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Governance and Monitoring Systems for Groundwater Over-exploitation Areas: A Case Study of Xiaogan City, Hubei Province

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Abstract This study focuses on the governance of groundwater over-exploitation in Xiaogan City, systematically analyzing the current status of over-exploitation, the implemented governance measures, and the effectiveness of the monitoring system. The findings indicate that comprehensive strategies, including law-based water management, enhancement of the monitoring network, strict enforcement of water drawing permits, optimization of water resource allocation, and promotion of a water-saving society, have contributed to a continuous rise in groundwater levels in Xiaogan City. Over the past decade, water levels in the center of the depression cone have risen by 4 m in the first aquifer and by 14 m in the second aquifer. The article also incorporates advanced technologies, including the "space-air-ground" integrated monitoring network and artificial intelligence-based prediction and early warning systems in the Haihe River Basin, alongside governance experiences from North China, to offer theoretical insights and practical guidance for developing groundwater over-exploitation governance and monitoring systems in comparable southern regions.

Key words Groundwater over-exploitation, Monitoring system, Management of over-exploitation areas, Xiaogan City, Water resource management

0 Introduction

Groundwater possesses significant resource characteristics and ecological functions. It constitutes a vital component of China's strategic water resource reserves and plays an indispensable role in mitigating regional water supply pressures, sustaining the health of rivers and lakes, and ensuring ecological stability. The *Regulations on Groundwater Management*, which came into effect on December 1, 2021, systematically delineate the legal responsibilities associated with the rational development and protection of groundwater from the aspects of investigation and planning, conservation and protection, control of over-exploitation, pollution prevention and control, as well as supervision and management. This regulatory framework signifies a new phase in the rule of law governing groundwater management in China.

However, the issue of groundwater over-exploitation in China continues to be critical. Over-exploitation occurs to varying extents in 21 provinces, autonomous regions, and municipalities nationwide, with some areas experiencing deep groundwater exploitation. Such groundwater over-exploitation not only compromises the sustainable use of water resources but also frequently results in a range of ecological and environmental problems, including land subsidence, the reduction of rivers and lakes, and ecological degradation. In recent years, the North China region has attained significant progress through systematic governance. By the end of 2025, compared to 2020, the groundwater levels in this region had generally increased. Specifically, the average shallow groundwater level in the managed areas rose by 3.76 m, while the average deep groundwater level increased by 7.65 m. Research conducted by Professor Long Di and his team from the Department of Hydraulic Engineering at Tsinghua University indicates that human intervention has been the decisive factor in the restoration of aquifers in North China. Consequently, North China has become the first region globally to achieve large-scale aquifer restoration.

Xiaogan City, as one of the few cities in southern China relying on groundwater as its primary water supply source, has maintained groundwater exploitation within the annual permissible limits over the years. Nevertheless, due to the suboptimal spatial distribution of the original exploitation wells within the urban area, localized over-exploitation has occurred, thereby posing a potential threat to the regional groundwater system. Furthermore, the existing monitoring network is insufficient to comprehensively and accurately capture groundwater dynamics and to analyze the characteristics of changes in the water resource environment. Consequently, a systematic review of the experiences in managing groundwater over-exploitation in Xiaogan City, alongside an analysis of the prevailing challenges, holds considerable theoretical importance and practical significance for enhancing groundwater monitoring systems in southern China and advancing the refined management of water resources.

In recent years, considerable advancements have been achieved in the research and development of technologies for controlling and monitoring groundwater over-exploitation. Regarding monitoring technologies, the Haihe River Basin has established a three-dimensional groundwater monitoring network characterized by a three-tier linkage system encompassing "national, basin, provincial and municipal levels", as well as "space-air-ground" multi-dimensional coordination. Utilizing gravity satellite remote sensing inversion technology, this network has enabled long-term and large-scale analyses of groundwater reserve dynamics. Concerning governance models, the Beijing - Tianjin - Hebei region has initiated a major project focused on "key technologies for the

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synergistic restoration of water volume, water quality, and water ecology", resulting in the development of a comprehensive technical framework encompassing "monitoring, assessment, governance, and control". In theoretical research, investigations into critical technologies, such as the mechanisms underlying groundwater over-exploitation, replenishment and restoration processes, and early warning and control systems, have been progressively deepened. Furthermore, novel technologies and methods, including artificial intelligence-based prediction and early warning systems, have been increasingly implemented. Collectively, these advancements offer valuable insights and references for the management of groundwater resources in Xiaogan City.

