Dynamic Assessment and Sustainability Strategies of Ecological Security in the Irtysh River Basin of Xinjiang, China

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Abstract: The drylands of China are extensive, and they are home to more than one-third of the country's population. However, the watershed territories of the drylands, where the majority of human activities are concentrated have long experienced strained human-land relationships, culminating in ecological security concerns. Correspondingly, it is essential to carry out a comprehensive assessment of the ecological security of dryland watersheds and to identify the key factors influencing ecological security in order to formulate strategies that ensure the sustainability of drylands. Premised on the Driving-Pressure-State-Impact-Response (DPSIR) model, this study developed an ecological security index and applied it to the Irtysh River Basin of Xinjiang, China, from 2000 to 2020. The obstacle degree model was applied to reveal the obstacles in two dimensions: criterion level and indicator level. The findings suggested that the ecological security comprehensive index in the Irtysh River Basin has increased significantly from 2000 to 2020, irrespective of the fact that it decreased during the study period and then increased. The ecological security level changed from 'critically safe' in 2000 to 'general safety' in 2020, with the state subsystem and pressure subsystem becoming ecological security weaknesses. The primary factors influencing the ecological security of the study area were water consumption, the area of high-efficiency water-saving irrigation, the proportion of wetland area, vegetation coverage, and livestock population. The ecological security of different counties in the basin varies greatly, whereas the factors that influence ecological security showed both similarities and differences among the counties. In light of on the findings, we proposed that future strategies for ecological security enhancement should concentrate on enacting the policy of localizing spatial differentiation, optimizing industrial structure, strengthening scientific and technological support in the field of water conservation, bolstering the treatment capacity of environmental facilities, and implementing the Mountains-Rivers-Forests-Farmlands-Lakes-Grasslands System to support the sustainable development of dryland watersheds.

Keywords: ecological security; obstacle factors; Driving-Pressure-State-Impact-Response (DPSIR) model; drylands; watershed; Irtysh River Basin

1 Introduction

Drylands cover approximately 41% of the earth's land area and support more than 38% of the world's population (Reynolds et al., 2007); China has 6.6 million km^2 of drylands that are home to approximately 580 million

people. Under the influence of both climate change and human activities, global ecological and environmental problems are becoming increasingly serious (Roy, 2016; Tu et al., 2019; Huang et al., 2020). These problems are particularly pronounced in dryland watersheds, in which human activities are concentrated. The ecological environments of dryland watersheds are fragile and can be described as water resource-based socio-ecological systems (Bestelmeyer et al., 2015). Scholars have conducted extensive studies globally, and examples of typical dryland watersheds include the Karnataka in India (Singh, 1991), the Hirmi watershed in Ethiopia (Gebrelibanos and Assen, 2015), the rural dryland watershed in central Chile (Valenzuela et al., 2009), the Rio del Carmen watershed (Porras et al., 2019). While the exploitation of limited water resources in dryland watersheds brings obvious economic and social benefits to humans, it also brings serious ecological and environmental problems that threaten sustainable development, including water ecosystem degradation, desertification, soil erosion, grassland degradation, and water environment pollution (Borrelli et al., 2017; Li et al., 2021a; Wei et al., 2022). In recent years, the Chinese government has paid great attention to the ecological security of the northwestern drylands watersheds and implemented initiatives such as grass-storage balance, expansion of nature reserves, and the Mountains-Rivers-Forests-Farmlands-Lakes-Grasslands System (MRFFLGs) to improve local ecological security (You et al., 2017; Gao et al., 2020; Liu et al., 2021). However, watershed ecological security is more of an integrated issue centered on the relationship between humans and the land. Thus, we need to understand the changes in each natural element while also considering economic and social factors (Fu, 2021). Therefore, it is important to combine natural and socioeconomic elements, while considering pressure, state, and response, to comprehensively assess the ecological security of drylands, which is the scientific basis for formulating regional long-term sustainable development strategies.

Regional ecological security entails that the ecological environment can satisfy the survival and development needs of human and biological communities while preventing damage to its own ecosystem service functions and structures, thereby ensuring that the 'social-ecological system' of the region remains in a sustainable state of development (Bi et al., 2020). Under the guidance of initiatives such as the United Nations Millennium Development Goals and the 2030 Sustainable Development Goals, ecological security has long been a research focal point in China and abroad. Research on ecological security has mainly focused on ecological landscape security patterns, regional ecological risks, ecosystem health diagnosis, ecological security evaluation and monitoring, and ecological security management (Li et al., 2019; Liu et al., 2022). Research has been conducted at diverse spatial scales, including the macroscale (e.g., global, continental, and national), the mesoscale (e.g., watersheds, regions, and provinces), and the microscale (e.g., lakes, biomes, and villages). Current research on watershed ecological security focuses on specific ecological concerns, such as water environment pollution, grassland degradation, soil erosion, ecological destruction of mining landscapes and biodiversity degradation (Paukert et al., 2011; Ding et al., 2015; Qiu et al., 2022; Wang et al., 2022a). Urbanization, industrialization, population growth, agricultural development, and land use have been utilized as external drivers in causal analyses (Shen et al., 2017; Wang and Pan, 2019; Doeffinger and Hall, 2021). On the other hand, according to some scholars consider human activities to have become an essential component of ecological security (Shao et al., 2014; Fan et al., 2020). Existing studies, however, lack quantitative evaluations that simultaneously consider the normal functioning of ecosystems and the sustainable development of human societies for the aforementioned issues. Fortunately, there has been a shift from single-factor to multi-factor comprehensive evaluation approaches for appraising ecological security. Specific methods for assessing ecological security include the ecological footprint model, Pressure-State-Response (PSR) model, Driving-State-Response (DSR) model, and Driving-Pressure-State-Impact-Response (DPSIR) model (Cano-Orellana and Delgado-Cabeza, 2015; Kagalou et al., 2012; Loiseau et al., 2012; Zhao et al., 2021a).

Existing studies have made significant progress in the field, however, there remain several outstanding questions. First, existing studies on watershed ecological security focus primarily on single-factor issues such as land use, ecological health level, and environmental pollution; few studies have assessed ecological security in these regions comprehensively. Second, an in-depth research is also required to strengthen the integrated as-

sessment of dynamic processes and spatial differences that make it challenging to identify the key regional issues and primary driving factors affecting ecological security through the coupling of geographical patterns and processes. In this study, using a typical dryland watershed (the Irtysh River Basin) as an example, we developed a comprehensive index of ecological security based on the DPSIR model from a system theory perspective. Whereupon, we assessed the spatial and temporal dynamics of regional ecological security, conducted a coupling analysis of patterns and processes, and identified the driving forces and factors influencing ecological security at various stages. The results can be applied to guide the development of ecological management strategies for dryland watersheds and offer a scientific basis for making ecological management decisions.

