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Comprehensive evaluation of the effect of regional groundwater overexploitation restoration

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ABSTRACT

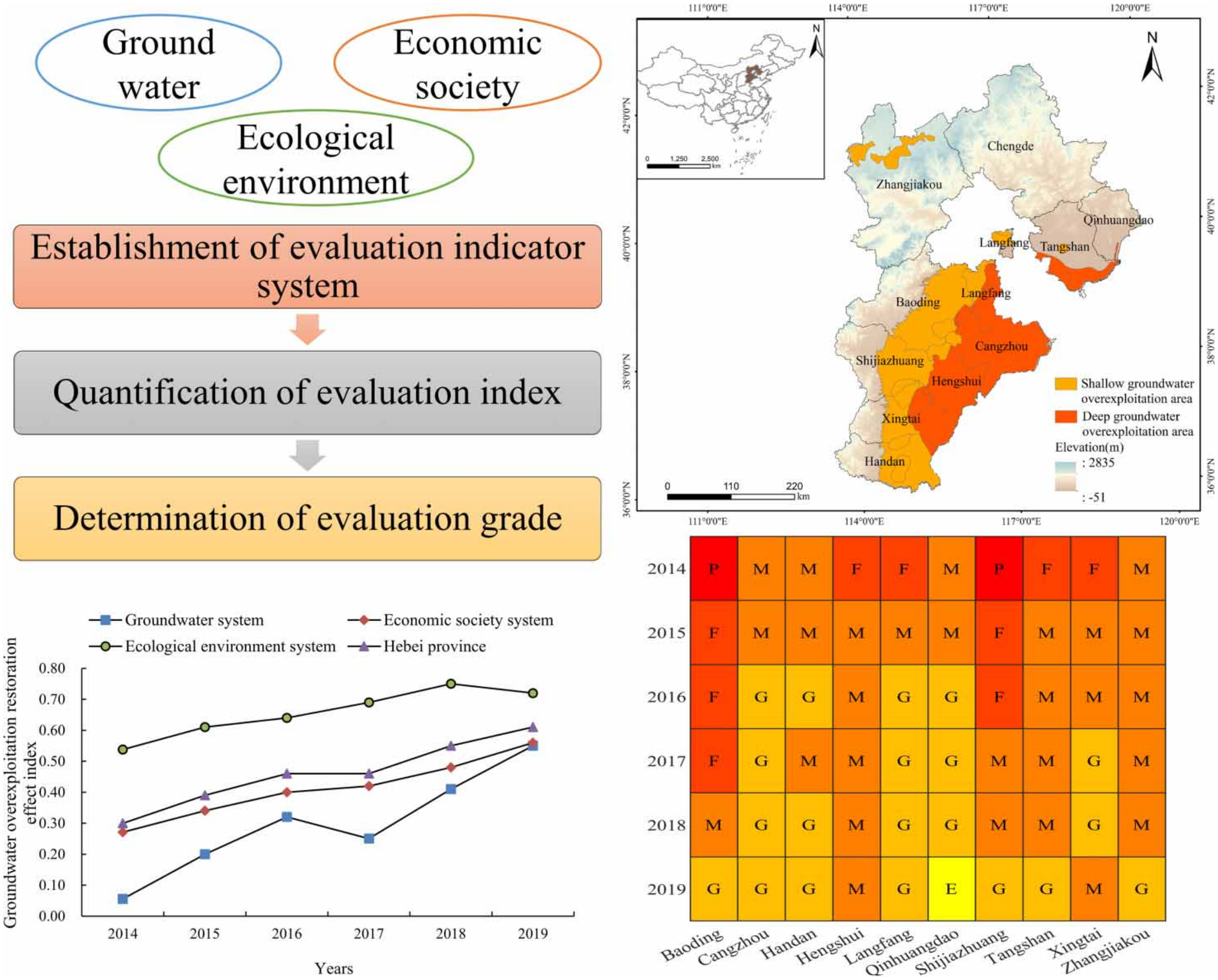
The traditional groundwater overexploitation restoration only considers the impact on groundwater, on the basis of which, this paper also comprehensively considers the impact on economic society and the ecological environment. Based on analyzing the effect of groundwater overexploitation restoration on the groundwater–economic society–ecological environment (GESEE) system, an evaluation indicator system covering the GESEE system was constructed, an evaluation method for the effect of groundwater overexploitation restoration was established, and the effects were evaluated for Hebei Province, China, from 2014 to 2019. The results showed that the effect of groundwater overexploitation restoration in Hebei Province was obvious, and the grade of the groundwater overexploitation restoration effect improved from fair to good. The grade of the groundwater overexploitation restoration effect in most cities was improved to good. The measures that most affected the effect of groundwater overexploitation restoration in Hebei Province are strict control of extraction and reduction of consumption, while measures such as the replacement of water sources also play a significant role. An evaluation indicator system constructed in this paper can help to promote sophisticated effect evaluation of groundwater overexploitation restoration and improve the understanding and management of groundwater overexploitation restoration.

Key words: effect evaluation, groundwater overexploitation, Hebei Province, restoration measures effect

HIGHLIGHTS

- An evaluation indicator system covering the groundwater–economic society–ecological environment system is constructed.
- An evaluation method for the effect of groundwater overexploitation restoration is established.
- The evaluation method is applied at both provincial and municipal levels in Hebei Province, one of the most severe groundwater overexploitation areas in the world.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Groundwater is an important part of water resources, with important resource functions and ecological environment functions (Chen *et al.* 2020). The sustainable development of groundwater is of great significance for supporting economic and social development and maintaining ecological environment stability. With the increase in population and the continuous development of the economy and society, groundwater has been widely developed and utilized. At present, the global groundwater exploitation has exceeded 1,000 billion m^3/a (Dillon *et al.* 2019). Global groundwater exploitation accounts for 33% of total water withdrawals and more than two billion people depend on groundwater, resulting in excessive groundwater consumption in many regions of the world (Sun *et al.* 2021).

