International Journal of Sustainable Studies, Technologies, and Assessments

IJSSTA

Original Article

Water Security and Technological Innovation in China

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Received: 04 October 2025 / Revised: 03 November 2025 / Accepted: 26 November 2025 / Published online: 30 December 2025

https://doi.org/10.5281/zenodo.18138911

Abstract: Water security is emerging as a critical issue for China because of various key factors, such as the unequal distribution of water resources and climate variability. As a consequence, China presents important structural imbalances between the humid South and the arid North, also causing groundwater depletion, subsidence and drought. These vulnerabilities need the integration of scientific observation and technological innovation in order to build sustainable and resilient water management frameworks. This study combines hydrological monitoring and advanced modelling to examine some crucial contexts in several Chinese regions and the water reuse strategies. By analysing data and new technologies, the paper aims to represent a scientific foundation for China's transition in the direction of climate-resilient governance and sustainability. Unlike most studies that focus on isolated hydrological or infrastructural components, this analysis proposes an integrated, machine-learning based framework that links hydrological, climatic and socioeconomic data to support climate-resilient water governance in China.

Keywords: *China, water security, climate resilience, groundwater depletion, technological innovation, predictive modelling.*

1. Introduction

Water security is one of the most relevant challenges that China is facing in the contemporary era. The unequal spatial distribution of water resources and the rising climate variability are damaging structural imbalances between the humid South and the arid North in the country. These conditions result in groundwater overextraction, widespread subsidence and increased exposure to droughts, with implications for the environment.

To mitigate these vulnerabilities, it is necessary to adopt an integrated approach, able to combine scientific observation, constant monitoring and technological innovation. In this context, advanced techniques and digital systems for the urban resilience and water reuse are central.

This paper aims to analyse some emblematic cases about Chinese water complexity (from the South-to-North transfer project, to the critical issues of the North China Plain, from the dynamics of Poyang Lake to the Sponge

Cities initiatives and water strategies in Tianjin) in order to deeply understand how data, technologies and innovation can contribute to the construction of a more sustainable and resilient water governance. The main purpose is to offer a scientific basis, able to lead new environmental policies, by integrating predictive modelling, governance mechanisms and multi-scale decision-making.

2. Literature Survey

The expression "Water Security" is central to scientific debate in China, which involves not only the environmental dimensions but also the socioeconomic ones. Recent research defines water security as the capability to guarantee a balance among availability, quality and water demand, and to prevent risks linked to extreme phenomena. The spatial inhomogeneity of resources and the increasing environmental variability have emphasized structural vulnerability, especially in the northern regions, where the intense exploitation of aquifers contributes to the water deficit. Even though China hosts 20% of global population, it owns only the 7% of global renewable water resources, a condition that is even worsened by rainfall concentrated in a few months and long dry seasons. These dynamics not only increase pressure on the availability of water for several uses, but also increase the likelihood of severe droughts, with significant effects on agricultural production and economic stability.

Two interconnected phenomena that the literature studies are groundwater depletion and land subsidence: in some Chinese plains, like the North China Plain, intensive irrigation, urbanization and growing demand have led to over-exploitation of aquifers, with a lowering of the groundwater surface and widespread subsidence phenomena. Studies based on satellite data show significant declines of groundwater resources and extensive subsidence, causing risks and damage for infrastructures and urban communities. At the same time, recent analyses show that droughts in China are becoming even more intense and frequent, pushing many regions under stress. Changes in water availability due to climate variability are exacerbating this trend, with serious impacts on food security and urban and rural water resources.

An answer to water shortage in northern China is the *South-to-North Water Diversion Project* (SNWDP), the biggest fresh water transfer project in the world. It has been created in order to divert some large volumes of water from humid southern basins to northern regions every year. Literature shows that this project has had interesting effects on pressure reduction of northern aquifers. Particularly, recent studies highlight that the contribution of diverted water has allowed some cities, like Beijing, to recover part of their declining groundwater resources, trying to reduce subsidence phenomena and increasing water resources resilience. However, the project is not without critical issues: analyses underline environmental costs, changes of river ecosystems and impacts on the hydrological regime of source areas, as well as issues related to economic sustainability throughout the project's life cycle.