1 Overview of the study area

1.1 Geographical location Xiaogan City is situated in the northeastern region of Hubei Province, with geographical coordinates 113°19′01″ – 114°35′12″ E, 30°23′22″ – 31°51′24″ N. It borders Wuhan, the provincial capital, to the southeast; adjoins Huangpi District and Hong'an County of Wuhan City to the northeast; shares boundaries with Luoshan County and Suizhou City of Henan Province to the northwest; and is contiguous with Tianmen, Jingshan, and other counties and cities to the west (Fig. 1). The city spans 164 km from north to south and 120 km from east to west, encompassing a total land area of 8 910 km^2.

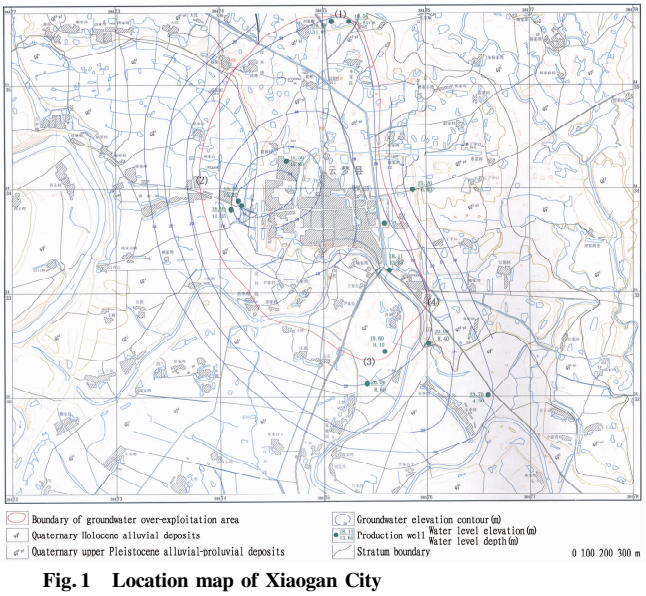

Fig. 1 Location map of Xiaogan City

1.2 Topography and landforms Xiaogan City is situated north of the Yangtze River and south of the Dabie and Tongbai Mountains, encompassing regions within both the Yangtze River and Huai River basins. The Yangtze River Basin covers an area of 8 438.12 km^2, while the Huaihe River Basin spans 471.88 km^2. The topography generally descends from north to south: the northern region consists of low mountainous terrain, with peak elevations typically ranging from 400 to 800 m; the highest points are Wuyue Mountain (880 m) and Shuangfengjian (873.7 m). The central area is characterized by hills with elevations between 50 and 150 m. The southern region comprises plains, rivers, and lakes, forming part of the Jianghan Plain, where elevations are below 50 m, with the lowest point located at Tongjia Lake in Xiaonan District (17.5 m).

1.3 Geological structure and hydrogeological conditions The regional geological framework is complex, encompassing two structural units: the Qinling Trough and the Yangtze Platform. This area is segmented by major regional faults, with the primary controlling fault identified as the Qingshankou Fault. Based on groundwater occurrence conditions, the characteristics of water-bearing rock formations, and hydrodynamic properties, groundwater in Xiaogan City can be categorized into five types: Quaternary pore phreatic water, Quaternary pore confined water, bedrock fissure water, bedrock pore fissure water, and carbonate rock fissure karst water (Fig. 2). It is noteworthy that prolonged groundwater exploitation has altered hydrogeological conditions in certain areas.