In China, due to long-term overexploitation, groundwater in some areas has been seriously overdrawn, forming a large-scale regional landing funnel and causing environmental and geological problems such as ground subsidence and ecological degradation (Guo *et al.* 2021; Yu *et al.* 2021) while leading to aggravated groundwater pollution. Most of groundwater overexploitation areas are distributed in northern China, and the overexploitation area in the plain is nearly 300,000 km^2 (Yu *et al.* 2018). The area of groundwater overexploitation in Hebei Province is approximately 69,700 km^2, accounting for 90% of the plain land area of Hebei Province and approximately 23% of China's groundwater overexploitation area (Yu *et al.* 2020). The North China Plain, where Hebei Province is located, is the world's largest groundwater funnel area (Qin *et al.* 2020).

In 2014, to control the increasingly serious problem of groundwater overexploitation in Hebei Province, the Chinese government launched a pilot project to explore groundwater overexploitation restoration measures and summarized the experience in order to provide support for other parts of China with similar groundwater challenges. In 2017, the scope of groundwater overexploitation restoration was extended to Shandong Province, Shanxi Province, and Henan Province. In 2019, China further intensified groundwater overexploitation restoration measures in the Beijing–Tianjin–Hebei region. The main measures were to use rivers and lakes to recharge groundwater under the premise of ensuring normal water use for urban and rural life and for production purposes in areas with serious groundwater overexploitation and better water resource conditions (Chen *et al.* 2021). With the increasing groundwater overexploitation restoration measures in Hebei Province, it is urgent to scientifically evaluate the effect of groundwater overexploitation restoration, so as to provide a decision-making basis for further formulating groundwater overexploitation restoration measures.

The evaluation indicator system is the basis for evaluating the effect of groundwater overexploitation restoration. Selim *et al.* (2014) evaluated the effect of groundwater overexploitation restoration on the environment in Aswan, Egypt, using groundwater level as an evaluation indicator; Chatterjee *et al.* (2018) used groundwater level as an assessment indicator to analyze the impact of four groundwater management measures, viz., regulation of groundwater extraction, artificial recharge to groundwater, on-farm irrigation management practices and water conservation practices such as recycle and reuse of water; Yang (2020) selected five indicators, including river surface, groundwater infiltration, groundwater level, river water quality, and public happiness, to evaluate the effect of river and lake recharge to groundwater in North China; Lei *et al.* (2021) analyzed the restoration effect of groundwater overexploitation zones in Korla City by selecting indicators related to the implementation status of engineering measures and the status of groundwater level and quantity.

Most previous studies have used groundwater level variation and the completion of restoration measures as evaluation indicators for the effect of groundwater overexploitation restoration, without considering the impacts of the restoration measures on the economic society and ecological environment. Groundwater overexploitation restoration not only affects the groundwater system, but also significantly affects the economic society system and the ecological environment system. During the implementation of groundwater overexploitation restoration measures, the rate of groundwater level decline has decreased, the balance of groundwater system exploitation and replenishment has gradually recovered, the area of groundwater landing funnel has decreased, the original method of groundwater development and utilization by the economic society has changed, the urban living and industrial and agricultural groundwater consumption has been reduced, the water quality of rivers has improved, the ecological water quantity and water surface area of rivers have increased, and the ecological environment has been improved. Therefore, the establishment of an evaluation indicator system for groundwater overexploitation restoration that covers the groundwater–economic society–ecological environment (GESEE) system helps to scientifically evaluate the effect of groundwater overexploitation restoration.

The objectives of this paper are to analyze the effect of groundwater overexploitation restoration on the GESEE system; to construct an evaluation indicator system for the effect of groundwater overexploitation restoration covering the GESEE system; to establish an evaluation method for groundwater overexploitation restoration; and to quantitatively evaluate the effect of groundwater overexploitation restoration in Hebei Province and cities from 2014 to 2019 to provide a reference for formulating restoration measures of groundwater overexploitation.

2. MATERIALS AND METHODS

2.1. Study area

Hebei Province is in the North China Plain, with an average annual precipitation of 531.7 mm. The spatial and temporal distribution of precipitation in Hebei Province is uneven, with a large annual variation; 70–80% of the annual precipitation is concentrated from June to September. Spatial distribution of precipitation shows decreases from the northwest to southeast. Hebei Province, with a total area of 188,000 km^2, consists of 11 cities. In 2019, the total population of Hebei Province was approximately 75.92 million, of which the urban population was 43.74 million, the annual regional GDP was 3,510.5 billion yuan, and the crop's planting area was approximately 80,560 km^2.

The average annual overexploitation of groundwater in Hebei Province is 3.801 billion m^3, including 1.578 billion m^3 of shallow groundwater and 2.224 billion m^3 of deep confined water. In 2014, the Chinese government launched a groundwater overexploitation restoration pilot project in Hebei province. The pilot project took 49 counties in four cities of Hengshui, Cangzhou, Xingtai, and Handan, where deep groundwater overexploitation was the most serious, as the pilot areas. In 2019, the groundwater overexploitation restoration in Hebei Province covered all 11 cities in the province, including 128 counties where overexploitation areas existed. Since the groundwater overexploitation restoration pilot project in 2014, the amount of groundwater exploitation in Hebei Province decreased from 14,207 million m^3 in 2014 to 9,644 million m^3 in 2019.

To evaluate the effect of groundwater overexploitation restoration in Hebei Province and various cities, 10 cities (except Chengde due to its hilly nature and less overexploitation restoration measures) in Hebei Province with groundwater overexploitation areas were selected as evaluation areas (Figure 1). Groundwater overexploitation areas are classified according to the groundwater buried conditions monitored by monitoring wells.

2.2. Data sources

The basic data for the evaluation of the effect of groundwater overexploitation restoration are mainly derived from the 'Hebei Provincial Water Resources Bulletin', 'Hebei Provincial National Economic and Social Development Statistical Bulletin', 'Hebei Provincial Economic Yearbook', and 'Hebei Provincial Geological Environment Status Bulletin', as well as groundwater monitoring, groundwater overexploitation area evaluation, water resources surveys and evaluation, groundwater overexploitation planning and other achievements.

