Research Topics

Sustainable development on water resources management, policy and governance in a changing world

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Sustainable development on water resources management, policy and governance in a changing world

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Editorial: Sustainable development on water resources management, policy and governance in a changing world

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Editorial on the Research Topic
Sustainable development on water resources management, policy and governance in a changing world

Water resource management holds a significant role in upholding human wellbeing, agricultural productivity, and the delicate equilibrium of ecosystems. The escalating challenges posed by climate change have led to frequent discussions about the water-energy-food nexus, which underscores the interplay between these elements and their impact on the climate. Consequently, water resource management has emerged as a crucial focal point for endeavors in sustainable development. The complexity of water management and policy formulation has amplified, particularly in economically developing nations, including those with lower to middle-income levels. Beyond the repercussions of climate fluctuations, several factors such as imbalances in power dynamics, restricted access to water resources, and socio-cultural and socio-economic disparities are further complicating the prospects for reaching sustainable water governance across various regions worldwide. Simultaneously, ecological harm and degradation in diverse global locales exert an influence on policies and the sustainable administration of water resources. In the face of the ongoing shifts in our global landscape, the availability and quality of water resources confront grave perils.

In this context, we are honored to introduce this Research Topic of our esteemed environmental journal, a Research Topic of scholarly articles. In this Research Topic consisting of six original research papers, two brief research reports, and one data report, we delve into the intricate web of issues surrounding water resources management, focusing on the policies and governance structures underpinning sustainable development. The importance of each of the following studies cannot be overstated, as they contribute significantly to our understanding of the complexities inherent in water resource management:

The first article on this Research Topic empirically shows a significant positive correlation between the advancement of marine science and technology and the overall sustainability of marine economies. The analysis ventures into the growth models of key marine economic zones, including the "Circum-Bohai Sea Economic Zone," "Yangtze River Delta Economic Zone," and "Pearl River Delta Economic Zone." The study employs a threshold panel model to dissect the influences of five critical factors: opening to international markets, government investment, financial development, human capital, and technology investment. Consequently, it becomes evident that a plethora of external influences converge, sometimes synergistically and at other times restrictively, to shape the overarching impact of innovation in the marine sector (Wu et al.).

Wang et al. venture into the realm of waterfront tourism sustainability in the West Strait of China. This exploration introduces an innovative framework for evaluating the sustainability of waterfront ecotourism. Developed through two rounds of expert consultation, this framework quantifies the significance of various indicators, offering valuable insights for stakeholders in the field. The weighted indicators encompass Waterfront Tourism Design, Ecotourism Experience, Aquatic Ecological Knowledge Sharing, Pro-Water Culture, Pro-Water Identity, Aesthetic Value of Water Landscape, Pro-Water City Brand, Infrastructure Construction, Regional Economic Development, Folkway Support, and Government Policy Support. Empirical data collected from five core cities in the West Strait region illuminate the critical impact of certain indicators, with Pro-Water Culture emerging as the most influential, followed by Aquatic Ecological Knowledge Sharing. In contrast, Pro-Water City Brand and Folkway Support exhibit negligible effects on waterfront ecotourism. This comprehensive evaluation framework paves the way for informed decision-making in the realm of ecotourism sustainability. In another research, Xu et al. embark on a journey to visualize the spatial distribution of water-polluting enterprises in Zhejiang Province, China. It scrutinizes the effectiveness of environmental regulations and underscores the prevalence of water pollution enterprises in regions characterized by lower environmental standards and weaker enforcement. The study employs advanced spatial analysis techniques to reveal that water pollution enterprises tend to cluster, needing more rigorous environmental oversight. These findings underscore the importance of optimizing industrial structures and enhancing surveillance of suburban water pollution enterprises to curtail their environmental impact.

In the follow-up study, the intricacies of collaborative watershed management within the Chehelchay region of Golestan province, Iran are endeavored to be unraveled (Rezaei-Moghaddam and Fatemi). It investigates the organizations involved in managing the watershed, dissecting the types and intensity of communication and interaction between these entities. This network analysis underscores the pivotal role of identifying key actors with substantial social power in the context of local natural resource management. By harnessing the capabilities and resources of these organizations and individuals, the runtime and cost of implementing natural resource projects can be significantly reduced. The study underscores the crucial role of social power and comprehensive participatory management as essential tools for fostering trust among local natural resource users. Moreover, it emphasizes the necessity of transitioning from traditional governmental management paradigms to more inclusive governance structures to ensure the sustainable management of natural resources and watersheds.

Our fifth contribution casts a discerning eye on groundwater quality within Jieshou City, uncovering potential health hazards stemming from abnormal ion concentrations. Through meticulous analysis of hydrogeological conditions, water chemistry, and ion sources, the study offers critical insights into the composition and characteristics of groundwater in the region. The results elucidate that the groundwater in Jieshou City is characterized as marginally alkaline water, dominated by Na + cations and HCO3− anions. Furthermore, the study reveals that Na+ and F− ions exceed the standard for Class-III water quality, with their concentrations positively correlated with monitoring depth. The primary sources of abnormal ions are traced back to fluorine-containing rocks, emphasizing the profound influence of local geological settings, hydrochemical factors, and human activities on groundwater composition by (Su et al.).

Ishaque et al. grapples with the formidable challenge of Pakistan's impending water crisis. The study accentuates the dire consequences of climate change, manifesting in recurring droughts and floods. It posits that inadequate water reservoirs, wasteful agricultural practices, minimal wastewater recycling, and water contamination pose severe health risks and substantial national security threats. The research unequivocally asserts that unless Pakistan addresses its burgeoning water crisis promptly, it has the potential to become the most pressing national security concern. To avert this catastrophe, the article advocates for integrated smart technology solutions, efficient water governance, and sustainable water management strategies. In another study on Pakistan, Majeed et al. takes us to the heart of disaster vulnerability by scrutinizing flash flood susceptibility in the district of Jhelum, Punjab, Pakistan. Employing geospatial models and sophisticated methodologies, this research endeavors to assess and understand the factors contributing to the region's vulnerability. The study meticulously considers eight influential flood-causing parameters, including the Digital Elevation Model, slope, distance from the river, drainage density, land use/land cover, geology, soil resistivity, and rainfall deviation. These parameters are carefully weighted using the Analytical Hierarchy Process (AHP) and Frequency Ratio (FR) methods, enabling a nuanced evaluation of flood susceptibility. This detailed spatial analysis is vital for disaster management authorities, infrastructure planners, and policymakers, providing them with crucial insights to better prepare for and mitigate the impacts of future floods.

Liu et al. employs a synergistic approach, combining the System Dynamics (SD) model and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method, to unravel the dynamic water resources carrying capacity (WRCC) of the Hangbu River basin. This novel method yields intriguing results, indicating that the WRCC of each scenario initially declines before experiencing a resurgence. Notably, the scenario that prioritizes water resources diverges from conventional WRCC studies and underscores the significance of the research method, as well as the specific development focus and level of the study area. The article concludes with prescient recommendations, emphasizing the importance of enhancing irrigation water use efficiency and adopting a forward-thinking approach to regional development.

The final contribution casts a spotlight on the profound impacts of typhoons on agriculture in Taiwan, a coastal region susceptible to extreme weather conditions. This study assesses agricultural losses and emphasizes the role of flood control infrastructure in safeguarding agricultural activities. The research employs Data Envelopment Analysis (DEA) and geographical mapping to unveil spatial disparities in agricultural losses caused by typhoons. Notably, the study highlights how flood control infrastructure has been instrumental in reducing agricultural damage in certain areas (Wei et al.).

As we reflect upon these nine remarkable contributions, a resounding theme emerges—the critical importance of water resources in the context of sustainable development. Whether it be the nexus between marine science and economic prosperity, the evaluation of ecotourism sustainability, collaborative watershed management, groundwater quality, or the looming water crisis, each article underscores the urgency of addressing water-related challenges. Furthermore, our examination of water pollution enterprises, water resources carrying capacity, flash flood susceptibility, and typhoon effects on agriculture all emphasize the intricate interplay between environmental factors, policy decisions, and governance structures. These studies collectively offer guidance and a road map for navigating the complex terrain of sustainable water resource management in an ever-changing world.

The research highlighted in this Research Topic provides valuable insights, not only for scholars and researchers but also for policymakers, practitioners, and the broader community. In closing, we express our heartfelt gratitude to the authors, reviewers, and all those who contributed to this Research Topic. We hope that the reader will find a useful reference on the sustainable management of water resources in this Research Topic.

Author contributions

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Conflict of interest

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Simulation of water resources carrying capacity of the Hangbu River Basin based on system dynamics model and TOPSIS method

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Water resources play a key role in development. The research on water resources carrying capacity (WRCC) is helpful to judge the development status and provide suggestions for regional policy-making. In this study, the System Dynamics (SD) model and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method are combined to calculate the change of WRCC of the Hangbu River basin from 2015 to 2035 under four development scenarios. The results show that WRCC of each scenario decreases first and then increases. The scenario that prioritizes water resources is the best for the Hangbu River Basin, under which the WRCC will increase to 0.631 in 2035, achieving a good level. This is different from other WRCC studies. Through analysis, the research method and the development level and focus of the study area may be the reasons for this difference. In addition, some suggestions were provided such as focusing on improving the efficiency of irrigation water use and looking at the long-term development of the region.

KEYWORDS

WRCC, SD model, TOPSIS method, different scenarios, regional development

1 Introduction

As an irreplaceable and strategic basic resource, water resources play a vital role in social development. The supporting degree of the river basin's economic and social scale is an important aspect of water resources research, and also a key factor restricting the sustainable development of the basin (Zuo et al., 2021). In 2014, the Chinese government put forward new water management policies with water conservation as the priority in response to the increasingly serious water shortage (Wang and Guo, 2021). The evaluation of WRCC is an essential key step in regional water control. WRCC is a concept with natural and social attributes (Feng et al., 2008), but its connotation and meaning are not clear (Hartmann et al., 2014). Hui and Jiang, (2001) believes that WRCC is the maximum support capacity that water resources in a certain region can provide to the social and economic development of the region under the influence of the dual mode of "natural and artificial", based on the foreseeable level of technology, economy, resources; and social development, based on the principle of sustainable development, and through reasonable optimization allocation. Xia and Zhu, (2002) defined WRCC as 'At a certain stage of water resources development and utilization, the available water to meet ecological water demand can maintain the largest socio-economic scale of the limited development goals of population, resources, and environment in the region'; Song et al, (2011) believed that WRCC is the largest environmental supporting capacity that human activities do not harm to the regional water environment at a certain stage of social and economic development; Ren et al, (2016) defined WRCC as the largest industrial, agricultural, population and urban scale that the number of water resources in a specific area can carry without damaging the society and ecosystem. In this study, WRCC is defined as the maximum development potential of the region that can be tapped by available water resources under the sustainable development of social technology and residents' living standards.

At present, there are many studies on the evaluation methods of WRCC. For example, Cao et al, (2020) used the principal component analysis method to evaluate the natural support of water resources in Fuyang; Wu and Jin, (2011) decomposed the weight structure of the evaluation index and established a projection pursuit model which uses the variable weight to evaluate the regional WRCC. Gong and Jin, (2009) adopted the fuzzy comprehensive evaluation method and found that Lanzhou meets difficulties in substandard water quality rather than the lack of water sources in terms of water resources. Peng and Deng, (2020) proposed the DOESBR conceptual model and evaluated WRCC in karst areas using combined weight assignment. Qi et al., 2021 analyzed the impact of climate change on agricultural WRCC in high-latitude basins by using a multivariate statistical analysis method. Liu et al., 2022a considered the interaction between people, water, and the city, pooled long-term data into a Human–Water–City evaluation index system consisting of 13 representative indicators, and used Principal component analysis to study the current and future WRCC in Wuhan. Hu et al., 2022 combine water supply-demand analysis and the S-shaped curve threshold analysis to calculate WRCC in Inner Mongolia. Other widely used methods include the artificial neural network Yu et al., 2020, the logistic attribution model Bai et al, (2019), and set pair analysis Wan et al, (2006).