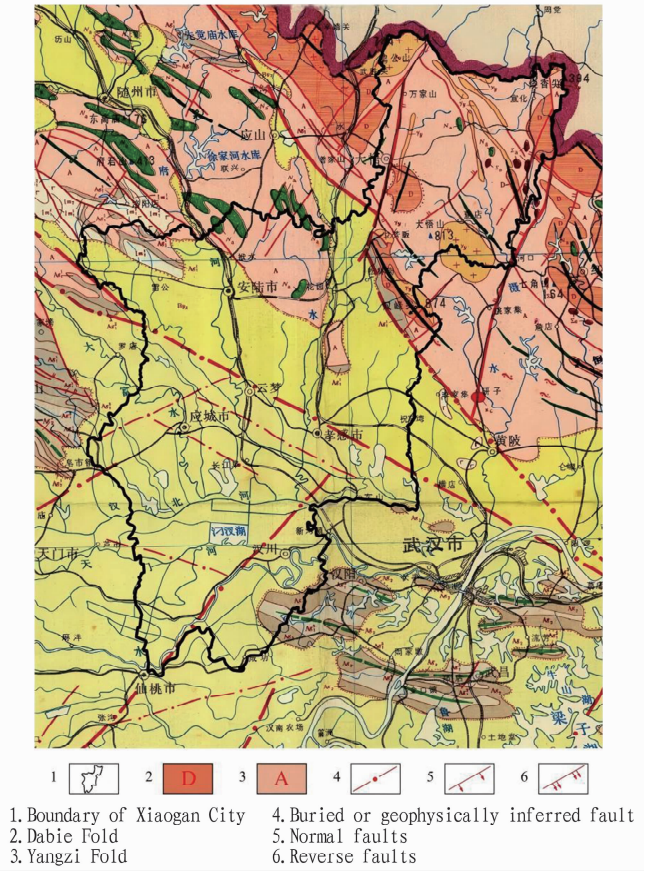

Fig. 2 Geological structure map of Xiaogan City

2 Zoning and analysis of groundwater over-exploitation areas

2.1 Criteria for determining over-exploitation areas According to the *Guidelines for the Evaluation of Groundwater Over-Exploitation Areas* (SL286-2003), three fundamental criteria are used to determine groundwater over-exploitation: the actual exploi-

tation volume exceeding the exploitable volume; a continuous decline in groundwater levels; and ecological and geological environmental issues resulting from groundwater exploitation. An area exhibiting any one of these criteria is classified as an over-exploitation zone.

2.2 Distribution of over-exploitation areas in Xiaogan City

In 2007, the People's Government of Hubei Province approved the *Zoning Plan for Groundwater Over-exploitation and No-exploitation Areas in Hubei Province* (EZH [2007] 54), which identified a total of 15 over-exploitation areas and 3 no-exploitation areas. Notably, Xiaogan City was designated with three over-exploitation areas.

(i) The groundwater over-exploitation area in Xiaogan City (No. 18207) extends from Xiongjiazui in the east to Liujiadawu in the west, and from Sanliqiao in the north to Laohuanhe in the south, encompassing an area of 76 km^2 (Table 1 and Fig. 3). This region represents the most significant zone of groundwater over-exploitation within Xiaogan City, characterized by a prolonged history of groundwater drawing and a marked decline in local water levels.

Table 1 Coordinates of the inflection points in groundwater over-exploitation areas of Xiaogan City

No.	Longitude	Latitude	No.	Longitude	Latitude
1	113°52′40″	30°56′32″	2	113°52′40″	30°54′57″
3	113°56′11″	30°54′57″	4	113°56′11″	30°56′32″

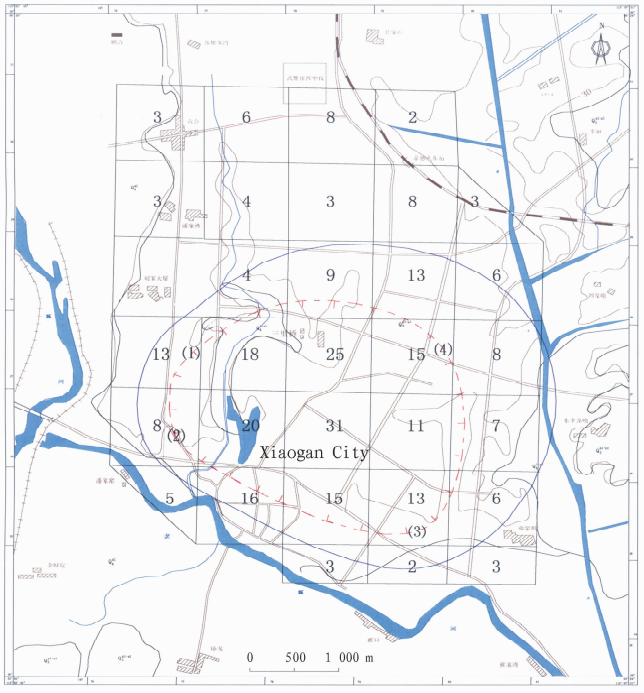

Fig. 3 Scope of groundwater over-exploitation areas in Xiaogan City

(ii) The groundwater over-exploitation area in the urban area of Yunmeng County (No. 18109) extends from Dongjiawan in the east to Huangjiahu in the west, and from Liujiafan in the north to Lijiataizi in the south, encompassing a total area of 7 km^2 (Table 2 and Fig. 4).