2.3. Evaluation method

2.3.1. Groundwater overexploitation restoration measures and their impact on the GESEE system

The restoration measures of groundwater overexploitation can be divided into two aspects: 'Increasing water sources' and 'Reducing exploitation'. 'Increasing water sources' means increasing the water supply through multiple channels, replacing

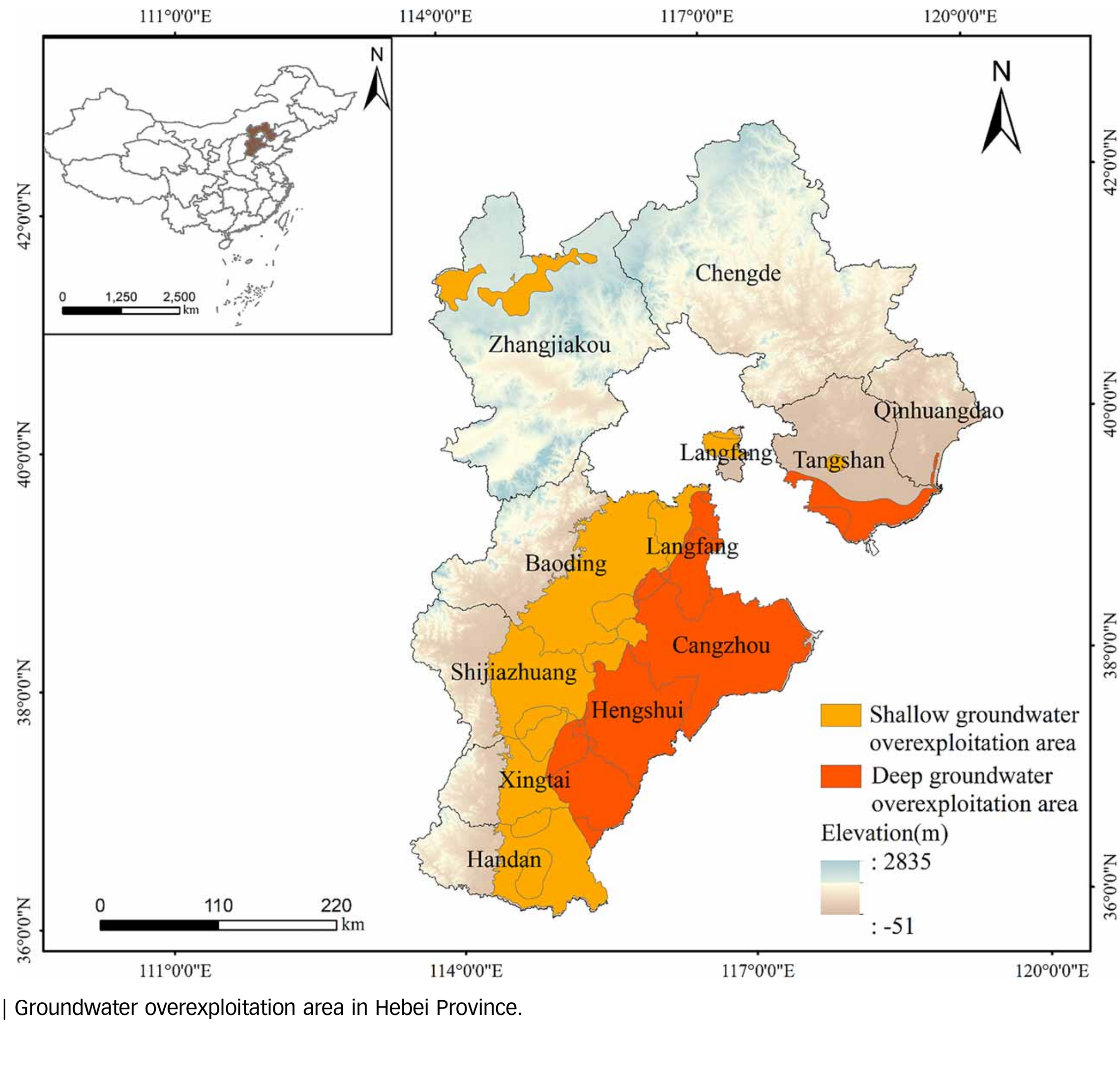


Figure 1 | Groundwater overexploitation area in Hebei Province.

groundwater sources, implementing river and lake recharge to groundwater or artificial recharge of groundwater, and improving the carrying capacity of regional water resources and the water environment. 'Reducing exploitation' means reducing groundwater overexploitation by controlling the agricultural planting structure and industrial development scale, promoting industrial, agricultural, and urban water-saving measures. The GESEE system is an organic whole, with each system influencing and constraining the other. The implementation of groundwater overexploitation restoration measures leads to many impacts on the GESEE system (Figure 2).

Through groundwater overexploitation control measures, we can effectively reduce the amount of groundwater extraction, suppress the amount of groundwater overexploitation, and either decrease the rate of groundwater level decline or slowly raise the groundwater level. The rise in groundwater levels increases the natural discharge capacity of the groundwater system to surface water bodies and consequently to river baseflow. The reduced thickness of the unsaturated zone results in an increased ability for precipitation or lake infiltration to recharge groundwater.

Adjusting planting structures may result in reduced food production and affect farmers' income. The development of agricultural water-saving irrigation can increase the area of water-saving irrigation and reduce the amount of groundwater use in agriculture. The implementation of industrial water conservation and emissions reduction can reduce industrial groundwater use. Promoting water resources tax reform, which levies for groundwater higher than surface water for similar uses, can guide users to reduce extraction on their own initiative.

The groundwater level rises, reducing the depth of water in the center of the groundwater landing funnel, thereby slowing down the rate of ground settlement so that ground cracks no longer lengthen or increase in number. The development of non-agricultural crops to replace agricultural crops, the implementation of returning farmland to forests and the creation of large-scale continuous forests can increase forest cover. Through the implementation of river and lake recharge to groundwater, the ecological water quantity and surface area of rivers increases, and the groundwater level around rivers raises.