Another key factor emphasized by literature is the urban management of water scarcity, with a particular focus on innovative programs such as Sponge Cities. This model presents ecological infrastructures in order to strengthen city capabilities to absorb, store and reuse rainwater, reducing the sudden rainfall effect and improving the availability of useful resources in dry periods. This strategy has been implemented in over thirty cities and it aims to recycle a significant amount of rainfall, in order to contribute to urban resilience.

Other cities, such as Tianjin, are adopting new strategies of water reuse and diversification of water sources, in combination with water saving and better demand management. All these urban programs have shown important improvements but are still facing challenges linked to long-term monitoring and public engagement, highlighting how water security solutions need dynamic and integrated approaches.

Beyond technical and hydrological dimensions, recent studies highlight governance and institutional constraints as key determinants of water security outcomes in China; however, fragmented regulatory frameworks often reduce the effectiveness of water management strategies. For this reason, it is necessary to create an integrated approach that combines technological innovation with institutional capacity and long-term planning. Recent research has explored the application of data-driven and machine learning approaches to water security assessment. Particularly, machine learning models have shown strong potential in capturing non-linear relationships among different variables, improving groundwater monitoring, drought prediction and scenario analysis.

This study is important to underline the multidimensional problem of water security in China. It involves climatic and infrastructural factors. Even though some infrastructural projects, like the SNWDP, have reduced the pressure on northern resources, there still are environmental, economic and social issues. In the meantime, several innovative urban solutions, like Sponge Cities and water reuse, offer new approaches to water management in metropolitan contexts. Some existing studies focus on isolated components of the water systems (hydrological processes, or urban resilience strategies), revealing in the literature a gap in the integration of predictive modelling and governance mechanisms. Addressing this gap requires interdisciplinary and data-driven frameworks, able to support adaptive and climate-resilient water management.

3. Proposed Methodology: comparative analysis of existing solutions

Starting from the limitations in existing water management approaches, this section introduces an integrated methodology thought for supporting adaptive and forward-looking decision-making.

The proposed methodology is based on the need to understand whether water management strategies in China are effective and to evaluate how they can be combined with new scientific and technological tools. The goal is to identify the strengths, issues and possibilities for improvement, in order to create a useful framework for the development of predictive models and innovative solutions.

3.1 Review of current water management strategies

The first phase involves a deep analysis of already implemented policies and interventions in the country.

This review is useful to detect the main approaches adopted by China, and their purposes:

- Big infrastructural projects, like the South-to-North Water Diversion Project (SNWDP), created to reduce the northern water deficit, through long-distant transfer. It tries to rebalance the national water availability by conveying large amounts of water from the southern regions to the northern basins, which are frequently under stress. This kind of intervention is a strategic pillar of Chinese national politics about water redistribution.

- Groundwater management policies, that aim to limit aquifers' overexploitation and to insert a constant monitoring systems – through satellite and *Gravity Recovery and Climate Experiment* (GRACE). These new technologies permit to track variations and critical areas, considering also the impacts of weather conditions. The introduction of integrated digital platforms has improved the ability to detect long-term trends and correct extraction policies.
- Urban resilience strategy, including the national program of Sponge Cities, that promotes green infrastructures and solutions based on nature with the purpose of increasing water retention capacity. The program aims to strengthen local water reserves and improve water quality by mixing natural processes with the urban pattern. Pilot experiences in Wuhan and Xiamen have shown significant results, but challenges linked to monitoring and coherence across different administrative levels still exist.
- Reuse initiatives and water recycle, adopted in many coastal cities like Tianjin, where wastewater reuse and low-energy desalination contribute to the diversification of sources. These strategies want to cut dependence on traditional sources and to support water-intensive industrial sectors.

3.2. Assessment of effectiveness and limitations of existing interventions

The above-mentioned strategies adopted in China show the important progress made by the country in the field of water resources management, but also how these interventions present structural limits that affect long-term effectiveness. The most emblematic case is the South-to-North Water Diversion Project which is energy-intensive. Moreover, it doesn't eliminate the structural dependence on a large infrastructure, which does not address the deepest causes of the water imbalance between North and South.

Groundwater management also has benefited from the introduction of advanced monitoring technologies, which today allow to observe precisely the evolution of aquifers and to detect the most vulnerable areas. Despite that, governance is still fragmented: regional regulations differ and the institutional coordination often is weak. In the cities, instead, the Sponge Cities program has introduced an innovative approach based on green infrastructures and the ability to absorb rainwater. Although in some cities the results are encouraging, the overall effectiveness remains uneven: many projects need ongoing maintenance that isn't always guaranteed, and in some cases adequate monitoring systems are lacking to assess their effects over time. The same applies for water reuse and desalination systems, which are a fundamental resource especially for coastal areas. However, these processes are expensive and hard to manage. For this reason, they represent important solutions but difficult to scale up or to consider as complete answers to the problem of water security.