2   Materials and Methods

2.1   Study area

The Irtysh River Basin originates in the northern Xinjiang, a typical arid region. In China, all the administrative divisions of the Irtysh River Basin are located in the Altay Region of Xinjiang; thus, the Irtysh River Basin in this study refers specifically to the Altay Region. The total area of the Irtysh River Basin is 118 000 km^2 (approximately 7.14% of the total area of Xinjiang), and the basin includes six counties, one city (Fig. 1). In 2020, the GDP of the study region reached 33.453 bil-

lion yuan (RMB), with a population of 657 000 and an urbanization rate of 38.97%. The basin is an important water source and strategic reserve of water resources in the northern Xinjiang. Thus, this watershed is key to maintaining the water tower of the northern border and the 'river of life' of Xinjiang (Fu, 2021). The basin is also one of the 25 important ecological function areas in China. Since the early 1960s, population growth, the rapid development of agriculture and industry, and the demand for water from the southern border have resulted in conflict between socioeconomic development and ecological protection, leading to problems such as reduced ecological water use, soil erosion, forest aging and degradation, damage to the mining ecosystem, water environment pollution, and grassland degradation (Liu et al., 2021).

2.2   Research method
2.2.1   *Evaluation index based on the DPSIR model*
Ecological security contains many economic, social, and ecological elements. Therefore, the evaluation of ecological security requires an evaluation index that considers both human activities and natural ecology. The PSR model proposed by the United Nations Economic Cooperation and Development Program (OECD, 1993) uses ecological and environmental problems as variables to explore the changes in the health status (S) of an ecosystem under the influence of pressure (P) caused by human activities. Several measures have been taken to eliminate risks to ecosystems and improve ecosystem
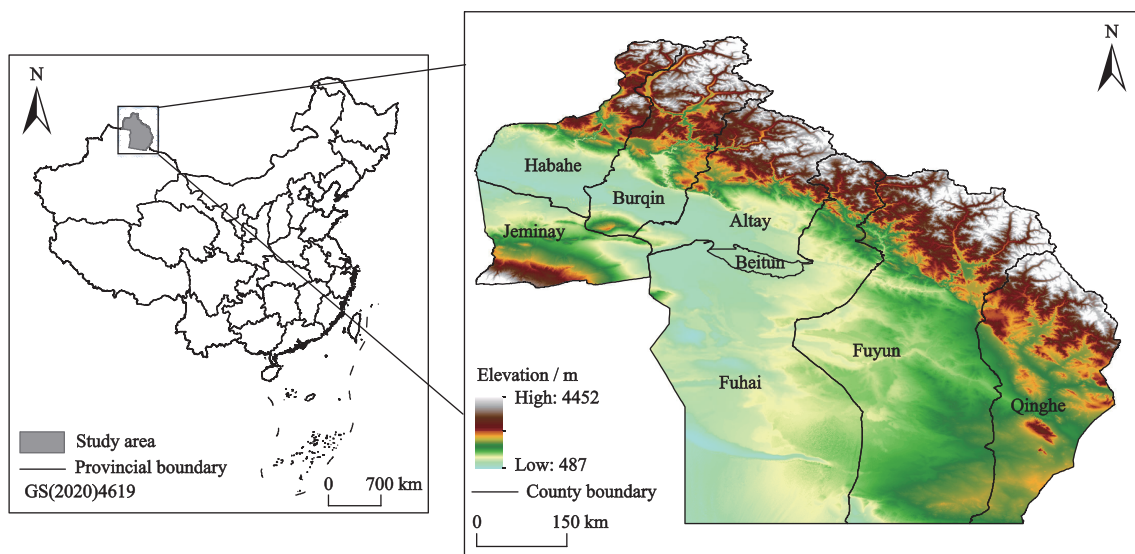

Fig. 1   The location of the Irtysh River Basin of Xinjiang, China

health in response (R) to changes in that state (Tscherning et al., 2012). To further address resource and environmental management, the DPSIR model was proposed by the European Environment Agency based on the PSR and DSR models (Cao et al., 2020; Agramont et al., 2022). The DPSIR model, which considers the economic, social, ecological environment, and policy elements, emphasizes the causal relationship between elements and has been widely used in fields such as sustainable development and ecological and environmental management (Wang et al., 2015; Kharrazi et al., 2017; Wei et al., 2019).

From the perspective of systems theory and in consideration of the actual regional development in the Irtysh River Basin, we applied DPSIR as the basic framework to study ecological security and analyze the issues related to ecological security in this arid basin. The DPSIR model of the watershed ecosystem security system is an orderly and sustainable operation and complex open-loop system emphasizing the symbiotic relationship between human activities and ecosystems (Kharrazi et al., 2017; Zhao et al., 2021b). Under the principle of circular cumulative causality, the development of human activities serves as a 'driving' (D) subsystem that affects the ecological security of the watershed (Lu et al., 2022). The development of this subsystem will increase the demand on the basin resources and environment. The careless economic development of the basin will increase pollutant emissions and overload the environmental capacity, generating 'pressure' (P) on water resources, creating water pollution, harming the carrying capacity of the basin; in turn, these changes will affect the health status (S) of the human socioeconomic and ecological system (Gomez et al., 2017). These effects include changes in air quality, soil erosion, and ve-

getation cover. Changes in the structure and state of ecosystem and human society resulting from conflict between them will lead to changes in the ecological security and sustainability of the watershed, which can affect the quality and function of the ecosystem along with social well-being (I) (Elliott et al., 2017). In order to reduce the negative impacts and promote the socioeconomic activities of the watershed and the ecosystem, stakeholders in the watershed should respond (R) with positive actions (e.g., enhancing ecological investment and raising the environmental awareness of residents) to preserve ecosystem security and ensure sustainable development in the watershed (Baldwin et al., 2016; Zhao et al., 2021b). This responsive subsystem will have a circular feedback effect on the 'driving, pressures, states and impacts' subsystem, which in turn will have a virtuous cycle on the overall watershed ecosystem security through the reconstruction and integration of its own internal elemental system (Fig. 2).

In this study, combined with the regional actual situation and the availability of data, we taken the Irtysh River Basin as an example to construct an evaluation index for ecological security in drylands. The index includes five subsystems and 25 indicators (Table 1).