2.3.2. Evaluation indicator system

Based on scientificity, feasibility, regionality, comprehensiveness and representativeness and in full consideration of the situation of groundwater overexploitation and its restoration measures implementation in Hebei Province and various cities, 16

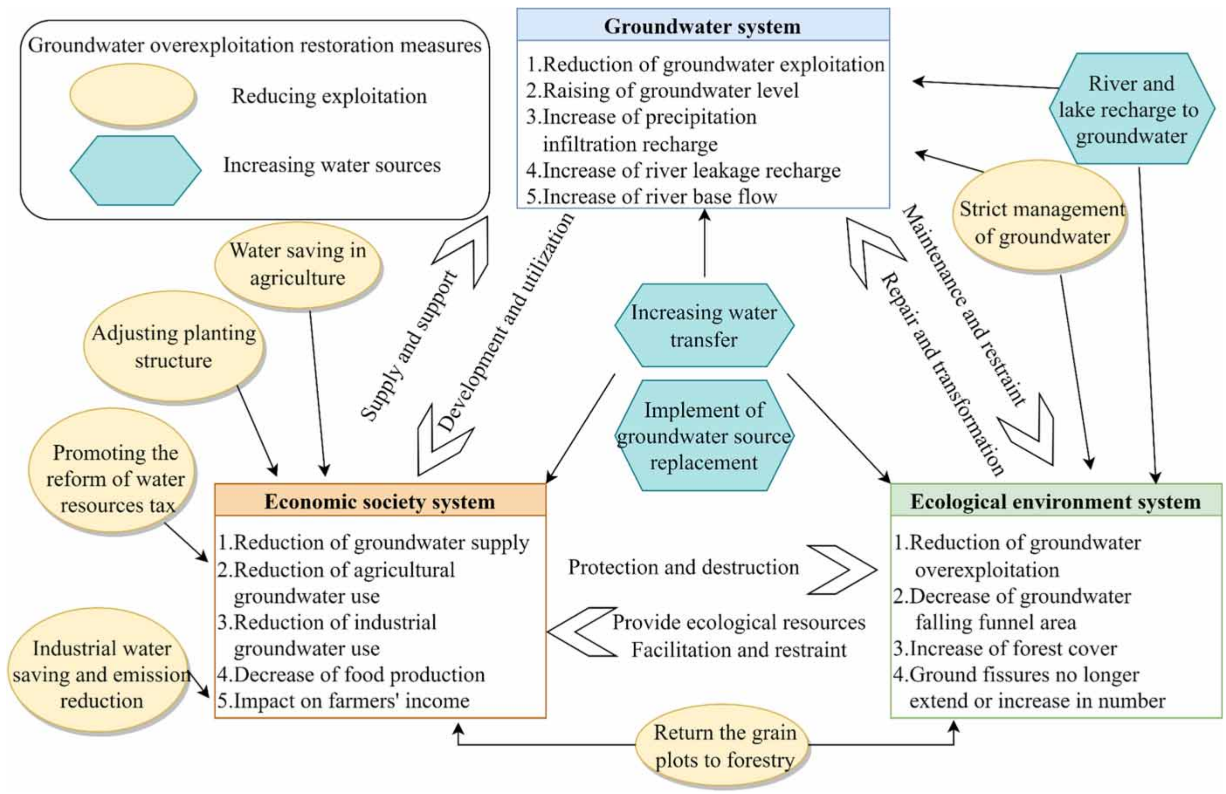


Figure 2 | Effect of groundwater overexploitation restoration on the GESEE system.

evaluation indicators covering the GESEE system are constructed. The evaluation indicator system of the groundwater overexploitation restoration effect in Hebei Province is shown in Table 1.

Evaluation indicators are divided into two categories: positive and negative. The positive indicator refers to an increase in the index of groundwater overexploitation restoration effect, where the larger the value indicates a better effect; the negative indicator refers to a decrease in the index of groundwater overexploitation restoration effect, where a larger value indicates a worse effect.

2.3.3. Comprehensive evaluation methodology

The comprehensive evaluation method of 'single indicator quantification–multi-indicator synthesis–multi-criterion integration' in the harmonious quantitative evaluation method is adopted (Zuo & Mao 2012), which has been widely used in water resources analysis and evaluation. The method consists of three steps: single indicator quantification, multi-indicator synthesis, and multi-criteria integration.

Since the dimensions of the evaluation indicators are not identical, to facilitate calculation and comparative analysis, the indicators of different dimensions are mapped to the [0,1] interval in order to calculate the groundwater overexploitation restoration effect index of each indicator. Each evaluation indicator has five characteristic node values, including the worst value (a), poor value (b), passing value (c), better value (d), and optimal value (e). The characteristic node values methodically determined by the relevant research results, the relevant norms or standards issued by the state or locality, and the relevant groundwater overexploitation area planning by the industry are shown in Table 2 (Yang *et al.* 2012; Wang & Yang 2013).

Based on the calculation of the groundwater overexploitation restoration effect index for a single indicator, the groundwater overexploitation restoration effect index of each criterion layer and the target layer is calculated according to the weighted summation method. The indicator weight is determined comprehensively by using the analytic hierarchy process and the entropy weight method (Li *et al.* 2018; Liu *et al.* 2019).

Table 1 | Evaluation indicator system for the groundwater overexploitation restoration effect in Hebei Province

Criterion layer	Indicator layer	Indicator type	Unit	Calculation method
Groundwater	Groundwater exploitation coefficient (C_1)	Negative	(%)	Shallow groundwater exploitation/allowable groundwater exploitation
	Variation rate of groundwater level (C_2)	Positive	(%)	Groundwater level differential
	Recharge coefficient of precipitation infiltration (C_3)	Positive	(%)	Precipitation infiltration recharge/precipitation
	River leakage recharge coefficient (C_4)	Positive	(%)	River storage variable/river runoff
	Change rate of river base flow (C_5)	Positive	(%)	Base flow storage variable/base flow
Economic society	Proportion of groundwater supply (C_6)	Negative	(%)	Groundwater supply/total water supply
	Proportion of agricultural groundwater (C_7)	Negative	(%)	Agricultural groundwater consumption/total agricultural water consumption
	Proportion of industrial groundwater (C_8)	Negative	(%)	Industrial groundwater consumption/total industrial water consumption
	Average irrigation water per mu (C_9)	Negative	(m^3/mu)	Water use for agricultural irrigation/irrigation area
	Water consumption per 10,000 yuan industrial added value (C_{10})	Negative	($m^3/10^4$ yuan)	Industrial water consumption/industrial added value
	Per capita output of grain (C_{11})	Positive	(kg/(per capita·a))	Total food production/total population
	Change rate of farmers' income(C_{12})	Positive	(%)	Total agricultural income/rural population
Ecological environment	Groundwater overexploitation ratio (C_{13})	Negative	(%)	Shallow groundwater overexploitation/allowable groundwater exploitation
	Funnel area change rate (C_{14})	Negative	(%)	Funnel variation area/total number of years
	Vegetation coverage (C_{15})	Positive	(%)	Vegetation area/total area
	No increase in ground fissures in *N* years (C_{16})	Positive	(a)	The number of years that the ground crack has not increased

Note: Mu is a unit of land area in China. One mu is about 666.667 m^2.