These strategies show that China has invested a lot and innovated in various sectors, but the country still has to face technical, administrative and economic limitations. Water and climatic dynamics require a more integrated approach, able to combine scientific observations, digital technologies and tools in order to support planning and water resources management over time. The proposed solutions are compared, considering their ability to reduce water deficit, mitigate overexploitation of aquifers and increase resilience to climate change. Furthermore, the comparative evaluation takes into account the environmental impacts, implementation and maintenance costs and the level of management complexity. Moreover, it is necessary that these strategies are flexible to adapt to advanced systems and tools that will be created. This comparative approach allows to highlight the strengths and limitations of different interventions, providing more effective and adaptive solutions in water resources planning.

4. Development of Machine Learning Model for Water Security

The development of a machine learning model for water security responds to the need to overcome the traditional approaches of water management by introducing new tools capable of anticipating the evolution of water systems in conditions of increasing climate variability. The main goal of the proposed model is to support decision-making processes through reliable predictions and dynamics of the main indicators of water stress, by integrating water, climatic and socioeconomic information. This model aims to detect recurring patterns and non-linear relationships between variables that influence the availability and the demand for water resources, enabling the prediction of critical phenomena such as the decline of aquifers, the intensification of droughts and the risk of subsidence. Another objective is to evaluate the potential effectiveness of different water management strategies by analysing several scenarios and supporting the allocation of resources in uncertain contexts. It also aspires to help the development of a more proactive and adaptive water governance, based on data, by reinforcing the ability to respond to long-term environmental and climate challenges.

The machine learning model shows the ability to capture non-linear interactions between different variables, that enables the anticipation of critical dynamics. It relies on hydrological, climatic and socioeconomic data, coming from both in-situ monitoring systems and satellite observations and official databases. Their combined use overcomes limitations related to data fragmentation and creates a coherent framework of water dynamics at different spatial and temporal scales.

Hydrological variables include groundwater levels and volumes, river flows and water quality data. Particular importance is given to information derived from remote technologies, such as GRACE satellite data, which are essential for estimating changes in groundwater storage and for identifying areas under stress and affected by subsidence.

Climate variables refer to precipitation, temperature, soil moisture and drought indices. All these parameters permit the capture of seasonal variability and long-term trends, linked to climate change (such as extreme events and prolonged droughts).

With regard to socioeconomic variables, they are basically data on population, urbanization, land use, water demand for domestic sectors and agricultural practices. All these are crucial for analyzing the interaction between humans and natural dynamics. Putting these three data categories together allows the model to detect the multidimensional feature of water security and to improve the accuracy of forecasts and scenario simulations.

The evaluation of the model's performance is important in ensuring its reliability and operational utility in supporting water resource management. It is measured using quantitative parameters – such as RMSE and MAE – that allow the assessment of the overall accuracy of forecasts. This model undergoes also a validation process based on historical data and techniques for comparing observed and estimated values, in order to verify the system's capabilities in different spatial contexts. The validation is performed through procedures for dividing data into testing sets and cross-validation techniques are adopted to decrease the risk of overfitting. In addition to statistical information, the evaluation includes a qualitative analysis of the results to avoid numerical interpretations and to ensure that the model's predictions are realistic and useful for contexts of water resources planning and governance. These criteria guarantee the reliable, transparent and replicable nature of this model, which is able to operate in a context characterized by complexity and uncertainty.

Machine learning techniques such as Random Forests and Gradient Boosting models can be employed for the analysis of heterogeneous hydrological and socioeconomic datasets and in order to identify the most significant drivers of water stress. Moreover, Long Short-Term Memory (LSTM) networks are suitable for modelling long-term trends in groundwater levels, drought indices and water demand. They are designed to retain information over long sequences, enabling the model to capture dependencies and trends in time series data, which is crucial for forecasting water stress under changing climate conditions. These approaches offer care and flexibility in capturing complex and non-linear relationships among variables, which makes them relevant for supporting scenario analysis and adaptive decision-making under uncertainty. However, predications coming from machine learning models remain subject to uncertainties related to various factors (data quality, spatial resolution). For this reason, the proposed model should be used as a decision-support tool rather than a deterministic forecast system.