WRCC of the basin is affected by many factors, and there is a coupling relationship between these factors. Although the above method can qualitatively evaluate the past WRCC of a specific region, it fails to comprehensively and systematically analyze and predict WRCC of the basin quantitatively. The SD model is a system simulation method proposed by Professor Forrester in 1958 (Niu and Sun, 2019), as a method suitable for describing complex systems and analyzing their dynamic behavior, SD can be used to deal with nonlinear, multi-feedback, and multi-level complex system problems (Forrester, 1997). The SD model can transform the interaction between different elements in a complex system into a series of interrelated data streams, and realize system simulation through dynamic feedback (Zhang et al., 2014; Zomorodian et al., 2018). For example, Sun and Yang, (2019) quantitatively evaluated WRCC of Xiong'an New Area by using the SD model, and proposed that the local government should control the expansion of secondary industry; Sun et al, (2017) used the SD model to simulate the status quo of water resources supply and demand in China over the past 15 years and found that the fundamental way to bridge the gap between water supply and demand is to improve water supply.

With only numerical values and no qualitative evaluation, the current state of water resources cannot be known. Since the SD model lacks a comprehensive qualitative evaluation, some scholars combine the SD model with other evaluation methods, such as combining the SD model with an improved fuzzy comprehensive evaluation method (Wang et al., 2021) or combining the SD model with the analytic hierarchy process (Yang et al., 2019). This kind of coupling method can systematically solve the problems of quantitative analysis and qualitative evaluation of regional WRCC. TOPSIS was originally proposed by Hwang and Yoon (1981) to help select the best alternative with a finite number of criteria (Tzeng and Huang, 2011). As a well-known classical MCDA/MCDM method, TOPSIS has received much interest from researchers and practitioners and has been widely used in water research (Behzadian et al., 2012). In this study, TOPSIS is used for qualitative analysis.

Therefore, an analysis and evaluation method combining the SD model and TOPSIS method is proposed in this paper. The SD model is firstly used to calculate relevant data on basin water resources, then the TOPSIS method is applied to calculate WRCC in the Hangbu River basin.

2 Materials and methods

2.1 Study area

The Hangbu River Basin is located in the west of Chaohu Lake Basin, with a drainage area of 4,246 km^2, as shown in Figure 1. The administrative areas involved in the Hangbu River Basin include Jin'an District, Lu'an City, Shucheng county and Huoshan County of Lu'an City, Feixi County, Lujiang County of Hefei city, and Yuexi County of Anqing city. Among them, the Hangbu River Basin in Huoshan and Yuexi Counties covers an

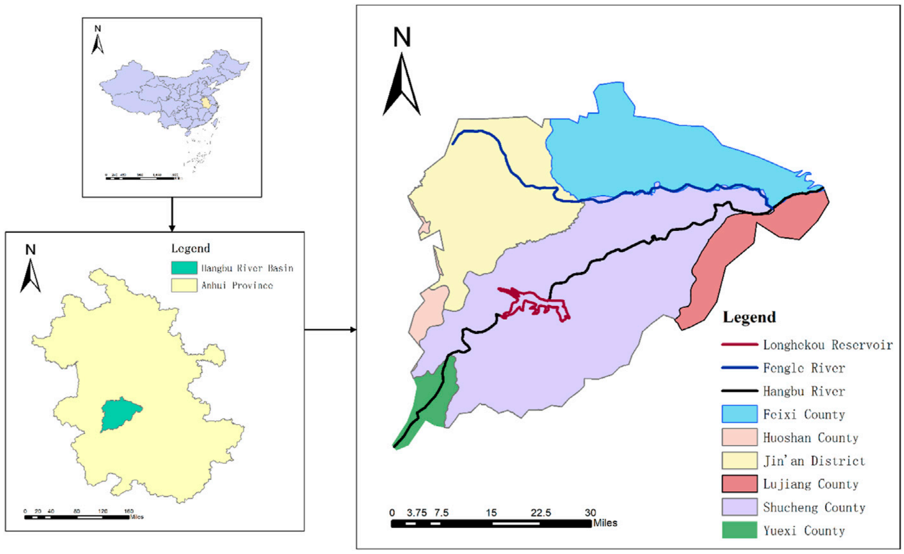

FIGURE 1
Geographical location of the Hangbu river basin.

area of 217.59 km^2, accounting for only about 5.13% of the Hangbu River Basin. This region is located in the upstream mountainous area, with few water users, and has little impact on the analysis of water resources in the Hangbu River Basin, so the two areas are excluded in this study. The Hangbu River Basin belongs to the subtropical humid monsoon climate zone in the north, with four distinct seasons and wet and warm climates. The multi-year annual precipitation of the basin is about 1,000 mm on average, the multi-year average relative humidity is 81%, the annual average evaporation is 1,397 mm, and the evaporation increases from southwest to northeast. The precipitation during the crop growth period is 780–850 mm. Also, the local place is featured by the sound rainfall and heat conditions, which can generally meet the needs of various thermophilic crops. The Hangbu River irrigation area in the basin is an important base for national grain crop production. In recent years, with the growth of population, the rapid development of the economy, and the increasing water consumption in irrigation areas, problems, such as periodic shortage of water resources and water environmental pollution have gradually emerged in the basin. The evaluation of WRCC of the Hangbu River basin will help alleviate the resource and environmental problems in the basin at this stage and ensure the sustainable development of the Hangbu River Basin.

2.2 Data

All data in this study are annual data. Water resources data are mainly from Lu'an water resources bulletin (2015–2020) (http://slj.luan.gov.cn/index.html) and Hefei Water Resources Bulletin (2015–2020) (http://sswj.hefei.gov.cn/), and socio-economic data are mainly from Lu'an national economic and social development statistical bulletin (2015–2020) (https://www.luan.gov.cn/), Hefei National Economic and social development statistical bulletin (2015–2020) (https://www.hefei.gov.cn/) and Anhui national economic and social development statistical bulletin (2015–2020) (https://www.ah.gov.cn/). The Rest of the data comes from Comprehensive Planning of the Hangbu River Basin (2019–2035).

2.3 System dynamics model

The SD model provides feedback on the structure and behavior of complex systems by building simulation models (Zhang et al., 2010). The SD model is often composed of a large number of nonlinear differential equations, which are solved by computer simulation. The core of the model is the state equation, which is used to describe the dynamic changes of the system (Wei et al., 2012). It can be expressed as follows,

$$\mathcal{X}_i(t + \Delta t) = \mathcal{X}_i(t) + f(\mathcal{X}_i, \mathcal{R}_i, \mathcal{A}_i, \mathcal{C}_i)\Delta t \qquad (1)$$

where $\mathcal{X}_i(t)$ is the value of the i-th state variable of the system at time t; t is annual; $\mathcal{R}_i$ means the rate change vector; $\mathcal{A}_i$ refers to the auxiliary vector; $\mathcal{C}_i$ is the parameter; $f()$ is a vector-valued function; Δt is the time step.

To build up an SD model, the variables that have a certain impact on the regional WRCC and have a large amount of data are selected. Then a flow chart (as shown in Figure 2) is drawn by Vensim software (version: Vensim DSS), including the domestic

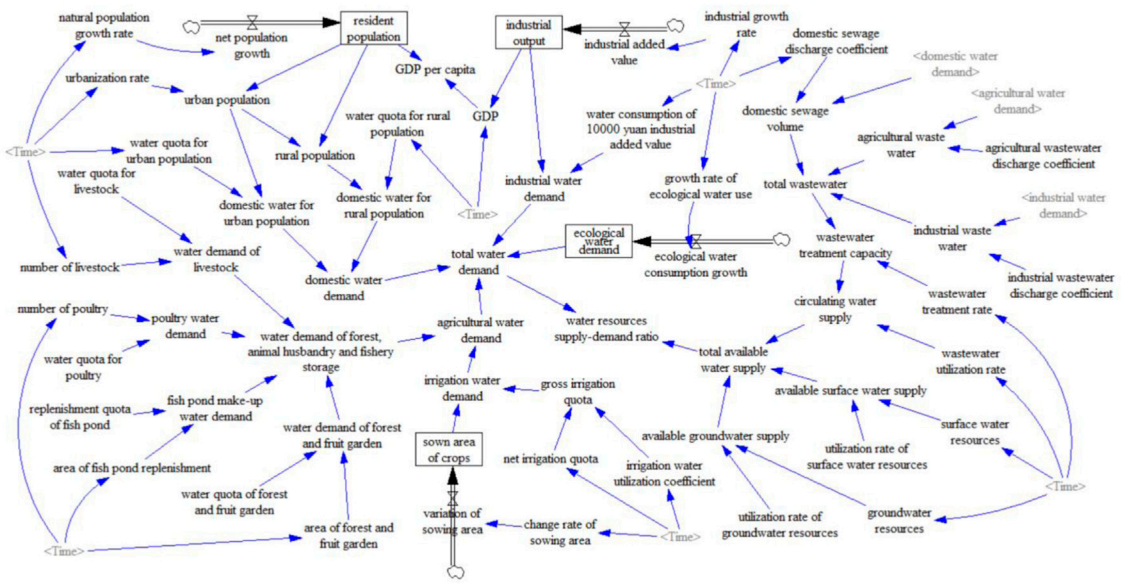

FIGURE 2
Flow chart of the SD model.

TABLE 1 Data table between water consumption of 10000 yuan industrial added value and time.

Time	2015	2016	2017	2018	2019	2020
water consumption of 10000 yuan industrial added value	168.6	156.4	138.0	132.0	102.2	95.13

water demand subsystem, industrial water demand subsystem, agricultural water demand subsystem, ecological water demand subsystem, and one water supply subsystem. Arrows are used to indicate the logical relationship between variables. Each variable is determined by all variables that point to it. All variables determined by time will change with the change of time, and the change of these variables will cause a change in the whole system. At each time node, each variable in the system has a unique value.

There are three kinds of variables in the flow chart: level variable, rate variable, and common variable The level variable is surrounded by a black border, which has its stock; Below the long black arrow is the rate variable, which is often determined by other common variables, and the rate variable determines the change rate of the level variable it points to. Some variables with complex numerical changes and little time correlation are represented by level variables, while others are represented by common variables. There will be some variables in the flow chart many times. Only one of these variables is displayed in black font, and the rest are displayed in gray font, which is called the shadow variable.

A formula or a data table is adopted to express the numerical relationship between variables. For example, the domestic water consumption of urban residents is equal to the urban population multiplied by the domestic water consumption quota of urban residents. The domestic water consumption of urban residents is calculated according to this formula. Table 1 demonstrates the relationship between water consumption of 10000 yuan industrial added value and time. Vensim software will fit the numerical relationship between the two according to this table and calculate the water consumption of 10000 yuan industrial added value in the subsequent time according to this table.

2.4 Error test

The role of the system dynamics model in the simulation of WRCC in the Hangbu River Basin is determined by whether the model can truthfully reflect the economic and social development of the Hangbu River Basin. Through parameter calibration, the calculation results can better reflect the status quo of the basin. Based on the research of Xu et al, (2020), the error degree of the

TABLE 2 Comparison of simulated and real values.

Time index		2015	2016	2017	2018	2019	2020
GDP (RMB 100 million)	Simulated value	550.71	627.07	711.19	803.48	904.37	1014.28
	True value	561.70	617.94	705.94	738.77	953.65	1007.85
	ARE (%)	1.96	1.48	0.74	8.76	5.17	0.64
Resident population (10000 persons)	Simulated value	198.23	199.81	201.17	202.30	203.21	203.89
	True value	198.23	199.61	200.23	202.94	203.97	203.76
	ARE (%)	0.00	0.10	0.47	0.32	0.37	0.06
Total water demand (100 million m^3)	Simulated value	8.78	8.79	8.80	8.81	8.83	8.86
	True value	9.21	9.36	9.74	9.76	9.75	9.59
	ARE (%)	4.66	6.11	9.68	9.70	9.39	7.64
Urbanization rate (%)	Simulated value	25.80	27.74	29.67	31.61	33.54	35.48
	True value	25.84	27.62	29.71	31.51	33.62	35.42
	ARE (%)	0.14	0.43	0.12	0.32	0.22	0.18
Irrigation water demand (100 million m^3)	Simulated value	6.99	6.92	6.85	6.79	6.73	6.68
	True value	7.05	7.18	7.09	6.99	6.88	6.87
	ARE (%)	0.79	3.61	3.37	2.88	2.13	2.75

TABLE 3 Evaluating index of WRCC.