Table 2 | Quantitative characteristic node values of groundwater overexploitation restoration effect evaluation indicators in Hebei Province

Evaluation indicators	Indicator type	Characteristic node value				
		a	b	c	d	e
Groundwater exploitation coefficient (C_1)	Negative	1.5	1.4	1.3	1.2	1
Variation rate of groundwater level (C_2)	Positive	0	0.3	0.6	0.8	1
Recharge coefficient of precipitation infiltration (C_3)	Positive	0	0.08	0.15	0.2	0.2
River leakage recharge coefficient (C_4)	Positive	0	0.08	0.15	0.2	0.2
Change rate of river base flow (C_5)	Positive	0	0.06	0.12	0.16	0.2
Proportion of groundwater supply (C_6)	Negative	0.8	0.6	0.5	0.4	0.3
Proportion of agricultural groundwater (C_7)	Negative	0.8	0.7	0.6	0.5	0.4
Proportion of industrial groundwater (C_8)	Negative	0.8	0.7	0.6	0.5	0.4
Average irrigation water per mu (C_9)	Negative	300	250	200	150	100
Water consumption per 10,000 yuan industrial added value (C_{10})	Negative	300	100	50	25	10
Per capita output of grain (C_{11})	Positive	300	400	500	600	700
Change rate of farmers' income (C_{12})	Positive	0	0.05	0.1	0.15	0.2
Groundwater overexploitation ratio (C_{13})	Negative	0.8	0.6	0.4	0.2	0
Funnel area change rate (C_{14})	Negative	0.4	0.3	0.2	0.1	0
Vegetation coverage (C_{15})	Positive	0.1	0.2	0.3	0.4	0.5
No increase in ground fissures in *N* years (C_{16})	Positive	1	2	4	6	8

The groundwater overexploitation restoration effect index reflects the regional groundwater overexploitation restoration effect, and the larger the groundwater overexploitation restoration effect index is, the better the groundwater overexploitation restoration effect. Referring to and drawing on relevant research results (Yang *et al.* 2012), combined with the actual situation in Hebei Province, the groundwater overexploitation restoration effect is divided into five grades according to the effect index: Excellent [1,0.8), Good [0.8,0.6), Medium [0.6,0.4), Fair [0.4,0.2), Poor [0.2,0), and expressed by E, G, M, F, P, respectively.

3. RESULTS

3.1. Effect of groundwater overexploitation restoration in Hebei Province

The effect of groundwater overexploitation restoration in Hebei Province from 2014 to 2019 is shown in Figure 3. The groundwater overexploitation restoration effect index in Hebei Province shows an upward trend, as do the groundwater overexploitation restoration effect indices of groundwater, economic society, and ecological environment systems. The groundwater overexploitation restoration effect grade in Hebei Province was fair in 2014 and 2015, medium in 2016, 2017 and 2018, and good in 2019. From 2014 to 2019, the groundwater overexploitation restoration effect grade of the groundwater system has increased from poor to medium, the groundwater overexploitation restoration effect grade of the economic society system has increased from fair to medium, and the groundwater overexploitation restoration effect grade of the ecological environment system has increased from medium to good.

Groundwater overexploitation engineering restoration measures need a certain period to fully have an effect. For example, groundwater water replacement for agriculture and industry can only be implemented after the completion of water diversion projects and water transmission network pipeline projects, which require a certain period for construction and a certain amount of time for the projects to fully reach their design capacity after completion and operation. The effect of groundwater overexploitation restoration has a lag, such as the groundwater landing funnel area, even if the groundwater exploitation reduction task is completed, the groundwater landing funnel area may still increase. Therefore, the index of groundwater overexploitation restoration effect in Hebei Province from 2014 to 2015 is low.

According to the specific indicators, the reasons for the changes in the effect of groundwater overexploitation restoration are analyzed. The trend of various indicators in Hebei Province from 2014 to 2019 is shown in Figure 4.

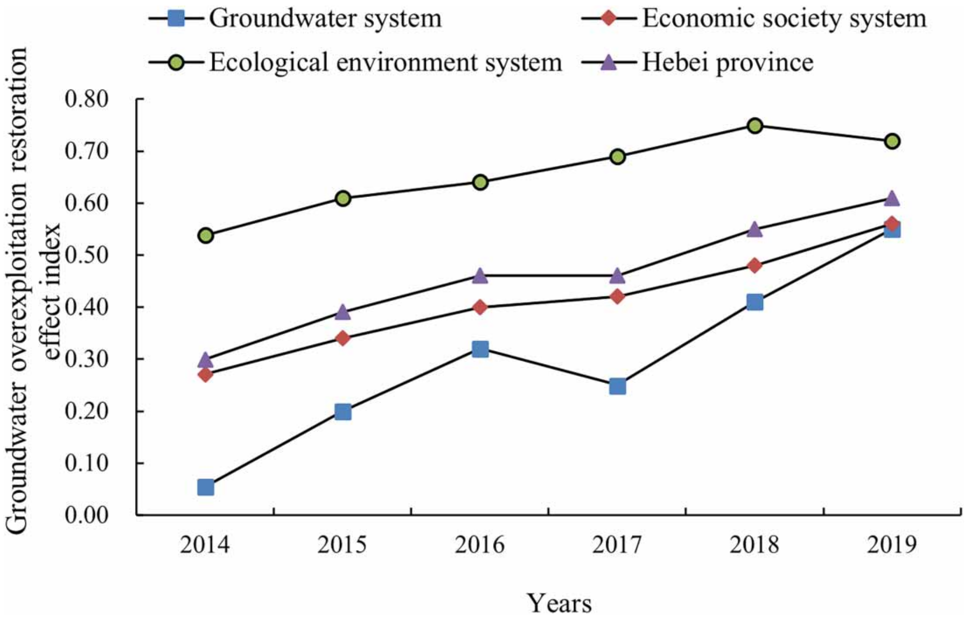


Figure 3 | Changes in the effect index of groundwater overexploitation restoration in Hebei Province from 2014 to 2019.

