological maintenance based on pressure-state-response (PSR) model, case study: Fuzhou city, China. Hum Ecol Risk Assess 28(7):734–761. https://doi.org/10.1080/10807039.2022.2081835
Li W, Liu YJ, Yang Z (2012) Preliminary strategic environmental assessment of the Great Western Development Strategy: safeguarding ecological security for a new western China. Environ Manage 49(2):483–501. https://doi.org/10.1007/s00267-011-9794-1
Li YP, Nie S, Huang CZ, McBean EA, Fan YR (2017) An integrated risk analysis method for planning water resource systems to support sustainable development of an arid region. J Environ Inform 29(1):1–15. https://doi.org/10.3808/jei.201700359
Li YY, Yao SB, Deng YJ, Jia L, Hou MY, Gong ZW (2021) Spatio-temporal study on supply and demand matching of ecosystem water yield service: a case study of Wei River Basin. Pol J Environ Stud 30(2):1677–1693. https://doi.org/10.15244/pjoes/126711
Li P, Chen TC, Wei C, Dai XY, Wu YY (2022) Assessment and analysis of water environmental risk using pressure-state-response model in Ningbo, China. Sensor Mater 34(11):4071–4082. https://doi.org/10.18494/Sam4088
Liu DL, Hao SL (2016) Ecosystem health assessment at county-scale using the pressure-state-response framework on the Loess Plateau, China. Int J Env Res Pub He 14(1):2. https://doi.org/10.3390/ijerph14010002
Liu XP, Huang YH, Xu XC, Li XC, Li X, Ciais P, Lin PR, Gong K, Ziegler AD, Chen AP, Gong P, Chen J, Hu GH, Chen YM, Wang SJ, Wu QS, Huang KN, Estes L, Zeng ZZ (2020a) High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015. Nat Sustain 3(7):564–570. https://doi.org/10.1038/s41893-020-0521-x
Liu Y, Eckert CM, Earl C (2020b) A review of fuzzy AHP methods for decision-making with subjective judgements. Expert Syst Appl 161:113738. https://doi.org/10.1016/j.eswa.2020.113738
Liu QQ, Wang SJ, Li B, Zhang WZ (2020c) Dynamics, differences, influencing factors of eco-efficiency in China: a spatiotemporal perspective analysis. J Environ Manag 264:110442. https://doi.org/10.1016/j.jenvman.2020.110442
Ma XJ, Wang Y, Wang C (2017) Low-carbon development of China's thermal power industry based on an international comparison: review, analysis and forecast. Renew Sustain Energ Rev 80:942–970. https://doi.org/10.1016/j.rser.2017.05.102
Marques A, Martins IS, Kastner T, Plutzar C, Theurl MC, Eisenmenger N, Huijbregts MAJ, Wood R, Stadler K, Bruckner M, Canelas J, Hilbers JP, Tukker A, Erb K, Pereira HM (2019) Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. Nat Ecol Evol 3(4):628–637. https://doi.org/10.1038/s41559-019-0824-3
Mu XM, Zhang L, McVicar TR, Chille B, Gao P (2007) Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. Hydrol Process 21(16):2124–2134. https://doi.org/10.1002/hyp.6391
Ogden LA, Aoki C, Grove JM, Sonti NF, Hall W, Locke D, Pickett STA, Avins M, Lautar K, Lagrosa J (2019) Forest ethnography: an approach to study the environmental history and political ecology of urban forests. Urban Ecosyst 22(1):49–63. https://doi.org/10.1007/s11252-018-0744-z
Ouyang ZY, Wang XK, Miao H (2000) China's eco-environmental sensitivity and its spatial heterogeneity. Acta Ecol Sin 20(1):9–12 (in Chinese)
Peng J, Liu YX, Wu JS, Lv HL, Hu XX (2015) Linking ecosystem services and landscape patterns to assess urban ecosystem health: a case study in Shenzhen City, China. Landscape Urban Plan 143:56–68. https://doi.org/10.1016/j.landurbplan.2015.06.007
Qiu DX, Xu RR, Wu CX, Mu XM, Zhao GJ, Gao P (2022) Vegetation restoration improves soil hydrological properties by regulating soil physicochemical properties in the Loess Plateau, China. J Hydrol 609:127730. https://doi.org/10.1016/j.jhydrol.2022.127730
Rapport DJ, Böhm G, Buckingham D, Cairns J, Costanza R, Karr JR (1999) Ecosystem health: the concept, the ISEH, and the important tasks ahead. Ecosyst Health 5(2):82–90. https://doi.org/10.1046/j.1526-0992.1999.09913.x
Ren LL, Shen HR, Yuan F, Zhao CX, Yang XL, Zheng PL (2016) Hydrological drought characteristics in the Weihe catchment in a changing environment. Adv Water Sci 27(4):492–500 (in Chinese)
Shamseldin AY, Jacquin AP (2009) Review of the application of fuzzy inference systems in river flow forecasting. J Hydroinform 11(3–4):202–210. https://doi.org/10.2166/hydro.2009.038

Song JX, Cheng DD, Li Q, He XJ, Long YQ, Zhang B (2015) An evaluation of river health for the Weihe River in Shaanxi Province, China. Adv Meteorol 2015:476020. https://doi.org/10.1155/2015/476020
Sun SW, Zhou SQ, Shi JH, Lin N, Xue GY, Lai AW, Li HL (2010) Calculation and comparison of vegetation net primary productivity (NPP) in Zhejiang Province with three models. Chin J Agrometeorol 31(2):271–276 (in Chinese)