Table 2 Coordinates of the inflection points of groundwater over-exploitation areas in the urban area of Yunmeng County

No.	Longitude	Latitude	No.	Longitude	Latitude
1	113°44′25″	31°02′31″	2	113°43′32″	31°01′35″
3	113°44′36″	31°00′42″	4	113°44′57″	31°01′03″

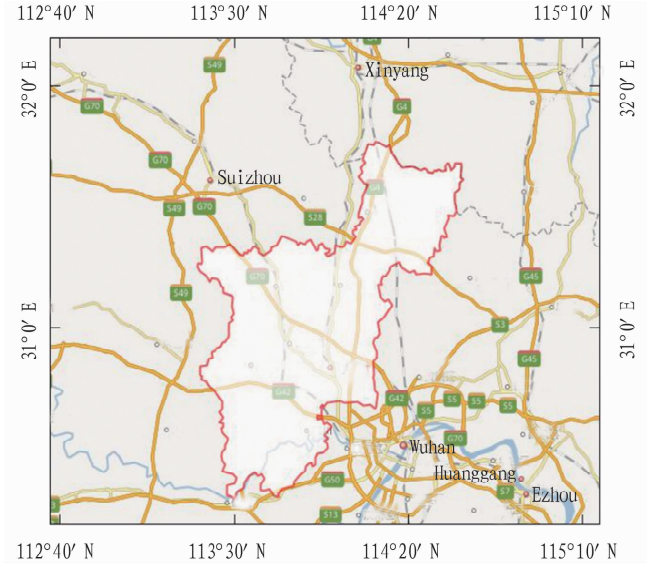

Fig. 4 Scope of groundwater over-exploitation areas in the urban area of Yunmeng County

(iii) The groundwater over-exploitation area in Yitang Town, Yunmeng County (No. 18108), extends from Tujiawan in the east to Fuhe in the west, and from the northern part of Yitang Town in the north to Pengnan of Caotang in the south, encompassing a total area of 1.76 km^2 (Table 3 and Fig. 5).

Table 3 Coordinates of the inflection points of groundwater over-exploitation areas in Yitang Town, Yunmeng County

No.	Longitude	Latitude	No.	Longitude	Latitude
1	113°42′35″	31°06′02″	2	113°42′12″	31°05′38″
3	113°42′29″	31°05′08″	4	113°42′50″	31°05′33″

2.3 Historical evolution of groundwater exploitation

Groundwater exploitation in Xiaogan City can be categorized into four distinct stages: (i) the initial exploitation stage (1950 – 1980), during which water was extracted from a limited number of motor-pumped wells; (ii) the rapid growth period (from 1980 onward), characterized by a significant increase in the number of exploitation wells driven by industrial and agricultural development and population growth; (iii) the peak exploitation period (1995 to the early 2000s), when both the number of exploitation wells and the volume of groundwater exploitation reached historical highs; and (iv) the adjustment period (2003 to the present), marked by a

gradual decline in the number of exploitation wells as a result of the implementation of regulatory management measures.