2.2.2 TOPSIS model

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) model was used to measure the ecological security comprehensive index (ESCI) of the Irtysh River Basin from 2000 to 2020. The TOPSIS model was proposed by Hwang and Yoon in 1981 (Hwang and Yoon, 1981), and has been widely used in multi-factor evaluation and decision making because it has the advantages of being realistic, intuitive and reliable without strict restrictions on data distribution, sample size and number of indicators (Behzadian et al.,
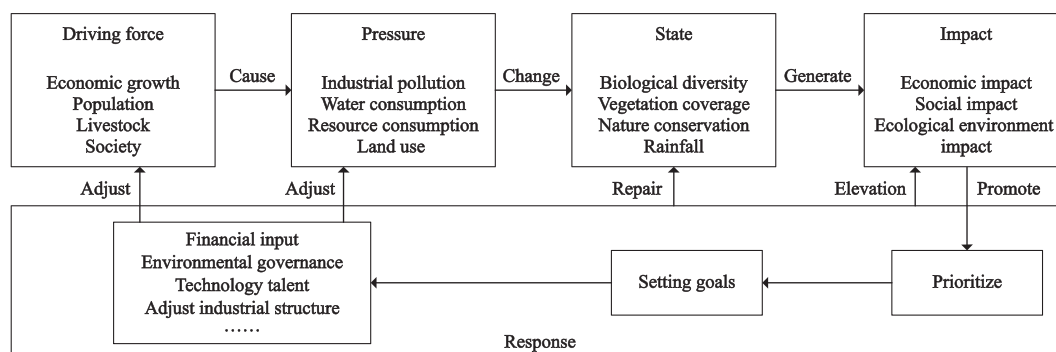

Fig. 2   The Driving-Pressure-State-Impact-Response (DPSIR) model for the dryland watersheds

Table 1   Index for the evaluation of ecological security in the Irtysh River Basin of Xinjiang

Subsystem	Factor		Meaning	Attribute
Driving (D)	D1	GDP growth rate / %	Potential for local economic growth	Positive
	D2	Natural population growth rate / %	Support or stress of population growth on watershed ecosystem maintenance	Negative
	D3	Urbanization rate / %	Impact of urbanization process on ecosystem	Positive
	D4	Population density / (people/km^2)	Resident population density, characterizing the distribution of sub-populations	Negative
	D5	Agriculture / billions yuan (RMB)	Scale of agricultural production	Positive
	D6	Livestock population / 10^4	The impact of agriculture and livestock on the ecological environment	Negative
Pressure (P)	P1	Electricity consumption / (kWh/10^4 yuan (RMB))	Pressure on resource consumption from regional economic development	Negative
	P2	Water consumption / (m^3/10^4 yuan (RMB))	Pressure on water resources from regional economic development	Negative
	P3	Tourism density / (person-time/km^2)	The combined pressure of tourism activities on local environmental capacity	Negative
	P4	Pesticide application / (kg/ha)	Pressure of agricultural production on the quality and security of land and water resources in the watershed	Negative
	P5	Fertilizer application / (kg/ha)	Pressure of agricultural production on the quality and security of land and water resources in the watershed	Negative
Status (S)	S1	Vegetation coverage / %	Terrestrial ecological status	Positive
	S2	Landscape diversity index	Richness of the landscape	Positive
	S3	Arable land / ha	Arable land occupied by construction land and abandoned condition	Positive
	S4	Average annual precipitation / mm	Regional water supply Status	Positive
	S5	Wetland area percentage / %	Water ecology Status	Positive
	S6	Industrial wastewater emissions	Water pollution status	Negative
Impact (I)	I1	Per capita disposable income of farmers / yuan (RMB)	Regional living standards, earnings	Positive
	I2	Urban unemployment registration rate / %	Employment, economic forms	Negative
	I3	GDP per capita / yuan	Affluence	Positive
	I4	Proportion of tertiary industry output / %	Regional industrial structure status	Positive
	I5	Grain yield per unit of arable land area / (kg/ha)	Arable land production capacity, representing the ability to guarantee food supply and the degree of food quantity security	Positive
Response (R)	R1	Efficient water-saving irrigation area / ha	Conserve water and improve water use efficiency	Positive
	R2	Percentage of fiscal expenditure on ecological and environmental management / %	Regional policy response, reflecting regional capacity to invest in ecological security and the degree of importance attached to it	Positive
	R3	Proportion of primary industry output / %	Industrial restructuring	Positive

2012). Firstly, the method finds out the 'optimal solution' and 'worst solution' of each index, and then calculates the distance between each index and the 'optimal solution' and 'worst solution'. Thirdly, the distance between the 'optimal solution' and 'worst solution' is calculated according to the 'optimal solution' and 'worst solution'. Finally, each solution is evaluated according to its distance from the positive and negative ideal solutions, and is considered optimal if it is close to the positive ideal solution and far from the negative ideal solution, and is considered the worst if it is far from the positive ideal solution and close to the negative ideal solution (Kim et al., 2013; Gu et al., 2021). The specific calculation steps refer to the study of Guo et al. (2021).

The calculated of the results, the closeness Z_c, takes a range of [0,1], the larger its value, the safer the ecosystem in the study area, and vice versa, the more deteriorated it is. There is no unified standard for basin ecological security evaluation grading, and the Z_c value is divided into five grades by combining the existing studies (Guo et al., 2021; Zhao et al., 2021b; Wang et al., 2022b) and the ecological security status of Irtysh River Basin (Table 2).

2.2.3 Obstacle degree model

As an important method to diagnose regional ecological security, obstacle model has been applied in many fields (Ou et al., 2017; Zhang et al., 2019). By measuring the obstacle degrees of subsystem-level and factor-level indicators (Fan and Fang, 2020; Wang et al., 2021a), this model can reveal the main barriers impeding ecological

Table 2 Criteria for the evaluation of ecological security in the Irtysh River Basin of Xinjiang

Ecological security level	Grading criteria	Ecological security status	Characteristics
I	[0, 0.20)	Unsafe	Economic and social development greatly exceed the carrying capacity of the ecosystem; the structure of the ecosystem is extremely irrational; the ecological function is seriously degraded; the resistance to interference is extremely poor; ecological restoration is very difficult; and the ecological security is seriously threatened
II	[0.20, 0.35)	Critical safety	Socioeconomic development largely exceeds the carrying capacity of the ecosystem; the structure of the ecosystem is very irrational; the ecological function is degraded; the resistance to disturbance is poor; and ecological restoration is difficult
III	[0.35, 0.50)	General safety	Socioeconomic development is close to the carrying capacity of the ecosystem; the structure of the ecosystem is not irrational, but ecological function is damaged to a certain extent; the ecosystem can maintain its basic operation and resist partial disturbance; and ecosystem recovery is not difficult
IV	[0.50, 0.70)	Comparative safety	Socioeconomic development is lower than the carrying capacity of the ecosystem; the structure of the ecosystem is reasonable; the ecological function is not degraded; the ecosystem has strong recovery ability and anti-disturbance ability
V	[0.70, 1]	Highly safe	Socioeconomic development is far below the carrying capacity of the ecosystem; the structure of the ecosystem is reasonable; the ecological function has not been degraded; the ecosystem is resistant to disturbance and does not require ecological restoration and reconstruction

security in the Irtysh River Basin.

$$N_{ij} = \frac{W_j \times V_{ij}}{\sum\limits_{i=1}^{m} \left(W_j \times V_{ij} \right)} \tag{1}$$

$$M_D = \sum_{j=1}^{6} N_{ij}; \; M_P = \sum_{j=7}^{11} N_{ij}; \; M_S = \sum_{j=12}^{17} N_{ij};$$

$$M_I = \sum_{j=18}^{22} N_{ij}; \; M_R = \sum_{j=23}^{25} N_{ij} \tag{2}$$

where i = 1, 2, ..., m, i is the criterion layer; j = 1, 2, ..., n, j is the indicator; W_j represents the contribution of the j-th index to the target; V_{ij} is the indicator deviation degree; N_{ij} is the indicator-level barrier degree; M_{ij} is the barrier degree of each subsystem; D, P, S, I and R are the drive, pressure, state, impact, and response; and M_D, M_P, M_S, M_I and M_R are the drive, pressure, state, impact, and response subsystem obstacle degrees, respectively.