Sun TT, Lin WP, Chen GS, Guo PP, Zeng Y (2016) Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. Sci Total Environ 566–567:627–640. https://doi.org/10.1016/j.scitotenv.2016.05.028
Sun JF, Yu Y, Wang WL, Zhu XP, Ma XH, Sun XL (2022) The PSR-FA-NAR model for assessing and forecasting environmental impacts: an empirical analysis of Changning-Weiyuan shale gas play in China. Front Env Sci 10:965728. https://doi.org/10.3389/fenvs.2022.965728
Tang DH, Zou XQ, Liu XJ, Liu PT, Zhamangulova N, Xu XWH, Zhao YF (2015) Integrated ecosystem health assessment based on eco-exergy theory: a case study of the Jiangsu coastal area. Ecol Indic 48:107–119. https://doi.org/10.1016/j.ecolind.2014.07.027
Vargas L, Willemen L, Hein L (2019) Assessing the capacity of ecosystems to supply ecosystem services using remote sensing and an ecosystem accounting approach. Environ Manage 63(1):1–15. https://doi.org/10.1007/s00267-018-1110-x
Walz R (2000) Development of environmental indicator systems: experiences from Germany. Environ Manage 25(6):613–623
Wang SJ, Fang CL, Guan XL, Pang B, Ma HT (2014) Urbanisation, energy consumption, and carbon dioxide emissions in China: a panel data analysis of China's provinces. Appl Energ 136:738–749. https://doi.org/10.1016/j.apenergy.2014.09.059
Wang Y, Duan FM, Ma XJ, He LC (2019) Carbon emissions efficiency in China: key facts from regional and industrial sector. J Clean Prod 206:850–869. https://doi.org/10.1016/j.jclepro.2018.09.185
Wang YT, Wang YS, Wu ML, Sun CC, Gu JD (2021) Assessing ecological health of mangrove ecosystems along South China Coast by the pressure-state-response (PSR) model. Ecotoxicology 30(4):622–631. https://doi.org/10.1007/s10646-021-02399-1
Wilkerson ML, Mitchell MGE, Shanahan D, Wilson KA, Ives CD, Lovelock CE, Rhodes JR (2018) The role of socio-economic factors in planning and managing urban ecosystem services. Ecosyst Serv 31:102–110. https://doi.org/10.1016/j.ecoser.2018.02.017
Wu CX, Weng XX, Xu RR, Gao P, Mu XM, Zhao GJ (2023) Changes in soil conservation function before and after the Grain for Green project in the Weihe River Basin. Sci Soil Water Conserv. https://doi.org/10.1449/S.20231130.1521.004 (in Chinese)
Xie GD, Zhen L, Lu CX, Xiao Y, Chen C (2008) Expert knowledge based on valuation method of ecosystem services in China. J Nat Resour 23(5):911–919 (in Chinese)
Xu Y, Yang F, Yan CZ (2020) Ecological health assessment of urban wetland in Xiong'an based on landscape pattern. Acta Ecol Sin 40(20):7132–7142 (in Chinese)
Yang T, Zhang Q, Wan X, Li X, Wang Y, Wang W (2020) Comprehensive ecological risk assessment for semi-arid basin based on conceptual model of risk response and improved TOPSIS model: a case study of Wei River Basin, China. Sci Total Environ 719:137502. https://doi.org/10.1016/j.scitotenv.2020.137502
Yao CS, Teng Y, Huang L (2015) Evaluation index system construction and empirical analysis on food security in China. Trans Chin Soc Agric Eng 31(4):1–10 (in Chinese)
Yu WJ, Ren T, Zhou WQ, Li WF (2020) Forest fragmentation and its relationship with urban expansion in Guangdong-Hong Kong-Macao Great Bay Area, China. Acta Ecol Sin 40(23):8474–8481 (in Chinese)
Zahabi M, Kaber D (2019) A fuzzy system hazard analysis approach for human-in-the-loop systems. Safety Sci 120:922–931. https://doi.org/10.1016/j.ssci.2019.08.029
Zhang F, Wang Y, Ma XJ, Wang Y, Yang GC, Zhu L (2019) Evaluation of resources and environmental carrying capacity of 36 large cities in China based on a support-pressure coupling mechanism. Sci Total Environ 688:838–854. https://doi.org/10.1016/j.scitotenv.2019.06.247
Zhang YY, Yang YJ, Chen ZX, Zhang SL (2020) Multi-criteria assessment of the resilience of ecological function areas in China with a focus on ecological restoration. Ecol Indic 119:106862. https://doi.org/10.1016/j.ecolind.2020.106862
Zhang HW, Dong YB, Xu DQ (2021) Accelerating exact nearest neighbor searchin high dimensional Euclidean space viablock vectors. Int J Intell Syst 37(2):1053–1802
Zhang YW, Zhang B, Ma B, Yao RP, Wang LB (2022) Evaluation of the water conservation capacity of the Weihe River Basin based on the Integrated Valuation of Ecosystem Services and Tradeoffs model. Ecohydrology 15(8):e2465. https://doi.org/10.1002/eco.2465
Zhao HH, Li PY, He XD, Ning J (2022) Microplastics pollution and risk assessment in selected surface waters of the Wei River Plain China. Expos Health 15:745–755. https://doi.org/10.1007/s12403-022-00522-z
Zhu C, Li Y (2014) Long-term hydrological impacts of land use/land cover change from 1984 to 2010 in the Little River Watershed, Tennessee. Int Soil Water Conserv 2(2):11–21. https://doi.org/10.1016/S2095-6339(15)30002-2

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