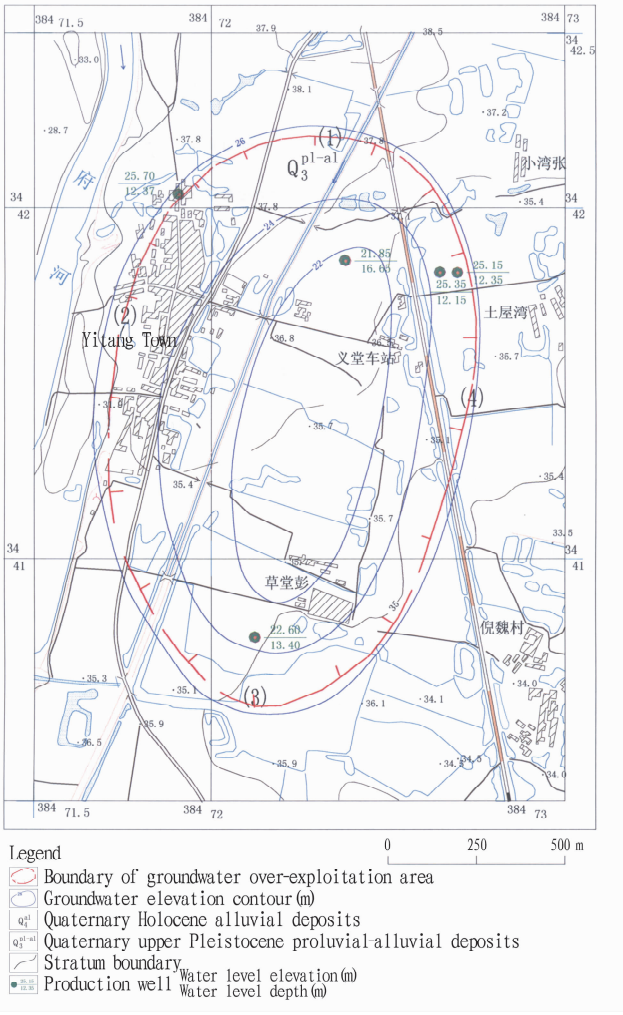

Fig. 5 Scope of groundwater over-exploitation areas in Yitang Town, Yunmeng County

3 Measures and achievements in the governance of groundwater over-exploitation

3.1 Governance measures system The Water Conservancy Department of Xiaogan City has implemented a contemporary water management policy emphasizing "water conservation, spatial equilibrium, systematic governance, and collaborative efforts between government and market". Consequently, it has established a comprehensive seven-in-one governance system to address groundwater over-exploitation.

3.1.1 Construction of a legal guarantee system. Laws and regulations, including the *Water Law*, the *Water Pollution Prevention and Control Law*, the *Regulations on License for Water Drawing and Levy and Administration of Water Resource Fees*, and the *Regulations on the Administration of Groundwater*, are rigorously enforced to enhance the dissemination and education of water-related legislation and to strengthen the law enforcement framework. Emphasizing the development of the water law system, the water administrative law enforcement system, and the water resources management system, it is imperative to comprehensively advance water governance and management in strict accordance with legal provisions, ensuring the stringent enforcement of approval procedures for groundwater withdrawal.

3.1.2 Improvement of groundwater monitoring network. In response to the challenge of comprehensively and accurately capturing groundwater dynamics, Xiaogan City has implemented several measures. First, it has intensified the development of the groundwater monitoring system to improve the timeliness and accuracy of data collection. Second, it has enhanced groundwater quality monitoring by expanding both the scope and the range of monitored parameters. Third, it has strengthened the capacity of the monitoring team and optimized the management framework. Fourth, it has improved the analysis of monitoring data and conducted groundwater trend forecasting. Currently, there are 26 water level monitoring points within the urban area. A total of 22 national groundwater monitoring stations have been established throughout the city, and 4 provincial stations have been upgraded and renovated, thereby effectively forming a groundwater monitoring network in the plain area. In 2021, plans were made to add 33 new monitoring stations to further enhance monitoring capacity.

3.1.3 Metering management for water users. A comprehensive network of water drawing metering stations is a critical prerequisite for the protection of groundwater and the management of over-exploitation areas. Xiaogan City has enhanced the monitoring and reporting of water drawing volumes by users and has employed the water usage statistics system of the Ministry of Water Resources to facilitate data reporting. Furthermore, the city has taken decisive measures to prevent unmetered water exploitation and the damage of metering facilities, thereby promoting a more scientific and rational approach to the development and utilization of groundwater resources.

3.1.4 Water drawing permit approval system. In accordance with applicable laws, regulations, and the *Interim Provisions on the Collection and Administration of Water Resources Fees* in Xiaogan City, a hierarchical approval system involving provincial, municipal, and county levels is implemented. For new, renovated, and expanded projects within restricted exploitation zones, rigorous water resource assessments are required to prevent high water-consuming projects from extracting groundwater. Currently, the urban water supply network fully covers the urban area of Xiaogan and adequately meets water demand. Except for a limited number of emergency water source wells retained, all other exploitation wells have been sealed.