2.3 Data sources and processing

The remote sensing images and land use data for vegetation cover were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). The digital elevation model data, administrative divisions, and other basic information were obtained from the National Basic Geographic Information Center (http://www.ngcc.cn). The annual precipitation data were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac. cn). Socioeconomic data were mainly obtained from the Xinjiang Statistical Yearbook (Bureau of Statistics of Xinjiang, 2001–2021), the Statistical Yearbook of Altay Region (2008–2019) (provided by local government in field research), the Statistical Bulletin of National Economic and Social Development of Altay Region and its Counties (Cities) (2003–2021) (http://www.xjalt.gov.cn/sjalt/020005/list.html), websites of official government entities such as the People's Government of Altay Region and its Counties (Cities) and the Bureau of Agriculture and Rural Affairs, and field research. It is worth noting that the urbanization rate and per capita income of farmers and herdsmen in each county (city) of the Altay Region in 2020 are missing; and these data were instead of 2019 data.

3 Results

3.1 Overall ecological security dynamics and obstacle indicators of the basin
3.1.1 Change in ESCI
The ESCI of the Irtysh River Basin increased from 0.24 in 2000 to 0.54 in 2020 by a significant margin. During this time period, ESCI has experienced a trend of decreasing and then increasing. The ESCI trend can be divided into four stages (Fig. 3): 1) deterioration from 2000 to 2005, when the ESCI declined to its lowest value (0.18) in 2005 and the ecological security level transitioned from critical safety to unsafe; 2) slow recovery from 2006 to 2010, when ESCI gradually in-
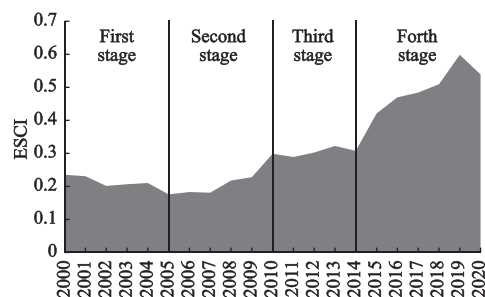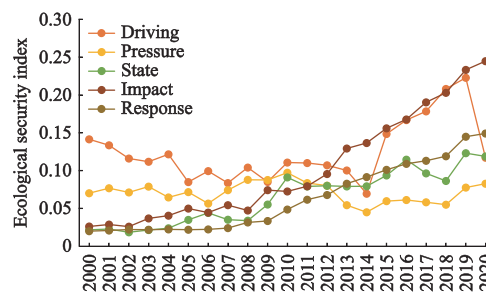
Fig. 3 The ecological security comprehensive index (ESCI) of the Irtysh River Basin of Xinjiang from 2000–2020

Fig. 4 Changes in the ecological security indices in different subsystems of the Irtysh River Basin of Xinjiang from 2000 to 2020

creased, reaching 0.30 in 2010, and the ecological security level changed from unsafe to critical safety; 3) from 2011 to 2014, the ESCI remained relatively stable, and the ecological security level at critical safety, indicating that the once an ecosystem is damaged, it is less resistant to disturbance and may entail more time to recover; and 4) from 2015 to 2020, the ESCI experienced a sharp rise. Even though the ESCI of the basin was lower in 2020 than in 2019 due to the impact of the COVID-19 pandemic, the ESCI in 2020 was still higher than in 2018. The ecological security level has been upgraded from critical safety to comparative safety.

3.1.2 Characteristics of changes in each subsystem

From 2000 to 2020, the ecological security indices of the various subsystems in the Irtysh River Basin ranged from 0.02 to 0.24. Prior to 2010, the indices of the driving and pressure subsystems were generally greater than those of the other subsystems. After 2010, the following indices declined in the following order: impact subsystem > driving subsystem > response subsystem > state subsystem > pressure subsystem (Fig. 4). Affected by the natural environment, geographical environment, social environment, and other objective factors in the early period, the economic base was weak, the development of economic and social undertakings was sluggish, the production and living conditions in agricultural and pastoral areas were poor, and the incidence of poverty situation was relatively severe. The Altai Region has leveraged the western development strategy to achieve new breakthroughs in water conservancy, transportation, energy and other infrastructures, in order to accelerate economic development and improve the living standards of farmers and herdsmen. Its comprehensive economic strength has been substantially enhanced, and its urbanization rate and natural population growth rate have been significantly accelerated, resulting in the highest driving force subsystem index, which has a ma-

jor impact on the ESCI. There is a tendency for ecological subsystems to deteriorate with the increase of human disturbance to natural ecosystem. To rectify the situation, it relies on abundant tourism resources and distinct environmental advantages, vigorously developing tourism, promoting new industrialization, guiding the majority of farmers and herdsmen to create employment through tourism participation, and optimizing the living conditions of residents. The index of the influence subsystem fluctuates and rises, whereas the population density, urbanization rate, and natural growth rate of the Altay Region exhibit a decreasing trend, resulting in a fluctuating decreasing trend of the index of the driving force subsystem, which is lower than the index of the influence subsystem.

The driving subsystem index ranged between 0.07 and 0.22, indicating the slow socio-economic growth of the Irtysh River Basin. The driving subsystem index declined from 0.14 in 2000 to its lowest value (0.07) in 2014, jumped sharply to 0.15 in 2015, increased marginally to reach its highest value (0.22) in 2019, and then fell to 0.12 in 2020. The index of the pressure system increased only slightly from 0.07 in 2000 to 0.08 in 2020. The pressure index fluctuated between 2000 and 2020, reaching its maximum value (0.10) in 2010 and its minimum value (0.04) in 2014, before rising again after 2015. During the study period, the index of the state subsystem increased from 0.02 to 0.12, indicating that the ecological condition of the Irtysh River Basin improved somewhat. Nevertheless, the state subsystem is still generally deficient, and ecological and environmental protection remains crucial. From 2000 to 2008, the index of the state subsystem remained relatively stable (between 0.02 and 0.04), and from 2009 to 2020, it increased steadily. During the study period, the index of the impact subsystem increased from 0.03 to 0.24

during the study period, indicating that ecological environmental protection in the Irtysh River Basin has fostered its economic and social development, and that the degree of impact has grown over time. In terms of ecological environmental protection and restoration, policies have been enacted such as the 'National Economic and Social Development', 'Ecological Environmental Protection Plan', 'Forestry Development Plan' and other plans which have been released every five years to promote ecological protection and restoration. In addition, policies have been formulated to preserve regional grassland ecology, protect grassland resources, realize grazing rest of the grassland and ecological animal husbandry. Regarding the sustainable use of water resources, the river (lake) leader system and the most stringent water resources management system have been strictly implemented strictly. The index of the impact subsystem increased gradually from 2000 to 2010, but accelerated significantly after 2011. The index of the response subsystem followed a similar trend to that of the impact subsystem. From 2000 to 2020, the response subsystem index increased from 0.02 to 0.15, indicating the successful implementation of policies to improve the carrying capacity of the ecosystem.