	Index	Positive/ Reverse	Reasons
Natural support	Water supply per capita	Positive	The higher the value, the more abundant the water resources in the region
	The ratio of water supply to demand		
Social technology level	Water consumption per 10000 yuan GDP	Reverse	The lower the value, the higher the water use efficiency
	Effective utilization coefficient of irrigation water	Positive	The higher the value, the higher the water use efficiency
	Wastewater utilization rate		
Social living standard	GDP per capita	Reverse	The paper defines WRCC as regional development potential, and the higher these two values, the lower the development potential and the lower WRCC.
	Urbanization rate		
	Water consumption rate of ecological environment	Positive	The higher the value, the better the ecological protection and the better the regional development potential

model is expressed by the absolute relative error (ARE) between the real data and the simulated data. The ARE calculation formula is shown as,

$$ARE = \left| \frac{Z_t'}{Z_t' - Z_t} \right| \tag{2}$$

where Z_t' is the simulated value of data in year t; Z_t means the true value of data in year t.

If ARE does not exceed 10%, the model is considered to be in line with the status quo and can be used for the simulation of future situations.

The values of each variable in 2015 are input in the SD model of the Hangbu River Basin, the simulated value of each variable from 2016 to 2020 is iteratively calculated, the ARE between the simulated value and the true value is calculated, and then the numerical relationship between each variable and the initial value in 2015 is adjusted to recalculate until the ARE value meets the requirements.

Based on 6 years of actual data from 2015 to 2020, five variables, including resident population, urbanization rate, total GDP, crop sown area, and total water demand, are selected to verify the reliability of the model parameters. The ARE calculation results are shown in Table 3. It can be seen from Table 2 that the ARE of the five variables is less than 10%. It can be seen that the SD model can reflect the actual situation well and is highly reliable.

2.5 Index system

2.5.1 Establishment of index system

The evaluation index system of WRCC is the standard and basis for the comprehensive evaluation and research on the coordinated development of regional water resources, society, ecological environment, and economy (Cao et al., 2019). The main body of WRCC system is the water resources subsystem, while the target is the socio-economic and ecological environment subsystem supported by water (SONG et al., 2018). In developing WRCC evaluation index system, the principles of scientificity, completeness, a combination of dynamic and static, qualitative and quantitative, comparability, and feasibility need to be taken into consideration (Wang et al., 2004). Due to the limited amount of data available from the data source, this study selects 8 evaluation indexes that have a great influence on WRCC of the Hangbu River Basin from three aspects: natural support capacity, social technology level, and social living standard, and constructs the evaluation index system of WRCC. The natural supporting capacity reflects the supporting effect of the natural conditions of regional water resources on social development, including the per capita water supply and the ratio of water supply to demand; The socio-techno level reflects the social utilization efficiency of water resources, including water consumption per 10000 yuan GDP, irrigation water utilization coefficient and wastewater utilization rate; Social living standards reflect the degree of social demand for water resources, including GDP per capita, urbanization rate, and eco-environmental water use rate. These eight indicators are also frequently used in the evaluation of WRCC. For example, Peng and Deng (Gong and Jin, 2009) take into consideration the per capita GDP, water consumption per 10000 yuan GDP, per capita water consumption, and ecological environment water consumption rate when evaluating WRCC of Guiyang; Zhang et al, (2021) included the per capita GDP, urbanization rate, water consumption per 10000 yuan of GDP, and agricultural irrigation water consumption rate in their study when evaluating WRCC in Nanjing, Wang et al, (2022) took into consideration the utilization rate of renewable water resources, the balance rate of water resources supply and demand, and the urbanization rate.

The impact of these eight indexes on WRCC can also be divided into positive and adverse effects. See Table 3 for details.

2.5.2 Normalization and standardization of index data

Since there are two kinds of indexes in the system, the subsequent data processing will be cumbersome without normalization. Therefore, the selected evaluation indexes should be normalized before the basin WRCC is evaluated (Wang et al., 2017). In the evaluation index system, the indicators that have a positive effect on WRCC are normalized by the following formula as follows,

$$\mathcal{Y}_{ij} = y_{ij} - \left(y_{i_{min}} - mod\left(y_{i_{min}}, y_i'\right)\right) \tag{3}$$

where y_{ij} represents the j-th sample data of the i-th index; $y_{i_{min}}$ denotes the smallest item of all sample data of index i; y_i' is $y_{i_{min}}$ the order of magnitude; $\mathcal{Y}_{ij}$ represents the j-th sample data of the i-th index after normalization.

The normalization formula of indicators that have a reverse effect on WRCC is shown as,

$$\mathcal{Y}_{ij} = 1\big/y_{ij} \tag{4}$$

After normalization, the index data are standardized to eliminate the influence of each index dimension on the evaluation system. The standardized formula is as follows,

$$\mathcal{X}_{ij} = \frac{\mathcal{Y}_{ij}}{\sqrt{\sum_{j=1}^{n}\mathcal{Y}_{ij}^2}} \tag{5}$$

where $\mathcal{X}_{ij}$ represents the j-th sample data of the *i*th index after standardization; n means the number of samples.

2.5.3 Index weight

As different indicators have different impacts on WRCC of the basin, the weight of each evaluation index should be given. To avoid subjective preference in evaluating the weight of each index, this paper integrates subjective and objective weighting methods to calculate the weight of each index.

2.5.3.1 Analytic hierarchy process

The analytic hierarchy process (AHP) is a subjective weighting method. Qualitative and quantitative levels are integrated to determine the index weight. AHP is often used to solve multi-dimensional decision-making problems. The calculation steps of the analytic hierarchy process are illustrated in detail in the literature (Du et al., 2022).

To obtain a reasonable objective weight for each indicator, the researchers in this study consulted the opinions of 9 experts, including 5 experts engaged in the research of water resources optimization and dispatching and 4 experts engaged in the research of urban flood control and drainage. Based on their scores on the importance of each indicator, nine groups of subjective weights were obtained by using AHP software. The nine groups of subjective weights passed the consistency test. In this paper, the average value of the nine groups of weights is taken as the subjective weight of the evaluation index of WRCC of the Hangbu River Basin.

2.5.3.2 Entropy weight method

The entropy weight method is an objective weighting method for information entropy. The information entropy and weight of the indicator are calculated according to the relative change degree of each value of the indicator. The greater the relative

TABLE 4 Weight of each index.

	Index	Subjective weight	Objective weight	Combined weight
Natural support	Water supply per capita	0.012	0.049	0.030
	The ratio of water supply to demand	0.458	0.041	0.249
Social technology level	Water consumption per 10000 yuan GDP	0.037	0.207	0.122
	Effective utilization coefficient of irrigation water	0.124	0.174	0.149
	Wastewater utilization rate	0.019	0.083	0.051
Social living standard	GDP per capita	0.193	0.243	0.218
	Urbanization rate	0.143	0.053	0.098
	Water consumption rate of ecological environment	0.014	0.149	0.082

change of the indicator value, the greater the weight of the indicator. The weight of the entropy weight method is calculated in the steps as follows:

(1) Calculate the proportion of the j-th sample value of the ith index:

$$\mathcal{P}_{ij} = \frac{\mathcal{X}_{ij}}{\sum_{j=1}^{n} \mathcal{X}_{ij}} \tag{6}$$

(2) Calculate the entropy of the ith index:

$$\mathcal{C}_i = -\frac{1}{\ln n} \sum_{j=1}^{n} \mathcal{P}_{ij} \ln \mathcal{P}_{ij} \tag{7}$$

(3) Calculate the different degrees of the ith index:

$$d_i = 1 - \mathcal{C}_i \tag{8}$$

(4) Calculate the weight of the ith index:

$$\mathcal{W}_i = \frac{d_i}{\sum_{i=1}^{m} d_i} \tag{9}$$

Where m is the number of indexes.

According to the water resources data of the Hangbu River Basin from 2015 to 2035 obtained from system dynamics simulation, the entropy weight method is used to calculate the objective weights of each evaluation index based on the SD model simulation data.

The paper takes the average value of subjective weight and objective weight as the combined weight of evaluation indicators. This method has not been thoroughly studied, but it is widely used Liu et al, (2022b); Li et al, (2022) and easy to operate, especially when we do not know which is more important, subjective or objective weights.

The weight values of each index can be seen in Table 4.

It can be seen from Table 4 that the ratio of water supply to demand and GDP per capita have a great impact on WRCC of the Hangbu River Basin. This is consistent with the rapid economic development of the Hangbu River Basin in recent years; At the social and technological levels, the effective utilization coefficient of irrigation water has a greater weight, which is also in line with the actual positioning of the Hangbu River Basin as a national important food production base.

2.6 TOPSIS method

TOPSIS method, namely, "technique for order preference by similarity to an ideal solution", can be adopted to rank the scenarios according to the Euclidean distance between each sample value and the ideal value. The basic principle is to establish the optimal (worst) scenario of the sample object, that is, the positive (negative) ideal point, determine the distance between the sample object and the positive (negative) ideal point, and obtain the proximity of the sample object to the ideal point (Wang et al., 2008; Wang et al., 2012; Sun et al., 2018). The calculation steps are as follows:

(1) Establish the index data as a matrix $X = (\mathcal{X}_{\mathbf{ij}})_{(m\times n)}$.
(2) Establish weight vector $W = (\mathcal{W}_1, \mathcal{W}_2, \ldots, \mathcal{W}_m)^T$.
(3) Calculate D_j^+ and D_j^-, which represents the distance between the sample data and the positive/negative ideal solutions. Both of them are calculated based on the formulas as follows:

$$D_j^+ = \sqrt{\sum_{i=1}^{m} \mathcal{W}_i \left(\mathcal{X}_{\mathbf{ij}} - \mathcal{X}_i^+\right)^2} \tag{10}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m} \mathcal{W}_i \left(\mathcal{X}_{\mathbf{ij}} - \mathcal{X}_i^-\right)^2} \tag{11}$$

Where $\mathcal{X}_i^+$ is the positive ideal solution of the sample, $\mathcal{X}_i^-$ is the negative ideal solution of the sample.

(4) Calculate C_j, which represents WRCC. The calculation formula is as follows:

$$\boldsymbol{C}_j = \frac{D_j^-}{D_j^+ + D_j^-} \tag{12}$$

TABLE 5 Classification of WRCC.

WRCC value	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
WRCC status	weak	poor	normal	good	excellent

The object $C_j \in [0, 1]$, the closer C_j is to 1, the better the calculation results; Otherwise, the situation will be worse.

2.7 WRCC classification

Different WRCC values correspond to different carrying capacity states. According to Yang et al, (2019), WRCC values are classified as shown in Table 5.

2.8 Scenario design

By adjusting the model parameters, the SD model can simulate the data of water resources under different regional development scenarios. For example, when looking for the optimal development plan for Mu Us Sandy Land, Liu et al., 2022b adjusted the main parameters such as industrial growth rate, water consumption per unit output value, irrigation water quota, and domestic water quota in the SD model, and simulated six development scenarios. Yang et al., 2015 designed four development plans by adjusting water resource constraints and population migration to simulate WRCC of Tieling.

It is difficult for most cities to have both economic development and water resources protection. Referring to the plan of the economy and water resources in the Comprehensive Planning of the Hangbu River Basin (2019–2035), four scenarios are designed, and the water resources data of the Hangbu River basin under various scenarios are simulated by the SD model, and then the TOPSIS method is used to calculate WRCC.

Scenario 1: the scenario of continuing the original development trend. The industrial structure and development plan of the Hangbu River basin will not be significantly adjusted during the forecast period. Under the simulation scenario, the urbanization rate, each growth rate, and all kinds of water quotas remain unchanged or change according to the historical trend.