3.1.5 Prevention and control of groundwater pollution. The discharge of the "three wastes" should be rigorously regulated. Wastewater with a high discharge volume must undergo treatment to comply with established standards prior to discharge. Abandoned or unsealed exploitation wells should be strictly sealed and filled in accordance with technical specifications. During the

irrigation period, the application of chemical fertilizers and pesticides should be carefully controlled, and the use of sewage for irrigation should be limited. Additionally, measures must be taken to minimize damage to the aquifer structure caused by deep engineering activities to prevent sewage infiltration.

3.1.6 Optimal allocation of water resources. The average annual water consumption in Xiaogan City is approximately 2.4 billion m^3, with groundwater constituting roughly 3% of this total. According to Document No. 30 issued by the Hubei Provincial Government in 2013, the total water consumption control target for 2030 is set at 3.363 billion m^3, allowing for an additional capacity of 963 million m^3. Although the urban area of Xiaogan is located merely 6.8 km from the Han River, its economic development is constrained by insufficient seasonal water inflows from the Fuhuan and Hanbei River basins. Therefore, it is imperative to enhance the construction of water conservancy infrastructure, undertake research on water diversion projects, and progressively substitute groundwater usage with surface water sources.

3.1.7 Construction of a water-saving society. It is essential to comprehensively advance the development of institutional frameworks, management mechanisms, and water conservation projects. Currently, Xiaochang County, Hanchuan City, and Anlu City have successfully passed the acceptance inspections for water-saving societies, while other counties and cities continue to make steady progress. By reducing the water quota for residents and decreasing water consumption per 10 000 yuan of industrial added value, total surface water usage can be diminished, thereby indirectly limiting groundwater exploitation.

3.2 Governance effectiveness Significant progress has been achieved in mitigating groundwater over-exploitation in Xiaogan City through sustained governance efforts. Over the past decade, groundwater levels have exhibited a stable upward trend. Specifically, the groundwater level in the center of the depression cone in the first aquifer has increased by 4 m, while that in the center of the depression cone in the second aquifer has risen by 14 m. This success is attributed to a comprehensive governance model that integrates multiple strategies, including legal safeguards, monitoring and early warning systems, engineering regulation and control, and management innovation.

3.3 Experience drawing and application of cutting-edge technologies Xiaogan City can benefit from the advanced groundwater treatment experiences implemented throughout China. Regarding monitoring technology, the Haihe River Basin has developed a multi-dimensional, collaborative monitoring network encompassing "space, air, and ground" components, enabling integrated data collection. Additionally, it has established a data-driven groundwater level prediction model utilizing various artificial intelligence techniques. Concerning governance models, the Beijing – Tianjin – Hebei region has developed a collaborative restoration technology system addressing "water volume, water quality, and water ecology". In terms of theoretical research, studies conducted by institutions such as Tsinghua University have demonstrated the critical influence of human intervention on aquifer recovery. The aforementioned experiences offer valuable technical support for enhancing groundwater management practices in Xiaogan City.

4 Current status of the monitoring system and optimization recommendations

4.1 Current status of the monitoring system During the initial phase of the national groundwater monitoring project led by the Ministry of Water Resources, Xiaogan City had established 22 national groundwater monitoring stations and upgraded 4 provincial monitoring stations, thereby effectively achieving comprehensive coverage of the groundwater monitoring network in the plain areas. Utilizing the Ministry of Water Resources' groundwater online compilation system, the city has enabled not only online data compilation but also real-time analysis, reflecting a relatively advanced level of informatization. Furthermore, the construction of 33 additional monitoring stations in 2021 has further strengthened Xiaogan City's groundwater monitoring capabilities.

Compared to the advanced "space-air-ground" integrated monitoring network in the Haihe River Basin, the monitoring system in Xiaogan City exhibits several deficiencies. First, the density of the monitoring station network is inadequate, resulting in limited monitoring capacity in certain areas. Second, the monitoring techniques employed are relatively limited, with emerging technologies such as remote sensing not yet fully utilized. Third, the capabilities for monitoring data analysis and early warning require significant enhancement. Fourth, the integration mechanism between monitoring and management processes necessitates further improvement.