5. Implementation steps of the proposed solution

The methodology for water security management is made up of several operational steps aimed at integrating data and simulation tools.

The first step concerns the analysis of the hydrological, climatic and socioeconomic data from in-situ monitoring systems, official databases and satellite observations, that are submitted to a cleaning process to identify missing values, anomalies and outliers. Moreover, temporal and spatial alignment of the data series is a critical step to guarantee consistency and to reduce distortions that could affect the next stages. Once cleaned, the data are ready for input into the predictive model, that includes spatial and temporal aggregation, with the purpose of reducing dataset complexity. At the same time, new variables are generated through feature engineering, allowing the synthesis of relevant information or the detection of non-linear relationships between hydrological, climatic and socioeconomic values. These operations facilitate result interpretation and create indicators of water stress, vulnerability and resilience.

The next step involves the development of water allocation models, that are created to integrate information on resource status and features of water network, permitting the assessment of the effects of different management strategies (infrastructural interventions, water saving programs, urban policies).

The final step concerns the integration of data and allocation models with the developed machine learning model. This is a very important phase in which the predictive model uses the information to generate forecasts on water availability, drought risk and subsidence, by constant data updates. These steps create an adaptive decision-support system able to simulate future scenarios and to support governance strategies.

6. Case study applications

The effectiveness of the predictive model and the strategies of water resources management is confirmed by applying this methodological framework to a series of case studies which are emblematic of the Chinese water complexity. The cases were selected according to particular criteria to ensure a comprehensive representation: geographic diversity, various kinds of water stress and different scales (from mega-infrastructures to urban contexts). The selected cases are presentative of different geographic and environmental contexts, in order to allow the analysis of structural phenomena such as the groundwater degradation, subsidence, droughts and challenges related to urban water governance.

A. **South-to-North Water Diversion Project**

The South-to-North Water Diversion Project is the most relevant water system of inter-basin transfer in the world and constitutes an instance of large-scale infrastructure management. It has been designed to reduce the inequity of water availability between southern and northern regions of China. It is made up of three main routes (Central, Eastern, Western) to transport large volumes of water to the North of the country. Nevertheless, the project faces several environmental and social issues. Water transfers, indeed, have altered ecosystems and caused pollution problems, requiring the relocation of local communities. Also, its high cost and management raise worries about long-term sustainability. Water recycling and desalination are strategies to mitigate these risks. What is necessary is the integration with a predictive water management model which can simulate future scenarios in order to verify the effectiveness of water distribution always respecting urban and agricultural needs and identifying environmental issues and opportunities.