3.1.3 Obstacle factors affecting the overall ecological security of the basin

With the exception of the pressure subsystem, the obstacle degrees of all subsystems in the watershed decreased from 2000 to 2020, and the main influencing factors shifted from the impact subsystem to the pressure subsystem. Specifically, during the period of ESCI deterioration (2000–2005), the improvement in ecological security in the watershed was most strongly influenced by the impact subsystem followed by the driving subsystem, the state subsystem, and the response subsystem. In the period of slow ESCI recovery (2006–2010), the improvement in ecological security in the watershed was mainly influenced by the driving subsystem and the impact subsystem, and the obstacle degrees of all subsystems decreased during this period. In the period of Plateau ESCI (2011–2014), the obstacle degrees of the driving subsystem, pressure subsystem, and state subsystem increased, and the former two subsystems played a major role in improving the ecological security of the watershed. In the period of rapid growth ESCI increase (2012–2020), the improvement in ecological security in

the watershed was mainly influenced by pressure subsystem and driving subsystem. Throughout the study period, the response subsystem had a weaker influence on the enhancement of watershed ecological security compared to the other subsystems (Fig. 5).

Indicator subsystem dimension, the top five indicators in terms of barrier degree from 2000 to 2020 were screened as the main obstacle factors. In the ESCI deterioration period (2000–2005), the ecological security of Irtysh River Basin was mainly influenced by water consumption, landscape diversity, urban registered unemployment rate, number of livestock, and industrial wastewater discharge. During the period of slow ESCI recovery (2006–2010), the ecological security in the basin was mainly influenced by pesticide use per unit of arable land area, wetland area, vegetation cover, and urbanization rate. In the stable ESCI period (2011–2014), the ecological security of the Irtysh River Basin was mainly influenced by the urbanization rate, fertilizer use per unit arable area, and the percentage of tertiary industry in GDP. Fertilizer use per unit arable area, population density, and GDP growth rate played key roles in the rapid improvement of ecological security from 2015–2016, while the rapid improvement in ecological security from 2017–2020 was mainly influenced by tourism density, electricity consumption, fertilizer use per unit arable area, and wetland area (Table 3).

3.2 Spatiotemporal differentiation of ecological security at the county level and the obstacle factors

This study analyzes the ecological security status of each county and the spatial and temporal evolution characteristics of each subsystem in 2000, 2010, and 2020 at 10-year intervals in order to assess the spatial and temporal distribution pattern of each county's ecological security status, based on the overall ESCI change pattern
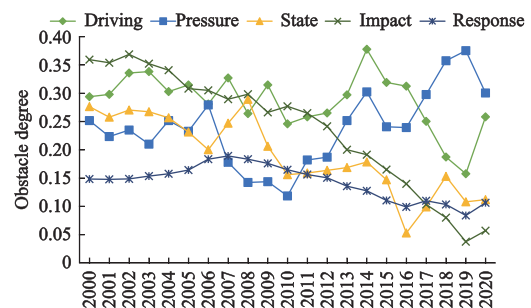

Fig. 5 Obstacle degrees of ecological security criterion subsystem in Irtysh River Basin of Xinjiang from 2000 to 2020

Table 3 Ranking of the main factors affecting the ecological security of Irtysh River Basin of Xinjiang

Year	The top five indicators				
	1st	2nd	3rd	4th	5th
2000	P2	S2	I3	R1	D6
2001	P2	S2	D6	R1	I5
2002	P2	S2	I3	D6	R1
2003	D6	P2	S2	I3	R1
2004	P2	S2	D6	I3	R1
2005	S2	P2	D6	R1	I3
2006	P4	I3	I5	R1	S2
2007	D2	P4	I3	S2	R1
2008	S1	I5	I3	D2	I4
2009	D1	I3	D2	R1	I1
2010	S1	I3	I4	I1	R3
2011	I3	I4	P1	R3	D2
2012	I3	I4	R3	S1	P1
2013	P5	I3	D2	P4	R3
2014	P5	D4	P1	S1	D2
2015	P5	D4	D1	S1	D6
2016	P5	D4	D6	D1	P3
2017	P3	P5	D4	R3	D6
2018	P3	P5	D4	R3	P1
2019	P3	P1	D4	R3	S3
2020	P3	P1	R3	D4	D1

Note: the meaning of letters in the table is the same as that in Table 1
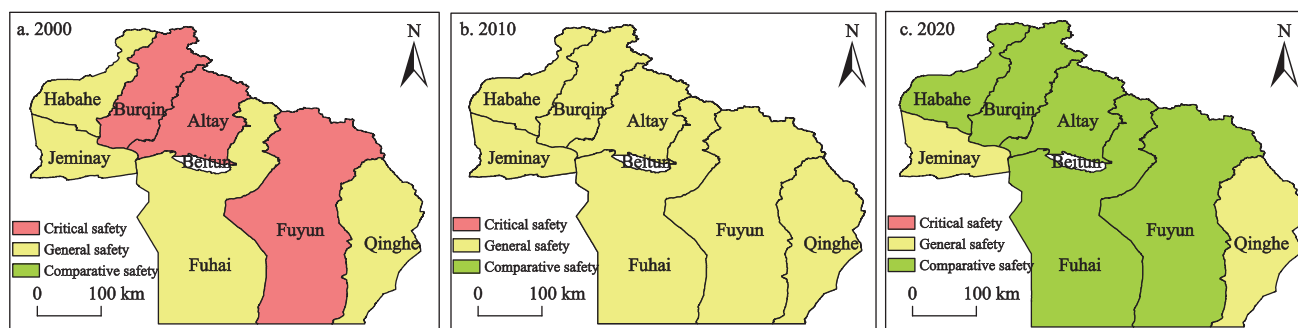
of the Irtysh River Basin.

3.2.1 Spatiotemporal divergence

The ESCI values of all counties in the Irtysh River Basin increased from 2000 to 2020, indicating a gradual improvement in the ecological security of each county. Among them, Altay City's ESCI experienced the greatest growth rate, from 0.23 in 2000 to 0.52 in 2020, with

three distinct phases: critical safety, general safety and comparative safety. Following by Fuhai, the ESCI value increased from 0.32 to 0.59, and the ecological security status improved from a state of general safety in 2000–2010 to a state of relative safety in 2020. During the study period, Qinghe and Jeminay had the lowest increase in the ESCI, and their ecological security status of the two counties was generally safe during the study period. In comparison to the upper and lower reaches of the river basin, the ESCI in the counties located in the middle reaches of the river basin increased more than in the upper and lower reaches.