4.2 Optimization recommendations In response to the aforementioned issues, the following optimization recommendations are proposed. First, supplementary investigations into groundwater hydrogeology should be conducted, and the configuration of monitoring network points must be scientifically optimized. Second, monitoring methods should be enhanced by progressively incorporating automated monitoring equipment and information management platforms, alongside the establishment of a comprehensive monitoring database. Third, the exploration and application of novel technologies and methods, such as remote sensing monitoring and artificial intelligence-based prediction, should be pursued. Fourth, the linkage mechanism encompassing "monitoring, assessment, early warning, and control" should be improved to ensure comprehensive support throughout the entire process, from data collection to management decision-making.

5 Existing problems and countermeasure suggestions

5.1 Existing problems (i) The awareness of the rule of law requires significant enhancement: certain water users demonstrate a limited understanding of regulations, including the *Water Law*, and exhibit weak awareness regarding the legal framework governing the utilization and protection of groundwater. Consequently,

illegal water withdrawals occasionally occur in industrial and agricultural production, as well as in urban and rural settings. (ii) Inadequate law enforcement: the existing water resources management system and associated regulations necessitate further improvement. The enforcement of water-related laws and regulations is currently insufficient, and both the rigor and effectiveness of supervisory mechanisms require strengthening. (iii) Incomplete monitoring and planning: there is an urgent need to develop and implement updated plans for the development, utilization, and protection of groundwater resources. Additionally, dynamic supervision should be intensified in both no-exploitation and over-exploitation areas. (iv) Limited technological support capacity: the analysis of monitoring data lacks depth, predictive and early warning capabilities remain weak, and the adoption of new technologies and methods is inadequate.

5.2 Countermeasure suggestions (i) Enhancing legal publicity and education: it is essential to intensify the dissemination of laws and regulations pertaining to groundwater, thereby increasing societal awareness of groundwater protection and fostering a conducive environment for lawful water management and scientific water use. (ii) Strengthening law enforcement and supervision systems: the water resources management framework and mechanisms should be improved, with an emphasis on building a robust law enforcement team, intensifying investigations and penalties for illegal water exploitation, and ensuring strict compliance with relevant laws and regulations. (iii) Advancing monitoring and early warning mechanisms: drawing upon the multi-scale "monthly, quarterly, and annual" monitoring and early warning system employed in the Haihe River Basin, a groundwater level change prediction and early warning system should be established to promptly detect and respond to over-exploitation dynamics. (iv) Promoting the application of scientific and technological innovations: active exploration of new technologies, such as artificial intelligence-based prediction models and remote sensing monitoring, is necessary to enhance the precision and scientific rigor of groundwater management. (v) Facilitating regional collaborative governance: strengthening cooperative water resource management with adjacent regions is crucial, alongside exploring the establishment of cross-regional mechanisms for groundwater protection and governance coordination.

6 Conclusions

Focusing on the governance of groundwater over-exploitation in Xiaogan City, this study systematically examines the current status of groundwater over-exploitation, the implemented governance measures, and the accomplishments in establishing a monitoring system. The main findings are as follows: Xiaogan City has developed a relatively comprehensive governance framework for groundwater over-exploitation through a combination of strategies, including law-based water management, enhanced groundwater monitoring, stringent regulation of water user metering, standardization of water drawing permits, intensified prevention and control of groundwater pollution, optimization of regional water resource allocation, and the promotion of a water-saving society. These governance efforts have yielded significant results. Over the past decade, groundwater levels in the center of the depression cones in the first and second aquifers have risen by 4 and 14 m, respectively, effectively mitigating the trend of groundwater over-exploitation. The monitoring system has largely been established, but continuous optimization is required concerning station network density, technological methods, and data analysis. It is advisable to draw upon the experience gained from constructing an integrated "space-air-ground" monitoring network in the Haihe River Basin to further strengthen monitoring and early warning capabilities. Xiaogan City, as one of the few southern cities relying on groundwater as its primary water supply, offers governance experiences that are valuable references for similar regions. Future efforts should focus on enhancing the application of scientific and technological innovations and fostering regional collaborative governance to advance groundwater resource management toward more scientific, precise, and intelligent approaches.

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