Scenario 2: the scenario of giving priority to economics. According to Anhui national economic and social development statistical bulletin in the past 5 years and the research of (Gu et al., 2021). The growth rate of the industry is increased to 200% of the original trend, the growth rate of crop sown area is increased to 200% of the original trend, and the

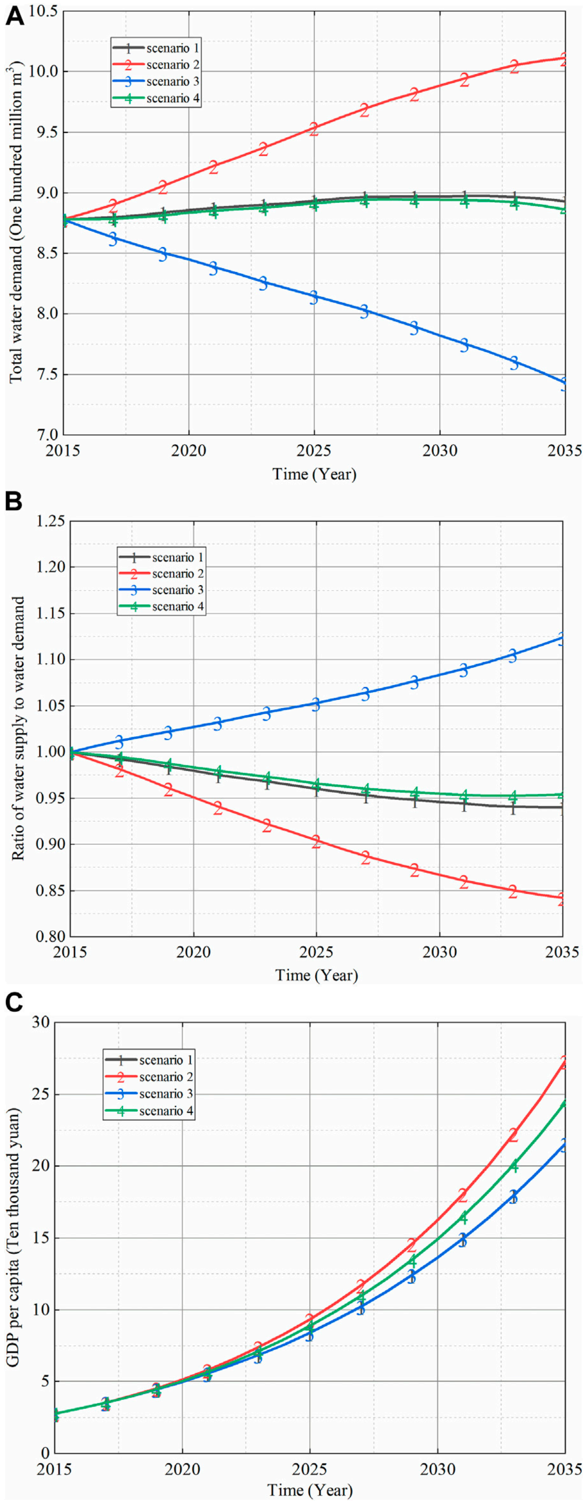

FIGURE 3
Simulation results of three variables.

10.3389/fenvs.2022.1045907

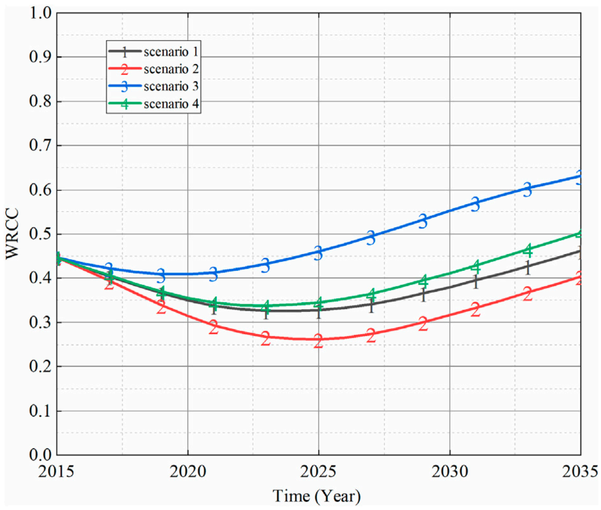

FIGURE 4
WRCC in four scenarios.

growth rate of urbanization is increased to 120% of the original trend. Other conditions are kept constant or changed according to historical trends.

Scenario 3: the scenario of prioritizing water resources. Based on the research of (Liu et al., 2011), combined with the actual water consumption of cities in the Hangbu River Basin, the reduction rate of a net quota of irrigation water is increased to 180% of the original trend, and the growth rate of domestic water quota is reduced to 50% of the original trend. The water consumption reduction rate of 10000 yuan industrial added value is increased to 120% of the original trend. The water quota for forestry, animal husbandry, fishery, and livestock are decreased to 80% of the original trend, the growth rate of ecological water is increased to 120% of the original trend, the utilization coefficient of irrigation water is increased to 120% of the original trend, and the utilization rate of wastewater goes up to 140% of the original trend. Other conditions remain unchanged or change according to historical trends.

Scenario 4: the comprehensive development scenario. Based on the research of (Wang et al., 2017), the economic development and water use of the basin are integrated. The growth rate of the industry is increased to 150% of the original trend, the growth rate of crop sown area is increased to 150% of the original trend, the growth rate of urbanization rate is increased to 110% of the original trend, the reduction rate of net water quota for irrigation is increased to 130% of the original trend, and the growth rate of domestic water quota is reduced to 80% of the original trend. The water consumption reduction rate of 10000 yuan industrial added value is increased to 110% of the original trend, the growth rate of ecological water is increased to 110% of the original trend, the irrigation water utilization coefficient is increased to 110% of the original trend, and the wastewater utilization rate is increased to 120% of the original trend. Other conditions remain unchanged or change according to historical trends.

3 Results and discussion

3.1 Results of each scenario

After SD model simulation and TOPSIS method calculation, the water resource data and WRCC of each scenario are shown in Figures 3, 4.

Under scenario 1, the total water demand in the Hangbu River Basin changes slightly, reaching a maximum value of 897 million m^3 in 2032, and then decreasing slightly. The total water demand in 2035 reaches 893 million m^3. The ratio of water supply to demand continues to decline, from 1.000 in 2015 to 0.934 in 2035, and the shortage of water resources becomes more and more obvious. With the development of water technology in the basin, the water use efficiency has been improved, and the annual decline rate of water resources supply and demand has gradually decreased, from an average annual decline of 0.0037 from 2015 to 2020 to an average annual decline of 0.0010 from 2031 to 2035. In terms of economic development, the GDP per capita of the basin will reach 215700 yuan in 2035. WRCC generally decreases first and then increases. It was 0.445 in 2015, drops below 0.400 in 2018, that is 0.382, falls to the lowest point of 0.325 in 2024, and then gradually recovers. It will return to 0.412 in 2032, and WRCC in 2035 will reach 0.464.

Under scenario 2, the water shortage in the Hangbu River Basin is more severe, and the total water demand continues to increase, reaching 1.011 billion m^3 by 2035. The ratio of water supply to demand continues to decline, from 1.000 in 2015 to 0.837 in 2035. In terms of economic development, the GDP per capita of the basin will reach 273000 yuan in 2035. The general change trend of WRCC is consistent with that in scenario 1. It is 0.445 in 2015, falls below 0.400 in 2017, that is 0.392, drops to the lowest point of 0.262 in 2025, and then gradually rises. It will recover to above 0.300 in 2029, which is 0.301, and rise to 0.406 in 2035.

Under scenario 3, the total water demand will continue to decrease in 2027 and will drop to 743 million m^3 in 2035. The ratio of water supply to demand continues to increase, from 1.000 in 2015 to 1.117 in 2035, and the growth rate increases from an average annual growth rate of 0.0043 in 2015–2020 to an average annual growth rate of 0.0064 in 2031–2035. In terms of economic development, the GDP per capita of the basin will reach 215700 yuan in 2035. WRCC shows an upward trend. WRCC is 0.445 in 2015, falls to the lowest point of 0.407 in 2020, and then gradually rises. It will rebound to

0.445 in 2024, reaching WRCC level in 2015, increase above 0.600 to 0.606 in 2033, and reach 0.633 in 2035.

Under scenario 4, the total water demand of the Hangbu River Basin changes slightly, reaching the maximum value of 895 million m^3 in 2028, and then decreases slightly. The total water demand will be 886 million m^3 in 2035. The ratio of water supply to demand decreases firstly and then increases, which drops to the minimum value of 0.946 in 2033, then rebounds slightly, and reaches 0.948 in 2035. In terms of economic development, the GDP per capita of the basin will reach 244300 yuan in 2035. The overall trend of WRCC is consistent with that of scenario 1. It is 0.445 in 2015, falls below 0.400 in 2018, that is 0.385, falls to the lowest point of 0.338 in 2023, and then gradually recovers. It will rise above 0.400 in 2030, which is 0.413 and WRCC will reach 0.504 in 2035.

3.2 Comparison of results

Under scenario 1, the ratio of water supply to demand in the Hangbu River Basin is slightly worse than that in scenario 4, better than that in scenario 2, and worse than that in scenario 3. In 2035, 6.6% of the water demand will not be met, and the basin will face a water shortage for a long time, and the water shortage is difficult to solve. In terms of economic development, the GDP per capita of the Hangbu River Basin in 2035 under this scenario is the same as scenario 3, lower than scenario 2 and scenario 4. From the perspective of WRCC, it will be lower than 0.400 for 14 years during the study period. During this period, WRCC is in a poor state. The overall level of WRCC is higher than that under scenario 2 and worse than that under scenario 3 and scenario 4.

Under scenario 2, the Hangbu River Basin has the lowest ratio of water supply to demand of the four scenarios. In 2035, 16.3% of the water demand will not be met, and the water resource gap is huge, suggesting that the shortage of water resources in this scenario will be an increasingly serious long-term problem under this scenario. In terms of economic development, the GDP per capita in 2035 under this scenario is the highest among the four scenarios, 11.75% higher than that under scenario 4 and 26.56% higher than that under scenarios 1 and 3. However, it should be noted that the GDP per capita in 2035 under scenarios 1 and 3 is RMB 215700, reaching US $34000 according to the exchange rate in April 2022, which approximates the level of moderately developed countries. Based on this, compared with the shortage of water resources, the economic advantage of this scenario is relatively weak and from the comparison of WRCC, it can be seen that the Hangbu River WRCC under this scenario is the worst among the four scenarios.

Under scenario 3, the ratio of water supply to demand in the Hangbu River Basin is the highest among the four scenarios. The ratio of water supply to demand will reach 1.117 in 2035, while that of the other three scenarios is less than 1.000, indicating that water resources are abundant in the near-term development process of the basin under this scenario. In terms of economic development, the GDP per capita of the Hangbu River Basin in 2035 under this scenario is the same as scenario 1, which is lower than scenario 2 and scenario 4. As for WRCC, it will always be higher than 0.400 during the study period and will exceed 0.600 from 2033, reaching a sound state and further providing strong support for the sustainable development of subsequent basins. Furthermore, the overall WRCC under this scenario is optimum.

Under scenario 4, the ratio of water supply to demand in the Hangbu River Basin is better than in scenario 1 and scenario 2, and worse than in scenario 3. In 2005, 5.2% of the water demand will not be met. However, it should be noted that the ratio of water supply to demand in this scenario will rise from 2033 to 2035, indicating that the basin will face water shortage during development in this scenario, but the problem may be improved or can be solved. In terms of economy, under this scenario, the GDP per capita of the Hangbu River Basin in 2035 is higher than scenario 1 and scenario 3 and worse than scenario 2. From the perspective of WRCC, it will be lower than 0.400 for 12 years during the study period, which is in a poor state. The overall level of WRCC outperforms that under scenario 1 and scenario 2 and is worse than that under scenario 3.

3.3 Water resources and development policy

In September 2020, China put forward the policies of "carbon peaking" and "carbon neutrality". It means that China will strive to reach the peak of carbon emissions by 2030 and achieve relatively zero carbon emissions by 2060. The "double carbon" policy requires all regions to improve science and technology, readjust the industrial structure and energy structure, and reduce their dependence on resources and the environment.

Compared with Western China and North China, the Hangbu River Basin has abundant water resources. The simulation reveals that such a relatively water-rich region will face a long-term water shortage if the current trajectory continues. Then, the local water shortage problem will be more serious in the future. Therefore, the "double carbon" policy is correct and will effectively improve sustainable development in all regions of China.

From a national perspective, the economy of the Hangbu River Basin is underdeveloped, and agriculture still dominates in the basin. Compared with the industry and service industry, agriculture consumes a huge amount of water under the same value of production, and the irrigation water use coefficient in the basin is about 0.535 in 2020, lower than the national average of 0.55. Therefore, the Hangbu River Basin is highly dependent on water resources. If the development plan of giving priority to water resources is not adopted, the basin will inevitably be posed with a water shortage. At that time, there will be a shortage of water resources, and the use of highly polluting resources, such as coal, will be restricted due to the "double carbon" policy. It is far from enough to rely on new energy to support the development of the basin. Therefore, in the context of the "double carbon" policy, the Hangbu River Basin must adopt a development plan that prioritizes water resources.