To further clarify the spatial differentiation of ecological security in the Irtysh River Basin of Xinjiang, the ecological security classification standard was applied to the comprehensive index of ecological security in 2000, 2010 and 2020. During the study period, the spatial distribution of ecological security in each county of the Irtysh River Basin was visually analyzed using Arc-GIS (Fig. 6). The spatial distribution pattern of each county's ESCI value shifted from being high in the east-west and low in the middle to being high in the middle and low in the east-west. Predicated on the indices and their trends over time, the seven counties were classified into the following three categories below.

The first category includes Qinghe and Jeminay, which, respectively, are located in the upper and lower reaches of the watershed, respectively. The ecological security status was always in 'critical safety' between in 2000 and 2010, and did not improve to 'general safety' until 2020; thus, the status improved by only one level after more than 20 yr of development. This indicates that the improvement of the ESCI in both counties faces obstacles such as a weak economic development foundation, a single industrial structure with a small scale,

Fig. 6 The ecological security comprehensive index (ESCI) level of different counties in Irtysh River Basin of Xinjiang in 2000, 2010 and 2020

economic development in its infancy, a low urbaniza-
tion rate, a fragile ecological environment, increased
glacier melting and shrinkage, overgrazing leading to
the degradation of natural grasslands, shrinking lakes, a
diminished wetland area, and soil erosion. In addition to
the increase in industrial and agricultural development
projects in Qinghe, insufficient engineering measures
have led to low water efficiency, resulting in a severe
ecological water supply shortage in the county. In addi-
tion to the damage to the geological environment of the
two river sources stemming from mining in Qinghe, and
there are numerous debts in the history of ecological
restoration. In Jeminay, there is a severe lack of water
resources due to the absence of perennial rivers. The
water resources per capita are only approximately 1/3 of
the average level for the entire region of Xinjiang. Lim-
ited by water resources, farmers and herdsmen lack the
means to produce, and Xinjiang's economic and social
indicators have been ranked in the bottom position in
Xinjiang for a long time. Jeminay is a typical 'few, mar-
ginal, and poor' county prone to disasters in China.

The second category includes Altay City and Burqin.
Since 2010, the ecological security level in these two
counties has risen from critical safety to comparative
safety, indicating that the socioeconomic and ecological
environmental protection measures implemented in
these two counties have produced remarkable results.
Taking advantage of the chance to create a national
demonstration area for all-area tourism, in conjunction
with local water resources, ice and snow, ecology and
other advantages, the two counties explore the integ-
rated development of tourism various industries, and ag-
riculture, for instance. This would serve to strengthen
the economy as a whole, increase local employment, in-
come and living standards and encourage local resid-
ents to seek employment. Altay City issued a number of
policies including the 'Altay City Ecological Environ-
mental Protection Responsibility List', 'Altay City Na-
tional Key Ecological Function Area Industrial Access
Negative List Implementation Plan', 'Altay City One
Pasture River Chief System Work Plan', and 'Altay City
Establishment of National All-Area Tourism Demon-
stration Zone Promotion Plan', 'Altay City Rural Dibao
Special Treatment Implementation Plan', among others.
Burqin issued the 'Implementation Plan for the Assess-
ment of County Ecological Environment Quality in the
National Key Ecological Function Area of Burqin',

'2014–2015 Winter Tourism Activity Plan for Burqin',
'Winter Tourism 'Three Festivals and One City' Activ-
ity Plan for Burqin', 'Planning Plan for Special Treat-
ment Facilities for Rural Domestic Waste in Burqin'
among others.

The third category includes Fuhai, Fuyun, and Ha-
bahe. The ecological security level in these counties has
evolved from critical safety to general safety and finally
to comparative safety, indicating that the ecosystem
structure in these counties has become reasonable, the
ecological function has been restored, and socioeconom-
ic development has steadily progressed. Fuhai is an agri-
cultural county, which is dominated by the primary in-
dustry, followed by the tertiary industry. Tourism has
developed rapidly in this county in recent years, and this
county has the largest wetland area in the study region.
Among the basin counties, Fuhai has the second largest
per capita GDP, per capita net income of farmers and
herdsmen, and value added of primary industry. How-
ever, the ecological security level in Fuhai still has
much room for improvement. Specifically, the ecologic-
al security in Fuhai is negatively affected by the de-
creasing amount of water coming from the upper
reaches of the Ulungu River and the increasing water
use in the irrigation district of the Ulungu River. The
cutoff period of the downstream area of the Ulungu
River is increasing year by year. Fuhai also facing in-
creased glacial melting and shrinkage, the degradation
of river valley forest and grassland, shrinking lakes, re-
ducing wetland areas, and land sanding. Habahe and
Fuyun has an industrial structure characterized by the
secondary industry, especially heavy industry. These
counties have high per capita net income of farmers and
herdsmen, per capita GDP, and unit arable land along
with low water consumption, pesticide use, and chemic-
al fertilizer use per unit arable land area. However, due
to the distance from the market and economic activities,
it is difficult to adjust the industrial structure of Habahe
and Fuyun. Moreover, due to the extensive destruction
of natural pastures caused by overgrazing, desertifica-
tion, and grass degradation on both sides of the Irtysh
River coupled with weak measures to conserve water
and replenish ecological water, it is difficult to replen-
ish the limited water supply in these counties.

3.2.2 Changes in obstacle factors affecting ecologic- al security at the county level

There were significant spatial variations in the obstacle

degrees in the watershed counties in the subsystem dimension. The ESCI of Qinghe was mainly influenced by the barrier degree of the pressure subsystem followed by the obstacle degrees of the state subsystem, impact subsystem, and driving subsystem. In Altay and Fuyun, the obstacle degrees of all subsystems except for the pressure subsystem decreased during the study period, and the barrier degree of the driving subsystem had the greatest impact on the improvement in ecological security. The ESCI of Fuhai, was mainly influenced by the state subsystem barrier, and the ranking of each subsystem barrier changed from state-impact-driving-pressure-response in 2000 to state-pressure-driving-impact-response in 2020. In Burqin, the pressure subsystem barrier degree was the only subsystem that increased from 200 to 2020 and was the dominant factor affecting ecological security. In Habahe and Jeminay, the response subsystem barrier degree generally increased during the study period. The increase in ESCI in Habahe was most influenced by the impact subsystem barrier in 2000 and the driving subsystem barrier in 2020. The main factors in the increased ESCI in Jeminay changed from the impact subsystem and state subsystem obstacle degrees in 2000 and 2010 to the state subsystem and driving subsystem obstacle degrees in 2020 (Table 4).