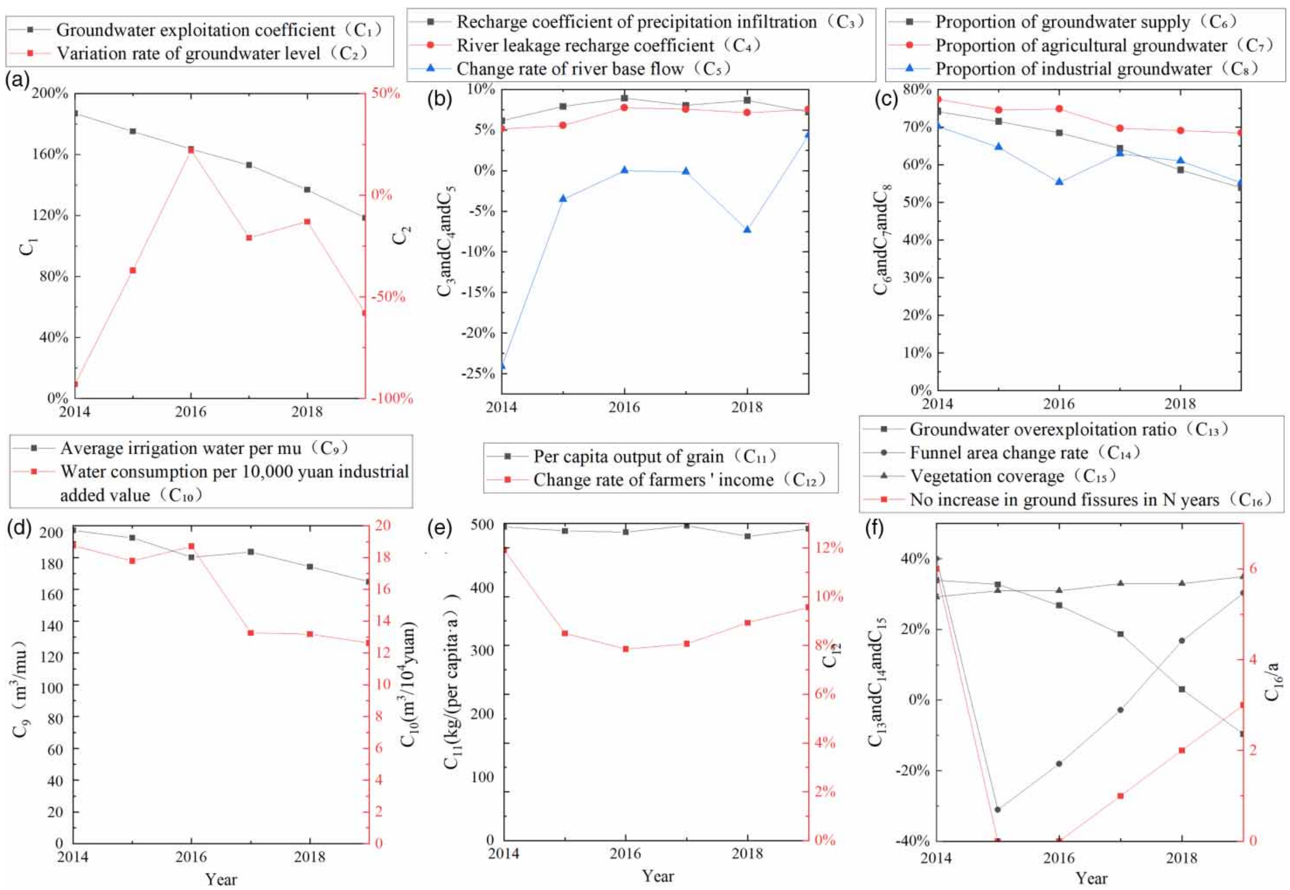


Figure 4 | Changes in the evaluation indicators of Hebei Province from 2014 to 2019.

After Hebei Province strengthened the management of groundwater abstraction permits, the negative indicator groundwater exploitation coefficient (C_1) continued to decrease. The implement of ecological water recharge to rivers and lakes led the positive indicator change rate of river base flow (C_5) to generally show an increasing trend. Through industrial, agricultural and domestic water conservation, adjusting the structure of planting and industry, and promoting water resource tax reform led to a continuous decline in the negative indicators of proportion of groundwater supply (C_6), proportion of agricultural groundwater (C_7), proportion of industrial groundwater (C_8), average irrigation water per mu (C_9) and water consumption per 10,000 yuan industrial added value (C_{10}). The negative indicator groundwater overexploitation ratio (C_{13}) continued to decrease. Through the return of farmland to forest, the positive indicators of vegetation coverage (C_{15}) and no increase in ground fissures in *N* years (C_{16}) gradually became larger. Hence, the groundwater overexploitation restoration effect grade demonstrated an improving trend.