3.4 Implications from the case study

Based on the analysis of this study, the scenario of giving priority to water resources is the best development plan suitable for the Hangbu River Basin. Previous studies on WRCC have considered comprehensive development as the best option, such as research on WRCC in Xi'an by (Niu and Sun, 2019) and research on WRCC of Xiong'an New Area by (Yu et al., 2020). After analysis, there are two main reasons for the difference. The first reason is the different evaluation standards and methods for WRCC, and the second reason lies in different regional development priorities. Xi'an and Xiong'an New Area are large cities that have been built or are being planned. The secondary and tertiary industries are relatively developed, and the primary industry accounts for a relatively low proportion. When comprehensive development plans are adopted for these cities, the regional water resources carrying capacity is optimized instead. As an important grain production area, the Hangbu River Basin has a large area of arable land and a high proportion of agricultural water. According to the national regulation that the red line of 1.8 billion mu of arable land should be preserved, the area of arable land cannot be reduced at will, so the water consumption for agriculture cannot be reduced significantly. Only by adopting the development plan of giving priority to water resources can we ensure that there will always be sufficient water resources for regional development.

Therefore, the following suggestions are put forward to the relevant urban governments in the Hangbu River Basin:

1) The water used for irrigation should be improved. At present, the efficiency of irrigation water used in the basin is low, and the waste of irrigation water is huge. Some measures can be taken, such as lining the irrigation canal and increasing the drip irrigation area of crops, to improve the effective utilization coefficient of irrigation water.
2) Economic development should not be taken as a priority. If the local places continue to be economy-oriented, regional resources will be consumed more rapidly. It is not worthwhile pursuing limited economic growth by consuming more water resources, because it will further hinder regional development.

4 Conclusion

According to the characteristics of water resources and water use in the Hangbu River Basin, the influencing factors of WRCC in the Hangbu River Basin are selected, the system dynamics model of the Hangbu River Basin is built, four scenarios of continuing the original development trend, economic priority, water resources priority and comprehensive development are designed, the changes of various data related to water resources in the Hangbu River Basin from 2015 to 2035 is simulated, and eight indexes that can reflect the carrying capacity of the Hangbu River Basin are selected. The changing trend of WRCC of each development scenario is calculated and compared based on the good and bad solution distance method. According to the results, the following conclusions are drawn:

1) With a reasonable flow chart design and parameter calibration, the system dynamics model can effectively simulate the change of water resources in the basin.
2) For the Hangbu River Basin, the development scenario of giving priority to water resources is the best.

If the scenario of continuing the original trend is adopted, the Hangbu River Basin will face a water shortage for a long time, and the water shortage is difficult to solve. If the economic priority development scenario is adopted, the economic situation of the basin will be greatly improved. At the same time, the basin will be very short of water, and the water shortage will become more and more serious. If the comprehensive development plan is adopted, the economic situation of the basin will be improved and the water resource shortage will also appear, but the water resource shortage under the plan may be improved or can be solved. The scenario of giving priority to water resources has significantly improved WRCC of the Hangbu River Basin, and abundant water resources can provide strong support for the sustainable development of the basin.

3) As a country with relatively scarce water resources per capita, China urgently needs to adjust its development mode. In this context, the 'double carbon' policy is appropriate.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YL and CG contributed to the conception and design of the study. XJ, ZZ, and YZ organized the database. CL and ZW performed the statistical analysis. YL wrote the first draft of the manuscript. CG wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Prediction of flash flood susceptibility using integrating analytic hierarchy process (AHP) and frequency ratio (FR) algorithms

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The landscape of Pakistan is vulnerable to flood and periodically affected by floods of different magnitudes. The aim of this study was aimed to assess the flash flood susceptibility of district Jhelum, Punjab, Pakistan using geospatial model and Frequency Ratio and Analytical Hierarchy Process. Also, the study considered eight most influential flood-causing parameters are Digital Elevation Model, slop, distance from the river, drainage density, Land use/Land cover, geology, soil resistivity (soil consisting of different rocks and soil formation) and rainfall deviation. The rainfall data was collected from weather stations in the vicinity of the study area. Estimated weight was allotted to each flood-inducing factors with the help of AHP and FR. Through the use of the overlay analysis, each of the factors were brought together, and the value of drainage density was awarded the maximum possible score. According to the study several areas of the region based on the parameters have been classified in flood zones viz, very high risk, high risk, moderate risk, low risk, and very low risk. In the light of the results obtained, 4% of the study area that accounts for 86.25 km^2 is at high risk of flood. The areas like Bagham, Sohawa, Domeli, Turkai, Jogi Tillas, Chang Wala, Dandot Khewra were located at the very high elevation. Whereas Potha, Samothi, Chaklana, Bagrian, Tilla Jogian, Nandna, Rawal high-risk zones and have been damaged badly in the flood history of the area. This study is the first of its kind conducted on the Jhelum District and provides guidelines for disaster management authorities and response agencies, infrastructure planners, watershed management, and climatologists.

KEYWORDS

remote sensing, GIS, AHP, FR, sentinel-2, DEM, flash flood, susceptibility

1 Introduction

Historically, flash floods have been more devastating to agriculture, infrastructure, animal, and human life worldwide (Relief, 2013; Braimah et al., 2014; Tariq et al., 2023). Different countries of the world are still more prone to the hazards of flash floods because of the changes in climatic conditions of the world (Das, 2019; Tariq et al., 2022e; Tariq and Mumtaz, 2022). The havoc of flash floods has been greater in those parts of the world that have not developed a system of forecast and flood effects mitigation (Kheradmand et al., 2018; Basharat et al., 2022; da Silva Monteiro et al., 2022). To avoid mass movement and reduce the aftermaths, it is crucial to develop a mapping system based on different parameters of cause and effects (Basin, 2021; Islam F. et al., 2022; Sharifi et al., 2022a; Hussain et al., 2022b). One of the major reasons for floods is heavy rainfall and the low discharge capacity of canals, rivers, and dams. To make a successful assessment of flash floods it is pertinent to have complete modeling of floods to manage the risk and mitigate the effects (Khalil et al., 2022a; 2022b; Moazzam et al., 2022).

Human is the major manipulator of the ecosystem since their origin on the surface of the earth. Land use methods and land manipulation like agriculture use and deforestation are some of the man-induced causes that affect recurrent floods (Bera et al., 2022; Fu et al., 2022; Haq et al., 2022; Prasad et al., 2022; Ullah et al., 2022). Therefore, awareness of the manipulations made by humans, susceptibility, and risk analysis is pivotal and essential to be done on an earlier basis (Costache et al., 2022; Tariq et al., 2022c; Ghaderizadeh et al., 2022; Jalayer et al., 2022). Geographic Information System (GIS) and remote sensing techniques are the most widely used techniques to know the physical and biological surface of the land and gather necessary data for flood modeling (Nashwan et al., 2019; Tariq et al., 2022a; Sadiq Fareed et al., 2022; Wahla et al., 2022). Nowadays, GIS and RS techniques have are crucial tools to develop multi-criteria zoning decision analysis (Nyaupane and Chhetri, 2009; Baqa et al., 2022; Tariq et al., 2022b). GIS techniques are used to prepare flood mapping of an area. Through remote sensing, zonation images are gathered to make a complete image with the help of Landsat 5, Landsat 7, Landsat 8, and Satellite Pour Observation Terre (SPOT) (Polychronaki et al., 2013). The Artificial Neural Network (ANN) model for flood (Abdullahi and Pradhan, 2018), imitation has widely been used for flood susceptibility and modeling in Malaysia and India. Additionally, the use of GIS has been more frequent to evaluate the most vulnerable areas to flooding. In different parts of the globe, GIS has more frequently been used to obtain flood susceptibility analysis, GIS-based frequency ratios models, and monitoring expected hazards (Waqas et al., 2021b; Hussain et al., 2022a; Khan et al., 2022; Shah et al., 2022). It is therefore apparent that amalgamation of the techniques of GIS and RS are more beneficial to obtain data in flood-related studies.

Over the years, the Analytical Hierarchy Process (AHP) in connection with GIS has got more popularity for mapping floods (Pal and Ziaul, 2017; Aslam et al., 2022; Imran et al., 2022; Moazzam et al., 2022). Also, the outcomes of GIS-based statistical calculations showed more accuracy than using spatial data alone. In flood susceptibility studies the use of logistic regression, decision tree, Shannon's entropy model, ANN, FRM, fuzzy logic, and AHP models have frequently been used (Sharifi et al., 2022b; Felegari et al., 2022; Zamani et al., 2022). AHP is the most widely used model and is a more efficient and easily understandable model. Other methods like bivariate statistical technique and frequency ratio are the most effective methods used in the assessment of natural calamities (Yerramilli, 2012; Abbas et al., 2021; Tariq et al., 2021e).

Flood is one of the most life-threatening disasters in the world. The occurrences of inundations have increased in the Global South during the last few decades. An estimated 539,811 humans died, 361,974 sustained injuries, and over 2.8 billion were affected by floods during the decade's between 1980 and 2009. The period between 1980 and 2016 observed a 1.6 trillion USD increase in damages. South Asia is the most affected part of the globe and accounts for more than half of the total death tolls of the world (Eckstein et al., 2019; Baloch et al., 2021; Felegari et al., 2021; Sharifi et al., 2021). Because of climate change, in the past few decades, a significant increase in the frequency and magnitude of floods (Moazzam et al., 2018) have been observed in the eastern rivers of Pakistan including the Jhelum. Since the bifurcation of United India, Pakistan has experienced devastating floods of history (Tariq et al., 2021a; Baqa et al., 2021; Hu et al., 2021). The flood of 2010 was held responsible for losses of 10 billion (USD). Keeping in view the damages of the inundation of 2010, different hydrological modeling were emphasized by the government of Pakistan. The Jhelum River basin originates from the west of the Himalayas and is one of the tributaries to the Upper Indus Basin (UIB) (Khalid et al., 2018; Ahmad et al., 2021; Ghaderizadeh et al., 2021). The climate of the Jhelum River basin receives two types of precipitations, namely the summer monsoon from India and the precipitations from westerlies circulations. Several studies suggest the Upper Indus Basin and the Himalayas as a hotspot to climate change (Chohan et al., 2015), which could significantly alter the water flow of the basin and ultimately the Jhelum River.

Flood susceptibility modeling is one of the key components of flood disaster studies (Dang et al., 2011; Siddayao et al., 2014; Moazzam et al., 2018, 2020; Kundzewicz et al., 2019). Jhelum River is the lower catchment of the Indus water basin and has experienced flood calamities periodically. So far, no flood susceptibility modeling has been performed for the Jhelum River. Flood risk modeling is a crucial part of river management and encompasses many factors such as topography, land use, slope, land cover, and rainfall intensity. Flood modeling has a pivotal role in flood risk management and hence this study is an attempt to meet the objective of flood management and risk mitigation. This study will provide a guideline to the National Disaster Management Authority Pakistan (NDMA) to manage flood disasters in Punjab and specifically in the Jhelum River of Pakistan. The main objectives of this study are to identify the zones of higher and lower risk Multi-Criteria Analysis-Analytic Hierarchy Process (MCA-AHP) and FR application. This study will help to the amalgamation of GIS and hydraulic model for the interpretation of recurrent flood hazards and reduce risk strategies developed through multiple activities.

2 Materials and methods

2.1 Study area

In Pakistan, the district of Jhelum may be found to the western of the Jhelum River. It is bounded on the north by Rawalpindi, on the south by Sargodha and Gujrat, on the east by Azad Kashmir, and on the west by the district of Chakwal. The climate of the area was

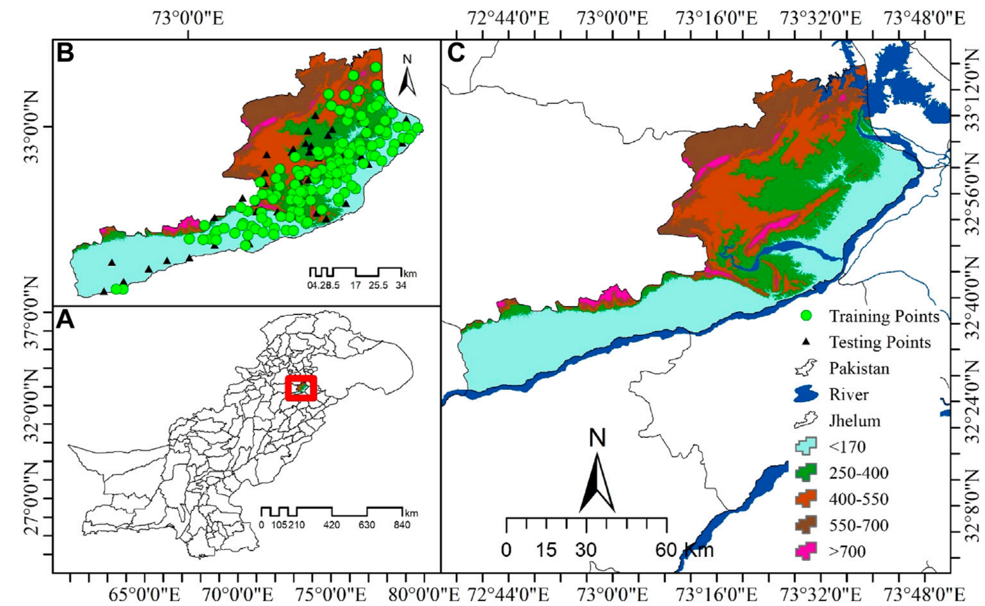

FIGURE 1
(A) Map of Pakistan, **(B)** Map of study area with testing and training points, **(C)** Location map of the study area (Jhelum), Punjab Pakistan.