The obstacle factors of the indicator subsystem dimension have both commonalities and differences among the districts and counties. In terms of commonality, the ESCI of the Irtysh River Basin counties in 2000 was mainly influenced by water consumption, pesticide use per unit arable land area, and the natural population growth rate, which were mainly distributed in the pressure, driving, and impact subsystems. In 2010, the ESCI of the basin counties was mainly influenced by the natural population growth rate, urbanization rate, wetland area, and vegetation cover, which were mainly distributed in the driving, impact, and state subsystems. These indicators are mainly distributed in the driving, impact, and state subsystems. In 2020, the ESCI of the basin counties was mainly influenced by tourism density, electricity consumption, population density, and the proportion of added value of primary industry to GDP. These indicators are mainly distributed in the pressure, driving, and response subsystems.

In terms of differences, the current ESCI of Qinghe, which is located in the upper reaches, was mainly influ-

Table 4 Obstacle degrees of the ecological security criterion subsystems in each county of Irtysh River Basin of Xinjiang from 2000 to 2020

County	Year	The top five indicators				
		1st	2nd	3rd	4th	5th
Qinghe	2000	P4	P2	P5	I1	I2
	2010	D4	P5	P4	S1	I1
	2020	P5	P1	S3	R3	I3
Fuyun	2000	D6	D4	I3	S1	I1
	2010	S1	D6	I4	D4	I3
	2020	P1	D6	P3	D1	S3
Fuhai	2000	P2	S3	S2	I1	I2
	2010	D3	S3	S1	S2	I4
	2020	S3	P5	S2	D1	S1
Altay	2000	D4	P5	D3	D6	I3
	2010	D4	D3	D6	R3	I1
	2020	P3	D4	D3	R3	D6
Burqin	2000	P2	P4	I5	P5	I1
	2010	P4	D2	I5	P1	P5
	2020	P3	P1	S3	R3	D1
Habahe	2000	P2	D2	I3	I5	I2
	2010	D2	I4	D4	R3	I1
	2020	P3	D4	D1	R3	I4
Jeminay	2000	P2	S2	R1	I1	S1
	2010	D3	S1	I1	S2	R1
	2020	P1	R3	D1	R1	S1

Note: the meaning of letters in the table is the same as that in Table 1

enced by fertilizer use per unit of arable land area, electricity consumption, and average annual precipitation. Electricity consumption, livestock population, proportion of tertiary industry in GDP, and industrial wastewater discharge had the greatest impact on ESCI in Fuyun. In contrast, ESCI in Fuhai was mainly influenced by average annual precipitation, fertilizer use per unit area, wetland area, and landscape diversity; these indicators are mainly distributed in the state subsystem. For Altay City and Habahe, their current ESCI is mainly influenced by tourism density and population density. In Burqin, the value of ESCI is mostly influenced by tourism density, electricity consumption, and average annual precipitation. For Jeminay, which is located in the downstream, ecological security is mainly influenced by electricity consumption, the proportion of primary industry to GDP, and GDP growth rate.

4 Discussion of Sustainability Strategies

4.1 Impact of implemented policies on changes in ecological security status

Compared to the static analysis of individual years in previous studies (Kagalou et al., 2012; Ou et al., 2017), the dynamic analysis of this study allows for a more in-depth examination of the policy reasons and mechanisms of action for the evolution of the ecological security status of the watershed. The river basin experienced sluggish economic expansion from 2000 to 2010. The agricultural sector took on the expansion of arable land to increase production and efficiency, which can easily lead to the phenomenon of 'wandering farming' or 'abandoning farming'. In animal husbandry, the increase in livestock is a source of income for farmers. The mining industry is not at a high level of all-encompassing development and utilization. On the one hand, crude production techniques lead to the destruction of vegetation, the degradation of habitat quality, and the diminution of soil and water conservation capacity (Liu et al., 2021). In contrast, water resource utilization efficiency and output per unit of water are poor. In 2012, the government of the Xinjiang Uygur Autonomous Region proposed transforming the Altay Region into a 'two sustainable' demonstration area for resource development and ecological environment protection, constructing a 'Xinjiang important parlor', and adhering to a twenty-word policy of 'protecting ecology, magnifying advantages, highlighting people's livelihood, forming characteristics, innovating and pursuing excellence'. The Altay Region is adapting to the Xinjiang Autonomous Region's policies regarding agriculture and animal husbandry, industry, tourism, energy, and an export-oriented economy. Utilizing its abundant tourism resources and distinct environmental advantages, the Altay Region is advancing environmental protection to force economic restructuring, vigorously expanding tourism and promoting new industrialization. These measures encourage the majority of farmers and herdsmen to engage in tourism to boost their income, stimulate their production, and improve their living conditions. In addition, the ecological security of the watershed has been strengthened as a result of the Altay Region's consistent adherence to a policy of development and protection synergy.

4.2 The key to improve the ecological safety of the watershed

Scholars are generally in agreement that water resources are the most significant factor influencing ecological security in dryland watersheds (Kagalou et al., 2012; Shen et al., 2017). However, the mechanisms of action in various types of drylands vary considerably. The results of this study in the Irtysh River Basin indicate that water consumption, the area of efficient water-saving irrigation, the proportion of wetland area, average annual precipitation, and industrial wastewater related to water resource use all have a significant impact on ecological security. In addition, barrier factors such as vegetation cover, number of livestock, pesticide use per unit of arable land area, and the proportion of industrial value added to influence the ecological security of the basin through their effects on water resource use and the water environment. By incorporating the pertinent findings of previous studies (Zhao et al., 2021b; Wang et al., 2022b), it is possible to derive three key recommendations to enhance the ecological safety level of the watershed. First, water resources are the factor with the smallest resource and environmental carrying capacity of the drylands, rendering them a crucial determinant for the scale of development and ecological health of the drylands. Second, the intensity of human activities, including the scale and type of utilization, determines whether the activities bring ecological risks. Third, due to the diverse resource background conditions and economic approaches of each district and county, there are substantial differences in water use efficiency and water use structure. In order to achieve the coordination effect of the benefits of regional water resources, ecology, and environment, enhancing the sustainable use of water is essential to ecological security in arid regions.

4.3 Sustainability strategy

Based on the ecological security evaluation results, obstacle factors and key dimensions, and combined with the actual research of the group, we propose the following strategies to improve ecological security.

First, targeted policies based on spatial differences should be proposed to avoid crude one-size-fits-all policies in watersheds. The results of this study indicate that problems related to ecological security and the contributing factors within the Irtysh River Basin are characterized by significant spatial differentiation between

the upstream and downstream and between close to and far from the river. This result is consistent with existing studies (Wang et al., 2021b). For the upstream Qinghe and the downstream Jeminay, the focus should be on ecological protection and restoration projects along with water environment monitoring and management. For Fuyun, Altay City, and Burqin, policies should focus on improving agricultural water use efficiency through ecological protection and restoration projects (e.g., developing tourism, returning farmland to forests, optimizing planting structures, implementing grassland ecological protection subsidies and incentives), and grass storage balance projects. Fuhai and Habahe should rebuild damaged mining ecosystems, restore vegetation, reduce soil erosion and geological disasters, strengthen ecological water replenishment projects, connect tourism development with other industries, stimulate urban and rural development, and form an industrial symbiosis pattern using the 'tourism plus' model.