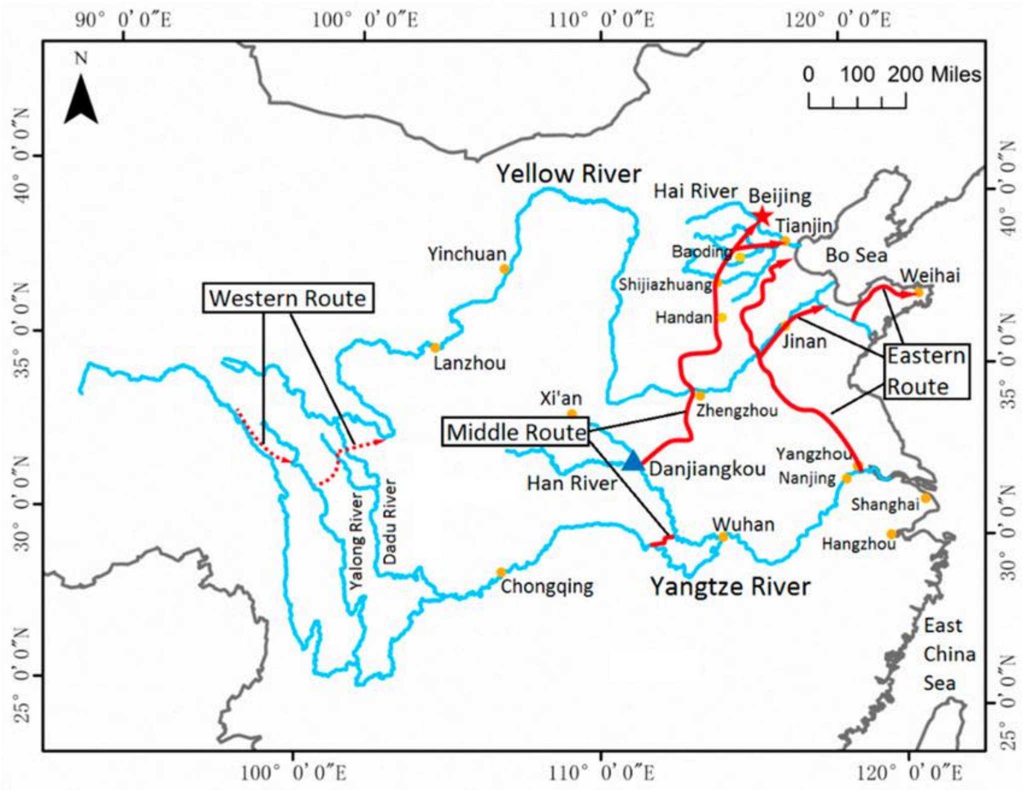

Figure 1. China's South-to-North Water Diversion Project (SNWDP)

https://www.researchgate.net/publication/334368472_China's_South-to-North_Water_Diversion_Project_Empowers_Sustainable_Water_Resources_System_in_the_North

B. **North China Plain**

North China Plain is an alluvial plain in northern China, made up of deposits from the Huang He, Huai and Hai rivers. It is characterized by high population density and intense agricultural activity and presents serious problems of groundwater depletion and subsidence. In addition, frequent and severe droughts are exacerbating water stress for agricultural and urban activities. In this context, the developed predictive model can play a fundamental role, by monitoring water availability in real time and simulating scenarios of water demand and distribution. In this way, predictions help to optimize resource allocation, reduce environmental risks and enhance regional resilience.