FIGURE 2
Flood risk zones of Jhelum district, Punjab Pakistan.

characterized as being semi-arid and warmly subtropical, with very warm summers and cold, snowy winters (Majeed et al., 2021b; 2022a; 2022c). The Jhelum District is a semi-mountainous range that receives an average of 880 mm of precipitation per year and has an average temperature of 23.6°C. The Jhelum River encompasses up to 247,102 acres of the surrounding plains on the mainland (Majeed et al., 2021b) (Figure 1). The elevation of the Jhelum River basin ranges from 235 to 6285 m above sea level (asl) and spreads over a drainage area of 33,342 km^2 (Majeed et al., 2022c). The second-largest reservoir of Pakistan, the Mangla dam is fed by the Jhelum River basin and, therefore, plays a key role in the hydrological system of Pakistan (Majeed et al., 2022b). The slope of the basin undulates, ranging from 0′ to 79′. The lower plains of the basin near the Mangla dam and northeastern parts reside on a gentle slope (0″–10″) (Majeed et al., 2021a).

2.2 Collection, preparation and data processing

2.2.1 Collection of previous flash flood data

To establish an accurate map of the flood susceptible areas, it is imperative to collect precise data of the previously flood-affected areas (Martinis et al., 2009). The accurate forecast of potential flash floods,

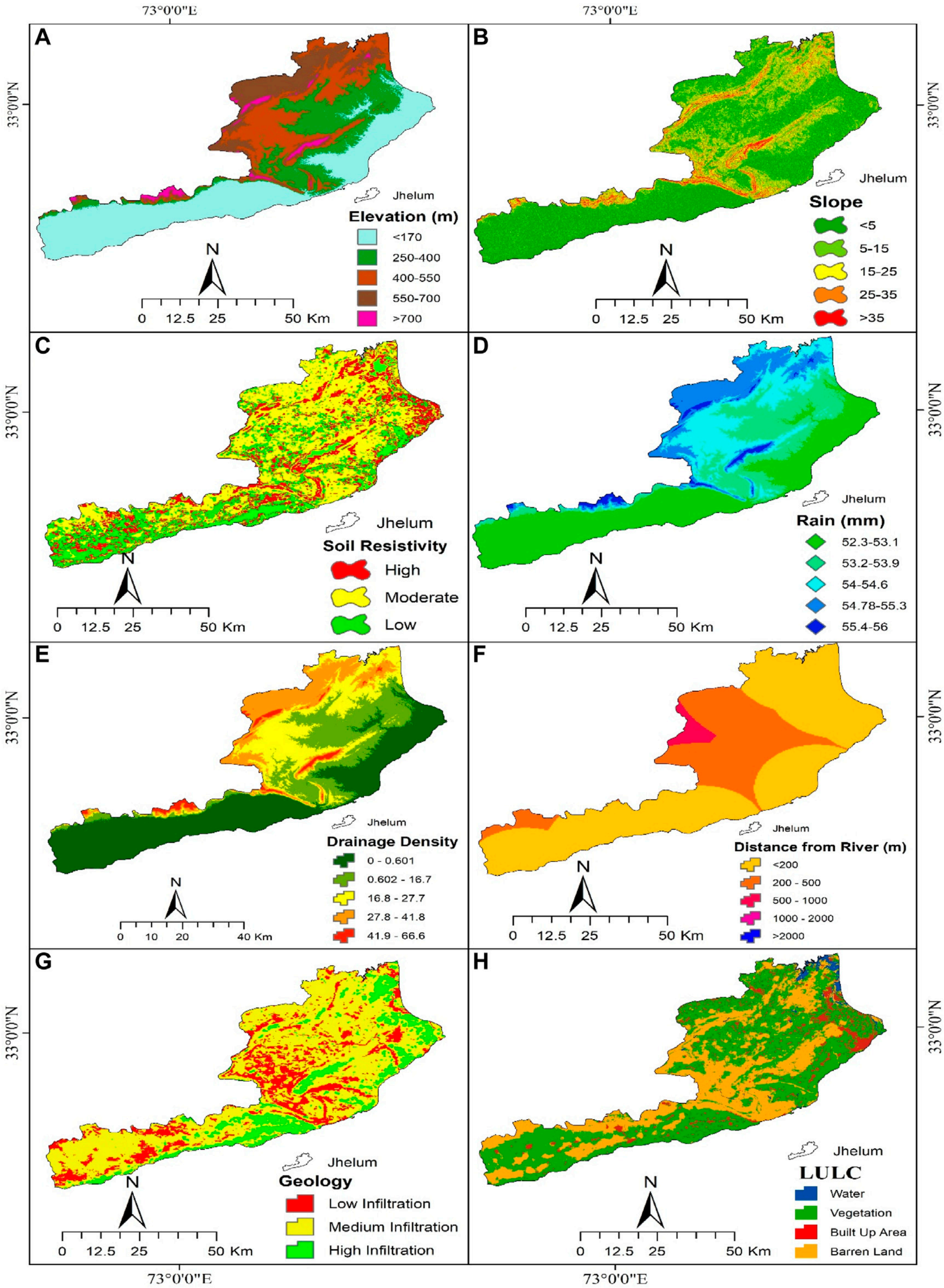

FIGURE 3
Conditions for flash flooding were mapped on maps: **(A)** Elevation, **(B)** slope, **(C)** soil resistivity, **(D)** rainfall, **(E)** drainage density, **(F)** distance from the River, **(G)** geology infiltration and **(H)** LULC.

in an area is possible only if we have preserved previous records of flash flood events. Some of the significant factors which determine the occurrence of flash floods, and hence the potential damage are; rainfall frequency, proximity to the stream, drainage, slope, density, soil type, and land use activities (Chen et al., 2022). All these factors are essential to be considered while planning and designing the inventory of flash floods and ultimately correct forecast. In the current study, we have taken data from 270 different zones which were previously affected and some non-affected zones. The classification of the area into different levels of potential risks is given in Figure 2.

TABLE 1 The sources from which various data were gathered and their implementation purpose.

Primary data	Spatila Resolution	Data Sources	Purposes of Maps
Optical remote sensing (sentinel-2 data)	10 m	USGS (Accessed on 20 June 2018)	LULC maps
DEM	12.5 m	Sentinel HUB accessed on 12 August 2019	Distance from the river, elevation, slope, Drainage density
Geological data	1/100,000	https://gsp.gov.pk/	Geophysical characteristics map
Soil data	1/100,000	https://soil.punjab.gov.pk/	Soil resistivity and structure map
Rainfall data	1/100,000	https://www.pmd.gov.pk/en/	Rainfall map

2.2.2 Classification of conditioning factors of flash floods

To conclude all the governing factors of a flood disaster, it is pivotal to classify the study area into different zones and study all the factors in different zones to draw guiding outcomes. In any area of flood risk, there are multiple factors while some of those factors operate in one zone and not in another zone (Sajjad et al., 2019). Therefore, to set a reliable picture of flood risk, a comprehensive field survey was conducted in different parts of the study area (Figure 3A). The selection of effective variables is preliminary to map flood-affected zones in any catchment area. Researchers face challenges while creating susceptibility maps (Majeed et al., 2021b; Tariq et al., 2021f; Haq et al., 2022). Therefore, we conducted a field survey to identify the potential flood-triggering variables. The most affected areas were visited, and data was collected based on the personal opinions of the residents (Table 1). We finally relied on a total of eight parameters such as elevation, slope, drainage density, distance from stream, geology, rainfall intensity, soil type, and LULC (Tariq et al., 2021d).

2.2.2.1 Elevation

Water keeps the tendency of flow from higher to elevation to lower elevation. The data on elevation shows the changes in the structure of the ground over a catchment area (Waqas et al., 2021a). In our study, the areas with lower elevation are more susceptible than higher elevation. In lower plains, the drainage is insufficient to drain all the water off. Therefore, the influx of water accumulates more in the lower elevations and proves hazardous. The DEM was used to differentiate several aspects (Tariq et al., 2021f). The relationship between the elevation and flood and hence the most prone areas are given in Figure 3A.

2.2.2.2 Slope

The hydrology of a catchment is always subjected to many attributes, which eventually define the magnitude of the external overflow. These factors govern the overland penetration, movement, and subsurface and length of stream. The combination of slope angles defines the shape of the slope. The slope is ultimately related to the composition of the soil, lithology, the organic and inorganic composition of the soil, and drainage (Sajjad et al., 2019). With the help of arc GIS, a slope chart was prepared to give different slope classes. The outcomes of the classification of the slope and hence the classification is provided in the (Figure 3B).

2.2.2.3 Soil resistivity and structure

Soil structure, texture, and moisture contents are the essential parameters to be considered during the flood assessment. Soil texture can markedly affect floods (Khan et al., 2011) because in sandy soil water is quickly drained and a little water is left for runoff. The clay soils induce flood more and hence the probability of flood rises when drainage of water decreases. We have designed the soil map based on the infiltration capabilities. The soil of the Jhelum district in this study has been classified into 3 classes; highly infiltrated, medium infiltrated, and less infiltrated. To assign weightage to each soil class, the soil with a high flood rate was ranked as 3 and the soil with a low rate was ranked as 1 (Figure 3C).

2.2.2.4 Deviation of rainfall

High rainfall is the direct cause of the heavy flood. Most of the flooding in Jhelum is recorded during summer ranging from July till September (Table 2). It is mostly because of the monsoon rainfall during the monsoon showers and high temperatures during the summer. During summer it was observed that heavy rainfall generates more runoff water (Moazzam et al., 2022). As a result, the volume of water that runs off during a downpour is crucial. Since a positive deviation in rainfall results in a flood and a negative departure in rainfall results in a drought, the variance in rainfall was employed as the starting point for the research of the flood. To mapping of the rainfall deviation, 5-year rainfall data was taken from the Meteorological department of Pakistan as. The following equation was used to calculate rainfall deviation.

$$Q = (L - Z) \times 100)/z \tag{1}$$

In the above equation Q = Rainfall deviation, L = recorded rainfalls, Z = the average rainfall. For mapping in this study, the IDW interpolation was used in ArcGIS (Hussain et al., 2011), as shown in the Figure 3D.

2.2.2.5 Drainage density

A measure of the river's overall length relative to its total area (Tariq et al., 2022b) is expressed by drainage density. In this work, the Strahler has been followed to evaluate the stream order (Strahler, 1952). Higher weightage was given to lower drainage density areas, while lower weightage was given to the areas with efficient drainage. Based on drainage density layer the sub-groups have been divided into six classes. The areas with low drainage density have been assigned a score of 0–6, while those with a higher drainage thickness are provided with 6 (Figure 3E).

2.2.2.6 Distance from river

The areas which are in closeness to the river have been inundated much historically. The areas near the river are more vulnerable whether it is a normal flood or flash flood. During heavy rainfall, the areas of lower plains specifically fall prey to the deluge (Tariq et al.,

TABLE 2 Last 10-year monthly rainfall data from 2009 to 2018 in District Jhelum.

Average monthly rainfall per year from 2009 to 2018												
Year	January	February	March	April	May	June	July	August	September	October	November	December
2009	56	34.4	21	31.2	22.8	49.5	130	164	22	0	11	−1
2010	2	75	18	13.2	51	76.7	259	198	60	23.4	−1	14.6
2011	−1	94.6	15.6	31.5	16.8	54.8	206.8	170	146	11.7	−1	0
2012	63.8	16.7	2	17.8	19.1	7.3	215.6	266	59	13	5.7	31.4
2013	11.8	100.5	9.5	45.5	14	83	269	242	88	1.8	32.6	.2
2014	2.2	27.6	148.8	84.1	73.5	25.1	123.3	158.4	240	54.8	1.5	0
2015	30.5	38.6	170.1	134.4	20.6	50.1	178.5	144.3	138	72.1	10.6	31.3
2016	22.3	33	117.8	10.8	25.5	143.6	280.1	197	54	5.3	1	−1
2017	105.7	8.6	16.6	85.6	31.7	87.4	261.8	311.9	66	0	6.7	16.3
2018	−1	40.7	8.5	63	35.9	44.3	206.2	251.0	34	10.4	5.4	15.6

TABLE 3 Quantitative evaluation of the relative importance of several flood-triggering elements.