Second, optimize the industrial structure and improve water use efficiency. Low industrial water use efficiency is a prominent problem in the Irtysh River Basin. The government should take the water consumption of 10 000 yuan (RMB) GDP as an important assessment index and promote the transfer of water resources to high-efficiency and high-water-saving industries by adjusting the water use structure of the three industries as well as each industry within the sector. In particular, the agricultural sector, which is the largest water user in counties (Tian et al., 2021), needs to reasonably adjust the crop cultivation structure in each county while promoting drought-resistant fine varieties to address the problem of agricultural water consumption exceeding control targets in most counties. In the industrial sector, industries that consume a lot of water, such as metal and non-metal mining and selection, textile and paper printing, are curbed, and the extension of industrial chains and the development of industries that consume less water, such as deep processing of oil and gas resources and clean energy equipment manufacturing, are encouraged. In particular, Fuyun and Habahe, which are mainly in the secondary industry, should ensure the sustained and stable development of the industrial economy in the future, and make up for the lack of industrial development by accelerating the transformation and upgrading of traditional pillar industries and extending industrial chains. In the tertiary industry, relying on the aesthetic

value of Altai's rich natural landscape, we should vigorously develop ecological tourism and realize the conversion of ecological resources to economic value. At the same time, drive more local farmers and herdsmen to switch from single primary industry to diversified employment and reduce the pressure on natural ecology.

Third, science and technology should be strengthened to promote water-saving technologies and equipment. The lack of scientific and technological capacity, specifically agriculture and environmental protection technology, is a key shortcoming that affects the ecological security of dryland basins. The first measure is the water saving and efficiency of agriculture. The government should continue to do a good job in the construction of large and medium-sized irrigation areas to improve the value of the utilization coefficient of irrigation water in the whole basin. 1) The groundwater level in the irrigation area can be lowered through the implementation of the renovation project of the drainage system in the irrigation area; 2) reduce the occurrence of soil perennial salinization in the irrigation area; 3) a modern water-saving irrigation area with networked supply and drainage, refined quantification of irrigation water and intelligent irrigation management can be built. In this irrigation area, irrigation quotas for different crops in each county will be determined scientifically and reasonably, and technologies such as sprinkler, micro-irrigation and drip irrigation will be promoted. The second measure is the environmental protection and water conservation in the industrial field. The government should vigorously promote technologies such as high-efficiency cooling, water recycling and waste water reclamation to improve the recycling rate of water resources. Domestic sewage facilities should be upgraded so that the treated sewage meets the standard of green water. New industrial enterprises should be encouraged to use water-saving processes, and update their production equipment, and reduce production water, wastewater, and waste discharge.

Fourth, environmental zoning should be strengthened, and the treatment capacity of environmental facilities should be enhanced. The limited water resources, small capacity, and easy pollution of water bodies are important features of dryland watersheds (Valenzuela et al., 2009). An environmental zoning and pollution source grading control system covering every inch of the country should be established. Management according to

three broad categories of space: living, production and ecology is a practical approach (Zhou et al., 2021). The living space category includes urban living places, rural living places, nomadic settlements, tourist places. The production space category includes industrial and mining production spaces such as mining areas, general manufacturing places, highly polluting industrial places, agricultural and animal husbandry production spaces (e.g., livestock and poultry farms, arable land, and gardens), and special production spaces. The ecological space category includes water connotation areas, soil and water conservation areas, and drinking water sources. The support system of environmental facilities in the watershed should also be improved. Cities and towns, in accordance with the local residents and tourist population, should promote the expansion and upgrading of domestic sewage treatment plants. Agricultural and herding areas and nomadic settlement sites should promote the construction of engineering facilities for the collection and treatment of domestic garbage and sewage, and these facilities can adopt a combination of fixed and mobile models so that a system for the collection, transfer and disposal of garbage covering agricultural and herding areas can be formed.

Fifth, MRFFLGs should be holistically and systematically implemented. In 2018, the Project of Ecological Protection and Restoration Project in the Altay, Irtysh River Basin was included in the third batch of national pilot projects. This project has achieved significant results in key ecosystem services such as watershed clearing, water flow, wind and sand control, soil conservation, product supply, and biodiversity conservation (Li et al., 2021b). However, it is not enough to focus on ecosystem restoration (Liu et al., 2021), the following measures still need to be implemented in the future: including the following three aspects: 1) forming a systematic protection and restoration network with the watershed as the basic geographical unit; 2) improving the weaknesses of institutions and mechanisms such as adaptive management and supervision and inspection systems; 3) promoting the 'MRFFLGs' and integrating 'industry, city, people and tourism' to form a large system project.

5   Conclusions and Outlook

In this study, the ESCI for ecological security was de-

veloped utilizing the DPSIR model framework from a system-theory standpoint. Using the ESCI, we evaluated the trend in ecological security in the Irtysh River Basin from 2000 to 2020. In addition, we assessed the challenges that are specific to each county as well as the basin in general. The key results are summarized as follows. 1) From 2000 to 2020, the ESCI at the basin level in the Irtysh River Basin of Xinjiang declined before increasing. Water consumption, area of water-efficient irrigation, wetland area, vegetation cover, and livestock population were the primary factors affecting ecological security in the basin. 2) Counties can be divided into three categories based on their ecological security status at the county level: low-level, stable ecological security (Qinghe and Jeminay); continuously improving ecological security (Fuyun, Habahe, and Fuhai); and rapidly improving ecological security (Altay and Burqin). Obstacle factors share commonalities with respect to a number of indicators while displaying stark distinctions in relation to others. Indicators with a high degree of similarity include water consumption, vegetation cover, and the proportion of the primary industry's value added. Indicators with significant variation include electricity consumption, livestock headcount, tertiary industry share, and landscape diversity index. 3) The strategy to enhance ecological security should place emphasis on five aspects: 1) focus on spatial variations; 2) improve the efficiency of industrial water use; 3) promote water-saving techniques and equipment; 4) implement environmental zoning control; 5) practise in depth of MRFFLGs.

Based on the territorial system of human-earth relationship, this study integrates natural and socioeconomic factors to offer a detailed assessment of ecological security in the Irtysh River Basin. In addition, the study analyzes key impediment factors from the perspectives of dynamic processes and spatial differences, which partially compensates for the deficiencies of existing studies in assessing the ecological security of dryland watersheds utilizing a single factor and static perspectives. Nonetheless, there remain a few weak points in this paper that need to be explored in depth. First, while the assessment units of prefecture-level cities and counties reveal the changes in regional ecological security patterns in general, more in-depth assessments are necessary at smaller spatial scales for specific ecological security issues and ecological processes. Second, albeit the spatial

and temporal differences of the barrier factors affecting ecological security have been brought to light, the mechanisms of the key barrier factors affecting ecological security need to be studied in greater detail. Third, for specific ecological security issues, it is still necessary to select typical case sites and adopt approaches such as the DPSIR framework to understand the feedback processes between human activities and ecological environment.

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