3.2. Effect of groundwater overexploitation restoration in various cities of Hebei Province

The effect of groundwater overexploitation restoration in 10 cities in Hebei Province with groundwater overexploitation areas from 2014 to 2019 was evaluated, as shown in Figure 5. The effect grade of groundwater overexploitation restoration in various cities is generally on the rise. Two cities with a poor groundwater overexploitation restoration effect grade in 2014 were upgraded to fair in 2015, and there were no further cities with a poor groundwater overexploitation restoration effect grade by

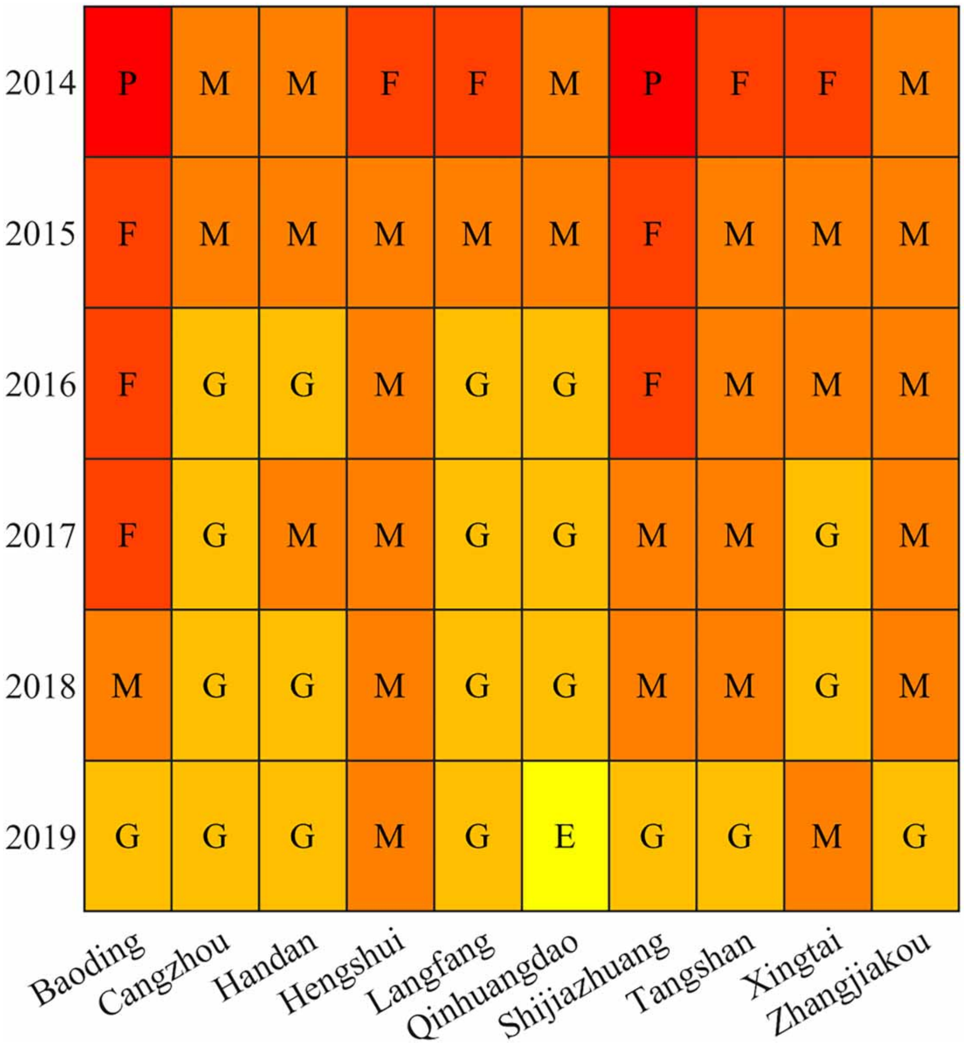


Figure 5 | Groundwater overexploitation restoration effect grade in various cities from 2014 to 2019.

2019; the number of cities with a fair grade for the groundwater overexploitation restoration effect decreased from four in 2014 to two in 2016 and one in 2017, and these cities were upgraded to medium or good by 2019; the number of cities with a medium grade for the groundwater overexploitation restoration effect increased from four in 2014 to eight in 2015, and these cities were upgraded to good or excellent by 2019. The effect of groundwater overexploitation restoration has been effective in all cities.

4. DISCUSSION

The groundwater overexploitation restoration effect index of various indicators for Hebei Province is shown in Figure 6. The four indicators that have a significant impact on the effect of groundwater overexploitation restoration for Hebei Province are groundwater exploitation coefficient (C_1), proportion of groundwater supply (C_6), proportion of industrial groundwater (C_8), and groundwater overexploitation ratio (C_{13}). The groundwater exploitation coefficient (C_1) and groundwater overexploitation ratio (C_{13}) are directly related to the measures of reducing groundwater overexploitation in 'Reducing exploitation'. Strict control of groundwater exploitation is the key to controlling these two indicators. The proportion of groundwater supply (C_6) and proportion of industrial groundwater (C_8) are related to the measures of controlling groundwater use in 'Reducing exploitation' and measures to replace groundwater sources with additional water sources in 'Increasing water sources'.