S. No.	Definition	Importance/Intensity value
1	Extremely important	8 and 9
2	Very strongly important	6 and 7
3	Strongly important	4 and 5
4	Moderately important	2 and 3
5	Equally important	1

2021f). In this study, the areas less at a distance less than 200 m were declared the most susceptible areas. The areas 3,000 m away are at minimum risk or no risk at all (Figure 3F).

2.2.2.7 Geophysical characteristics

The hydrological response is dependent mainly on the geology of a catchment (Siddiqui et al., 2018). The earth's top layer and the successive layers down the earth define the amount of runoff. Comparatively, the impermeable layer offers more runoff than the impermeable layer. Lower basin is being composed of clay soil is highly vulnerable to flooding. This research examined the role of different layers of rock and soil in the occurrence of floods by measuring their permeability. Each layer was assigned a weightage and finally, a susceptibility guide was built up. The geological features of the basin are presented in Figure 3G.

2.2.2.8 Land use and land cover

Flood mapping is a complex process and relies on a bunch of variables. LULC is one of the variables to be considered during flood mapping. Land cover is not uniform across a catchment area and is subjected to both natural vegetation cover and man-made manipulations. Land cover such as grassland, scrubby layer, tree layer which cover the surface of the earth, play a key role in determining flood impact and hence the outcomes. Different vegetation cover has different retention capacity and therefore control the runoff to varying extent presented in Figure 3H. Thus, LULC utilization are critical variables during the flood analysis (Mahmood et al., 2016).

3 Methodology

3.1 Analytical hierarchical process (AHP)

The technique centers on developing a matrix that depicts the relative value of each candidate solution. Policymakers use it when relevant to explain phenomena and make confident decisions. In the AHP factors are evaluated, weightage is given to each variable and factor that contributes to the flood. The AHP is one of the most acceptable multi-criteria decision-making approaches (Waqas et al., 2021a).

3.2 Frequency ratio (FR)

The frequency ratio method of analysis is widely used in hydrological research. Statistics in FR are based on the correlation between dependent and independent variables in space. The spatial association between the dependent and independent variables makes the basis of FR statistical studies (Rahman et al., 2021). In this study, the flood-inducing factor like the rainfall, topography, slope, climatic conditions, and local factors were taken as the independent factors. The frequency ratio model has been used as a successful tool in several other studies.

3.3 Data collection and preparation

The conditioned flood maps used in this analysis were created in a raster format with a pixel size of 12 m. It was therefore possible to calculate frequency ratios for each class of conditioning factors by superimposing the inventory map on top of the maps of those factors (Zhang et al., 2019). After that, we used the ratio from the frequency table to determine the importance of each variable class. The major components and their impact on the flash flood were validated and chosen using the selection of correlation-based characteristics.

TABLE 4 The characteristics that contribute to floods and the component weights they were given in the flood susceptibility mapping (SFWVs).

Pairwise comparison of flood susceptibility factors									
Factors	DR	DD	SL	E	R	S	G	LULC	Weight (%)
Distance from the river (DR)	1	2	3	5	5	6	7	8	32.1721
Drainage density (DD)	.5	1	2	4	3	5	6	7	21.7699
Slope (SL)	.33	.5	1	4	5	6	7	8	20.1825
Elevation (E)	.2	.25	.25	1	2	4	6	8	10.1752
Rainfall (R)	.2	.33	.2	.5	1	2	4	6	6.8744
Soil (S)	.17	.2	.17	.25	.5	1	2	5	4.3431
Geology (G)	.14	.17	.14	.17	.25	.5	1	2	2.6377
Land use/cover (LULC)	.13	.14	.13	.13	.17	.2	.5	1	1.8452
Consistency ratio = .0737									

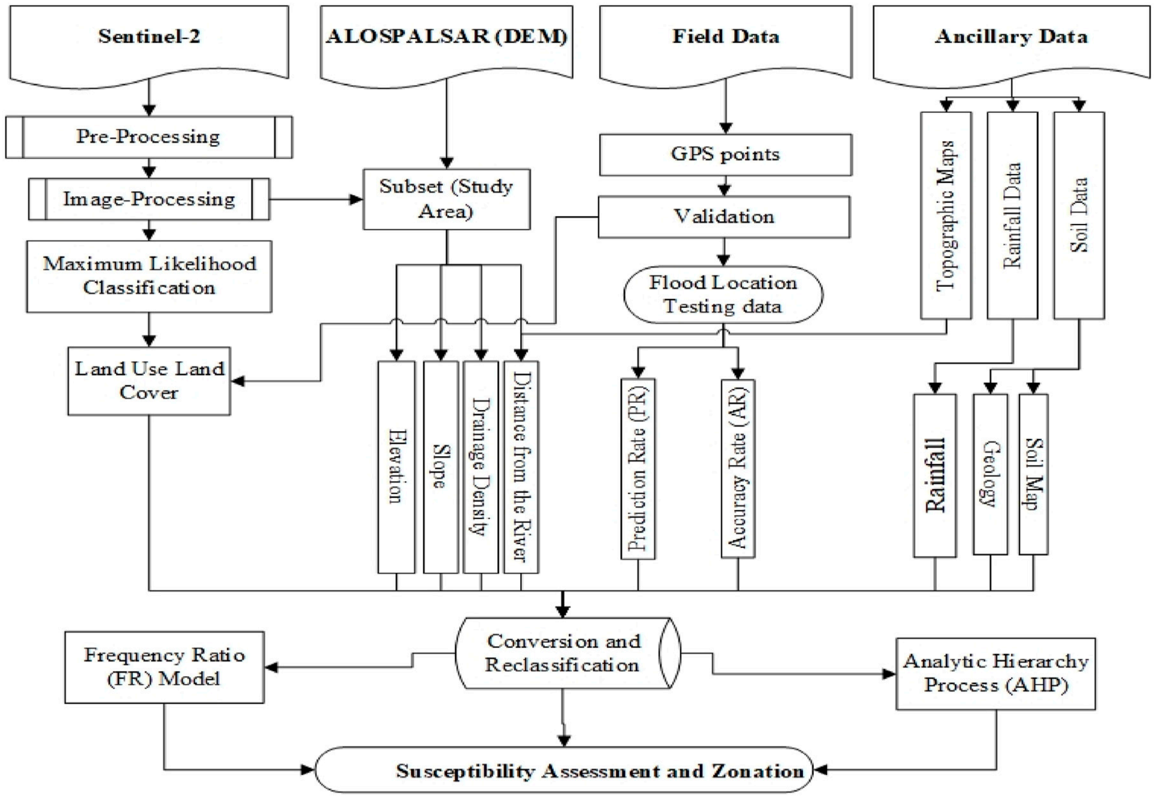

FIGURE 4
This study's approach is depicted as a flowchart.

3.4 Training and record set generation

The vulnerability of different areas in the district Jhelum was classified into two sections of 30% and 70% ratios. Here, we sampled the conditioning factors required to train the data set weight with 70% of the susceptibility data. The remaining 30% of the data on susceptibility was used to draw samples of the conditioning factors used to determine the weight of evaluation. A model's effectiveness with respect to the training subset and the test set might be affected by the ratio's collection. In this simulation, we chose a 70/30 split. All these steps were carried out using Arc GIS 10.8 (Moazzam et al., 2020).

3.5 AHP modelling and selected factor weight value

In our analysis, specifically, we employed AHP modeling to compare and contrast a few key flood-causing factors and get their respective Selected Factor Weight Values (SFWVs) (Waqas et al., 2021a). A survey was made in the Jhelum district to evaluate the relative implication of diverse flood factors and their position on given preferences. It is always a challenging task to determine which factor is more potential cause of flood in a certain region as resulted in Table 3. A numerical value was determined for one of these factors.

Keeping in view the meanings and importance values of the flood variables a pairwise contrast matrix was constructed. Values were assigned to all the variables starting from 1–9 to all the flood causing variables. The weights and values were given because of the relative significance of all the flood causing variables (Islam M. M. et al., 2022). The weights given to each possibility mirrored each other's opposites (Table 4).

The AHP method was used to get the hierarchical structure of all the components that lead to a flood, and the eigenvector of the selected weight factor was examined and adjusted by determining the CR (Mondal and Maiti, 2013; Khosravi et al., 2016; Ali et al., 2019). The accuracy and importance of the resulting rankings can be evaluated by comparing the factor weight value of various factors. As a result, the following Eq. (2) was used to get the eigenvector:

$$Ax = \lambda max^{X} \tag{2}$$

where λ stands for eigenvalue, x stands for eigenvector of n criteria, and a stands for comparison matrix of n criteria. A stable reciprocal matrix has a maximum eigenvalue (λ max) = total number of comparisons. For this reason, calculating the ratio of consistency is crucial. When the CR hits 0.1, the judgment collection is deemed inconsistent and must be repeated. Equally, if the CR number is close to 0, the judgment is totally consistent, and a value between 0 and 0.1 is frequently referred to as consistent. The following Eq. (3) can be used to calculate the consistency quotient:

$$CR = CI/RI \tag{3}$$

In above Eq. (3) CR = consistency ratio, CI = consistency index, RI = random index. The calculation of RI was made based on. However, the following equation was used to calculate CI:

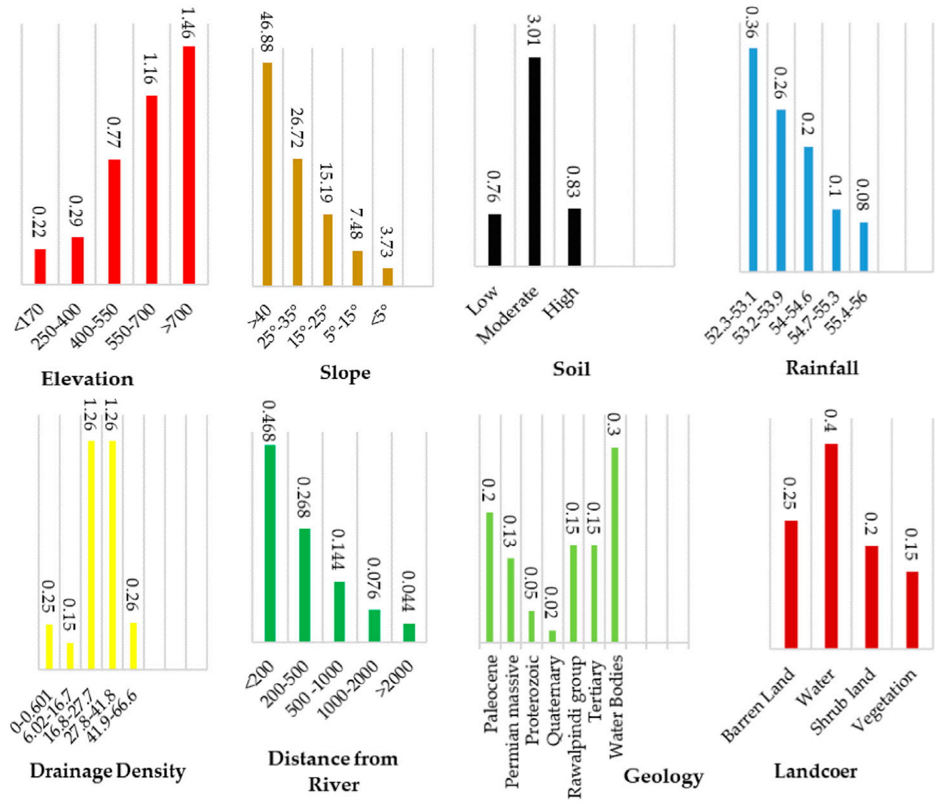

FIGURE 5
Factors that increase the likelihood of flooding, used to create a flood risk map based on class frequency ratios.

$$CI = \frac{\lambda\max - N}{N - 1} \quad (4)$$

Where λmax = cumulative number, and N represents the cumulative number of sub factors. When multiple variables contribute to an event's final outcome, like in the case of ecotourism evaluations, AHP can be used on a variety of scales (Alexakis and Sarris, 2014), for the collection of land and development of postharvest technology, for the assessment of transmission of an infectious disease. Overall methodology of used in current research is given as Figure 4.