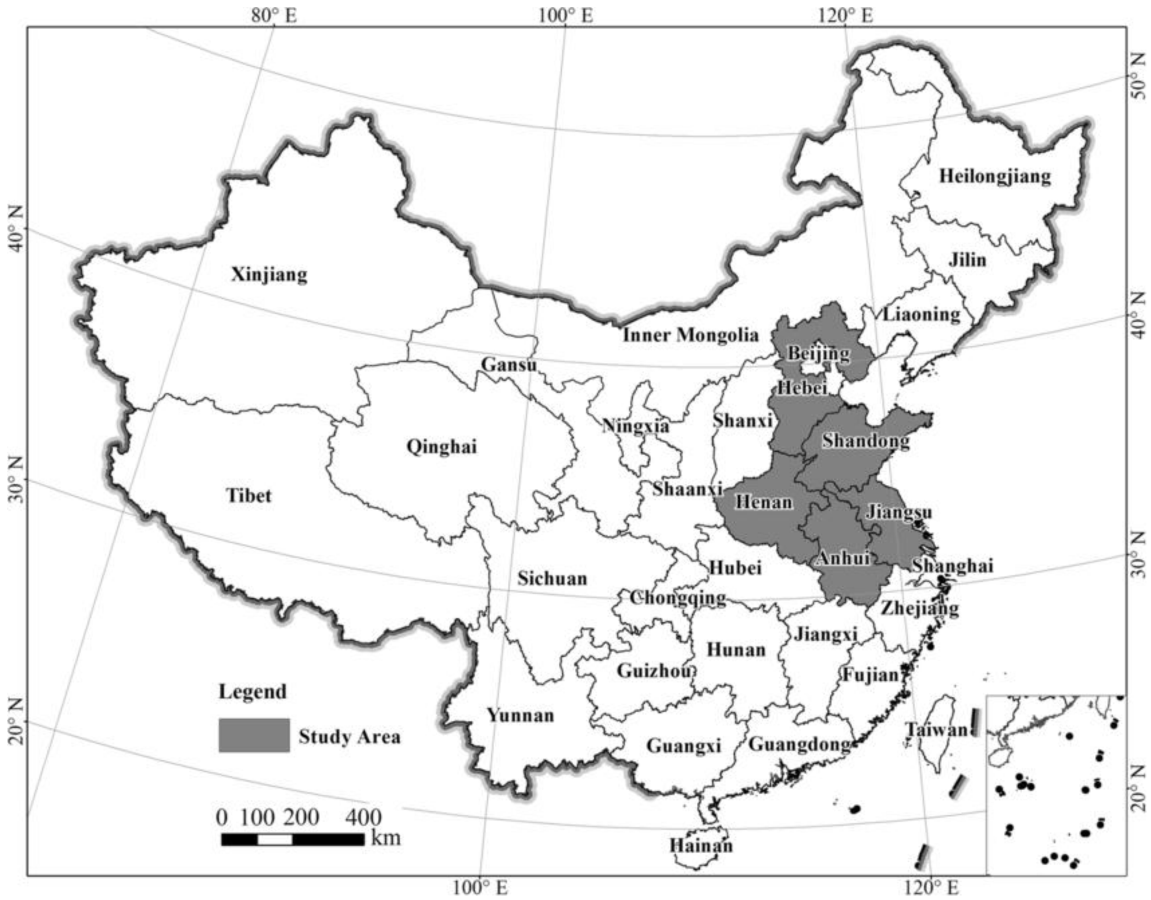

Figure 2. North China Plain

https://www.researchgate.net/publication/330229779_Adaptive_irrigation_measures_in_response_to_extreme_weather_events_empirical_evidence_from_the_North_China_plain

C. Poyang Lake, Sponge Cities and water strategies in Tianjin

Besides large infrastructural interventions, China tries to reach out innovative solutions for water management in natural and urban contexts.

Poyang Lake, the largest freshwater lake in the country, is well-known for its complex hydrological dynamics caused by river regulation, seasonal climate variability and human activities. Sustainable management requires monitoring tools for water levels, droughts and floods. In addition, in urban areas China has implemented initiatives such as Sponge Cities in Wuhan and Xiamen, in order to improve water resilience through green infrastructure that is able to absorb, retain and reuse rainwater. All these projects reduce the effects of extreme rainfall and increase water availability during dry periods.

Finally, coastal cities like Tianjin have adopted water reuse and desalination strategies to diversify water sources and to reduce reliance on groundwater. The integration of a predictive model permits to assess the effectiveness of each strategy, by optimizing the resource allocation and enhancing the overall resilience of natural and urban water systems.

7. Analysis and experimental results

The analysis of the experimental results underlines the potential of the proposed predicative picture as an operational tool for water security in China. By combining hydrological, climatic and socioeconomic data, this model provides a dynamic representation of water system management, moving toward a long-term approach.

One of the most important outcomes is the development of dynamic groundwater maps, which are useful for constant monitoring of aquifers across different regions. These maps are crucial for revealing long-term trend in groundwater levels and for identifying areas that are exposed to critical stress, such as depletion or subsidence. The predictive performance of the model was assessed by comparing simulated outputs with historical observations, and the results show a high degree of consistency and reliability of the model's capacity to anticipate critical developments rather than merely describing past conditions, strengthening its relevance for decision-making under uncertainty. Simulations of infrastructural interventions, water reuse policies, urban resilience measures and demand-management strategies highlight the power of integrated approaches compared to isolated solutions, particularly in reducing pressure on aquifers and enhancing flexibility during extreme climatic events. Furthermore, the proposed framework supports a proactive governance model, where future risks can be anticipated and mitigated through planning.

However, it is important to acknowledge the limitations of the available data, which may not fully capture local variations in hydrological and socioeconomic conditions. The predictive results present uncertainties due to assumptions made in model formulation; in addition, there is a risk of bias in the model, deriving from data gaps or measurement errors, that could influence the accuracy of forecasts. For this reason it is essential to ensure strong interpretation and cautious application of the results in decision-making.

8. Conclusion

Water security represents one of the most worrying environmental and socioeconomic challenges for China, worsened by spatial imbalances and climate variability. This study has addressed these concerns by proposing an integrated, data-driven framework which combines hydrological, climatic and socioeconomic information for the creation of a predictive model. The analysis shows the potential of technological innovation and resilient governance strategies.

Moreover, the representative case studies have contributed to alleviate water stress but they are also facing crucial limitations, that require integrated approaches in order to connect natural and human systems. The development and the application of a machine learning model permit groundwater mapping and forecasting of aquifer depletion and drought phenomena. In this way, the experimental results confirm the model's effectiveness in supporting decision-making processes in conditions of uncertainty and climate stress.

Future research could further develop this framework by integrating real-time governance feedback and applications to other water-stress regions, showing its relevance for sustainable and climate resilient water management.

Beyond the Chinese context, the proposed framework may offer valuable insights for other regions that are experiencing water scarcity and climate variability, contributing to wider international debates on sustainable and climate-resilient water governance.

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