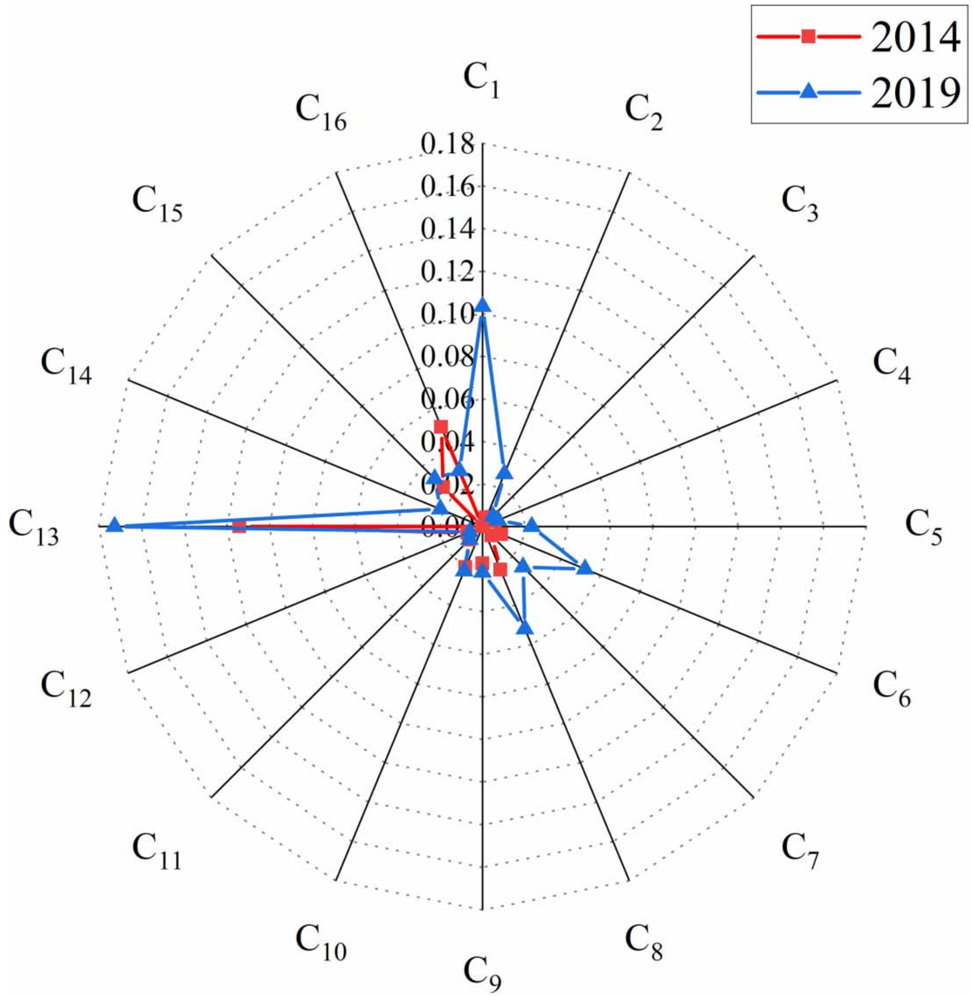


Figure 6 | Changes in groundwater overexploitation restoration effect index of evaluation indicators for Hebei Province in 2014 and 2019.

According to the above results, 'Reducing exploitation' contributes more to the effect of groundwater overexploitation restoration than 'Increasing water sources'. Li *et al.* (2021) also studied the effect of different measures on the groundwater overexploitation restoration efficiency and came to a similar conclusion that 'Reducing exploitation' such as adjusting planting structures and water-saving irrigation is more efficient than 'Increasing water sources' such as farmland water conservancy projects. Moreover, 'Increasing water sources' measures such as the replacement of water sources needs to build pipelines and other projects, and the implement of ecological water recharge to rivers and lakes requires rivers and lakes to complete the cleaning task. These measures require significant investment and will take some time to begin to work. In addition, the external transfer of water is unstable, with a certain degree of uncertainty and the same dryness and abundance. Although 'Increasing water sources' measures are more involved and have a relatively low restoration effect, they are still indispensable in order to meet water demand. Measures such as the replacement of water sources can be used to coordinate water consumption while suppression of groundwater exploitation is taking place.

In summary, strict control of exploitation and fundamental reduction of consumption is the key to controlling the problem of groundwater overexploitation, and increasing water sources is an indispensable way. There is a need to consider the priority of groundwater overexploitation restoration measures, to appropriately increase the scale of investment in high-efficiency measures, to optimize the scale of other measures, and to consider the sustainability of restoration as well as the synergies between long-term and short-term restoration. Therefore, in the process of groundwater overexploitation restoration, reasonable tasks and targets should be set for suppressing groundwater exploitation, and the replacement of water sources and the implement of ecological water recharge to rivers and lakes should be used as supplementary means.

The measures that have a greater impact on each city in Hebei Province can be analyzed from the changes in the groundwater overexploitation restoration effect index of various indicators in various cities. For the seven cities of Baoding, Cangzhou, Handan, Langfang, Qinhuangdao, Shijiazhuang, and Zhangjiakou, both 'Reducing exploitation' and 'Increasing water sources' measures have a large effect. In particular, the implement of ecological water recharge to rivers and lakes in Baoding causes significant changes in river baseflow and plays an important role in the management of groundwater overexploitation. For Hengshui city, the measures of controlling groundwater use in 'Reducing exploitation' and measures to replace groundwater sources with additional water sources in 'Increasing water sources' contribute significantly. For Tangshan and Xingtai cities, the measures of reducing groundwater overexploitation in 'Reducing exploitation' are more significant. In the future process of groundwater overexploitation restoration, each city should strengthen the measures that have a greater impact on the effect of groundwater overexploitation restoration in that city, so that they can be as effective as possible, while supplementing the measures that are insufficient.

5. CONCLUSIONS

This paper analyzed the effect of groundwater overexploitation restoration on the GESEE system, constructed an indicator system for evaluating the effect of groundwater overexploitation restoration, and evaluated the effect of groundwater overexploitation restoration in Hebei Province and various cities. This research is of great significance for promoting the process of groundwater overexploitation restoration and realizing the sustainable use of groundwater resources. The main conclusions are as follows.

(1) During 2014–2019, the effect of groundwater overexploitation restoration in Hebei Province was remarkable, and the effect grade was improved from fair to good. The effect grade of different subsystems was upgraded from poor, fair, or medium to medium or good. All cities achieved results in groundwater overexploitation restoration. By 2019, all cities in Hebei Province had achieved a medium or higher groundwater overexploitation restoration effect grade, and there was one city with a groundwater overexploitation restoration effect grade of excellent.
(2) Strict control of exploitation and reduction of consumption is the key to solving the problem of groundwater overexploitation, and 'Increasing water sources' measures such as the replacement of water sources and the implementation of ecological water recharge to rivers and lakes are indispensable and important means. The measures that have a greater impact on the effect of groundwater overexploitation restoration are different for various cities. Each city should strengthen the measures that have a greater impact on the effect of groundwater overexploitation restoration in that city while supplementing the measures that are insufficient.

Although this paper comprehensively considered the impact of groundwater overexploitation restoration on the GESEE system, many factors influence the effect of groundwater overexploitation restoration. Some indicators, such as the better groundwater quality rate and the ground subsidence decline rate, are not included in the indicator system in Hebei Province due to the difficulty of collecting relevant data, which has a certain influence on the results. In future studies, these data need to be collected in a targeted manner to further consolidate the basic information.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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