3.6 FR model and the SCWV

We used the following equation to calculate the Frequency Ratio (FR) for every class of selected factors;

$$FR = \frac{\frac{PpixE}{PpixT}}{\frac{\Sigma pixE}{\Sigma pixT}} \quad (5)$$

$PpixE$ = number of pixels, p = flood class, $PpixT$ = count number of pixels. $\Sigma pixE$ = all pixels for the flood class, $\Sigma pixT$ = overall number of pixels in the research area. In cases where the resulting FR value was greater than 1.0, it was determined that a strong and equitable correlation existed between the flood training locations and the pertinent factors and high-risk class. If the value of FR is less than 1, then the significance of flood risk is low and the relationship is negative. In this investigation, we anticipated that each category's FR value would serve as the class weight (SCWV). In the present AHP and FR model research, the Flood Vulnerability Index (FVI) was also computed to show the widened flood susceptibility relevance from very high to very low flood risk zones. The SCWV representing each class of the variables chosen and the SFWV chosen for flood events were factored into the FVI calculation using the following Eq. 6:

$$FSI = \sum\nolimits_{n=1}^{n} (\omega i \times \mathrm{FR}) \quad (6)$$

Where n = cumulative number of variables chosen (n = 7), ωi = weight of variables and FR = frequency ratio of each class.

4 Results and discussion

4.1 Relative importance of the FR method's flood susceptibility variable classes

Flood susceptibility mapping is one of the approaches that help policymakers to devise a plan to decrease a risk factor. Being fed by the river Jhelum, the District of Jhelum is always prone to flooding, especially during the monsoon showers. Historically, the area has many catastrophic events. There are many independent flood-inducing conditions and have played important roles during the flood history of the region. A statistical dataset was prepared for all the eight conditioning factors as given in Figure 5. The spatial relationship of all these eight factors with flood risk is given below. Weight values were assigned to each factor. Weight value

TABLE 5 Flood estimated risk zones in km^2.

S. No.	Name	Risk zone (Km^2)	Risk zone (%)
1	Very low risk	2,458.26	67
2	Low risk	361.87	9
3	Moderate risk	496.11	13
4	High risk	239.81	7
5	Very high risk	86.25	4
	Total area	3,642.30	100

shows the relative importance based on each class and provides detail for understanding the role in the generation of the flood (Tariq et al., 2022d).

A quantitative analysis was made to establish a relationship between the historic site of flooding and the geographical and geological variables that influence the flash flood events as shown in Figure 5. According to the results, the altitude class vector was heavily skewed toward the 170–700 m elevation range. In terms of soil slope angle, the highest value was found in the 45° and higher category. A greater amount of emphasis is placed on the northwest slope. There was a much larger effect of the weights in the 400–400 m vector distance from the fault class than there was in any other group. Following an investigation into the river's length, it was determined that the greatest load that the soil could support given its inclination was 2500 meters class. The second highest weight was taken by the rainfall layer as given in Table 4. Given these results, it was clear that the critical frequency of flash floods (Zhang et al., 2021) belonged to the rainfall class. In addition to the other factors, rainfall amounts above this threshold may potentially induce floods, depending on the duration. When comparing different land uses, vegetation and residential land uses along the river and on moderate slopes were given greater weighting factors. The geology of this area had more weight than any other factor.

4.2 Effects of risk factors on the probability of flooding

The purpose of our research was to establish a connection between flood-prone areas and the causes of flooding. After taking into account all of the data, it was determined that precipitation levels are a strong predictor of both drought and flooding (Zhang et al., 2019). More precipitation than usual is represented by a higher range, whereas a lower range implies drier-than-usual conditions. Each factor's weight in the AHP reflects its relative importance based on the others. The value of the class weight demonstrates the relative significance of the various classes for each element and offers insightful particulars that can be used to investigate the function of flood generation, as described in (Figure 5). The rainfall was considered to identify the risk of flood. Figures 3, 5 indicate that there was a deviation of rainfall ranging 18–137 mm, which gives an FR value of less than 1, indicating these areas to be more vulnerable to flood as compared to less precipitation region. Having FR values below 1 indicates a protective relationship between flood hazard and elevations between 2.5 and 5.0. Estimated FR values varied from 2.077 to 4.911 on slopes steeper than 45 degrees and 5–40 degrees, respectively, showing that this region of the research area is more prone to flooding. The corresponding slope angles ranged from 3.73 degrees to 46.88 degrees. There were more severe floods in some areas along the riverbanks than in others, and vice versa. According to the river distance analysis, a distance of 2,500 m from the river had values of FR ranging from .54 to .56, 1.21 to 1.26, and .48 to .54, indicating that places further away from the river had a lower F value and, as a result, less risk was involved.

4.3 Flood vulnerability mapping and demarcation of risk area

Final susceptibility zones were constructed using the factor weight and the class values obtained from the FR and AHP studies based on the volume of the weight and using the GIS environment. Similar to what is done in, the SCWV of all selected subsets of the same variable was employed (Figure 5). In order to determine a region's sensitivity to flooding, we added up the FR values for all of the potential causes (Siddiqui et al., 2020a; 2020b; Tariq et al., 2020; Tariq and Shu, 2020). The flood susceptibility index was calculated by the summation of all the flood-inducing factors identified. A higher flood susceptibility index shows a greater possibility of flood events. On the contrary, the lower FSI value suggests that chance of a flood event is less. To identify and recognize the flood risk zones, the FSI database was organized into 5 susceptibility areas (Mousa et al., 2020; Freeshah et al., 2021; Tariq et al., 2021f; Zainab et al., 2021). The zones were categorized into very low, low, moderate, high, and very high-risk zones, covering an area of 2,458.26, 361.87, 496.11, 239.81, and 86.25 km^2, respectively (Table 5). During the visit to affected areas (Mattalia et al., 2021), some severely damaged areas were identified. The following areas were damaged mostly in the past flood history.

TABLE 6 Accuracy and success rate of flood prediction are estimated using a susceptibility mapping approach.

Susceptible class	Flood testing points (30%)	Accurate points in class	Prediction accuracy (%)	Flood training points (70%)	Accurate points in class	Success rate (%)
Very low risk	6	66	80	13	188	84
Low risk	8			19		
Moderate risk	20			20		
High risk	25			82		
Very high risk	30			75		
Total	89			209		

4.4 Validation

Assessment and confirmation of accuracy are key procedures in flood risk management and vulnerability studies (Mohammadi et al., 2021; Mumtaz et al., 2021; Rahman et al., 2021; Shah et al., 2021). In order to verify the validity of the performed analysis and model, an accuracy evaluation is conducted. Several metrics, such as area under the curve, prediction of accuracy, and success rate, can be used to assess the precision and validity of a measurement. Accuracy was evaluated in this work by measuring PA and SR at flood training and test sites using the following Eqs 7, 8.

$$PA = \frac{\Sigma ap}{\Sigma tp} \tag{7}$$

$$SR = \frac{\Sigma sp}{\Sigma tnp} \tag{8}$$

Where *ap* is the number of times that an item was accurately tested for food safety, *tp* is the number of times that any item was tested for safety, *sp* is the number of times that an item was successfully trained, and tnp is the number of times that any item was trained. Prediction accuracy (PA) and success rates (SR) are two measures of how well a forecast really turns out. Using the preceding formulae, an accuracy value of 1.0 indicates that the model has been handled without bias, whereas a value of less than 0.75 is considered to be the norm. The success rate was calculated using a sample of 210 (70%) of the locations utilized in the FR simulation, while the forecast accuracy was calculated using 90 (30%) of the flood locations observed throughout the simulation (Hamza et al., 2021; Tariq et al., 2021c; 2021g; 2021b). Also, areas that are at low, medium, high, or extremely high risk of experiencing flooding in the future have been designated as such. It was calculated that the forecast's accuracy was 0.81 (or 81%) and its success rate was 0.84 (or 84%) (Table 6). It was concluded that the frequency ratio model should be employed for the flood analysis of the Jhelum district in Punjab because it has a forecast accuracy of more than 80%.

5 Conclusion

The role of susceptibility maps can't be negated in the flood management system of Jhelum District by the management departments of the government. This flood analysis was performed to establish a map of all the susceptible areas of the Jhelum District. The main goal of this research was to increase understanding of emergency management among citizens, local governments, and other government agencies. Past flood dangers and incidents that occurred regularly over a period were analyzed using a frequency ratio calculated from flood and non-flood based data. In this study, we used geographical data from a variety of sources to provide a complete picture. The study relied on a restricted version of the publically available ALOS-PALSER DEM, which had a resolution of 12.5 m. More precise flood mapping can be achieved with increased DEM resolution. According to the results, the most important elements that contributed to the occurrence of a flood were the following: distance from the river (0.245), rainfall variance (0.315), land use/cover (0.256), and soil clay content (0.521). The SFWV for slope angle was 0.1235 and the SFWV for elevation was 0.325; both of these factors contributed to the floods. Since the Jhelum area is rather flat close to the river Jhelum, the study shows that climatic (rainfall) and locally-based factors have a much more substantial effect than topographic (elevation and slope) considerations. The prediction accuracy was 81% and the success rate was 84%, as determined by validation results based on flood position data.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

MM: Conceptualization, methodology, software, formal analysis, visualization, data curation, writing—original draft, investigation, validation, writing—review and editing. LL: Methodology, software, formal analysis, visualization, data curation, writing—original draft, investigation, validation, writing—review and editing. MA: Writing—review and editing. AT: Methodology, software, formal analysis, visualization, data curation, writing— original draft, investigation, validation, writing—review and editing, supervision. SQ: Methodology, software, formal analysis, visualization, data curation, writing—original draft, investigation, validation, writing—review and editing. ME-H: Writing—review and editing. MES: Writing—review and editing. AA: Writing—review and editing. QL: Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Spatio-temporal impacts of typhoon events on agriculture: Economic losses and flood control construction

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Agricultural production has high correlations with natural hazards and water resource dynamic. Extreme rainfall brought by typhoons has a profound impact on agriculture in Taiwan. How typhoons impact agricultural activities and outputs is lacking research, especially in coastal regions such as Taiwan. In this report, the impacts of typhoon on agricultural loss from 2006 to 2019 in Taiwan was measured and called attention to the role of flood control construction in sustaining agricultural activities. With the help of Data Envelopment Analysis and geographical mapping, it is found that there are spatial differences in agricultural losses caused by typhoons. The main results indicate that the efficiency scores bring a inverse U-shape trend from the year 2007 (efficiency .718) to 2019 (efficiency .708). Looking further, Tainan City, Yunlin City, Chiayi County and other plain areas are vulnerable to hazards because the efficiency scores in these counties all below than 70%. However, some areas with prominent flood control construction showed a trend of agricultural damage reduction. This paper suggests that scholars should collect relevant data in the future and pay attention to the macro relationship between regional flood control construction and agricultural damage.

KEYWORDS

output efficiency, agricultural losses, drainage facility, Taiwan, typhoon

1 Introduction

Agricultural production is deeply affected by the environment and climate, and it is more at risk from natural hazards than any other industry. Because Taiwan is located in a subtropical region and is affected by warm humid air currents and ocean currents, it has an oceanic climate. However, because it is close to the mainland and the weather system mostly moves from west to east, Taiwan is also affected by the continental climate. The Tropic of Cancer (23.5 N) passes through the central part of Taiwan Island, so the southern climate is tropical, and the northern part is subtropical, with warm and humid climate. On the east coast, the mainstream Kuroshio flows northward, bringing in hot and humid air currents, with the prevailing winds in different seasons, such as northeast wind in winter and southwest wind in summer, causing rain on the windward slopes and inland mountainous areas, making Taiwan abundant in rainfall. Taiwan is often affected by typhoons from June to September each year (Bayrak et al., 2021). On average, three to four typhoons hit Taiwan in summer and autumn each year. Although it brings abundant rainfall, the time and space distribution of rainfall is very uneven, which often causes hazards such as floods and soil flows. However, if the rain brought by typhoons is lacking, droughts are prone to occur in winter. According to statistics from the agricultural department of the Taiwan government, meteorological hazards are the main source of agricultural hazards in Taiwan. Typhoons and the heavy rains it brought are the main hazards (Chuang and Ho, 2021). Chen et al. (2018) pointed out that 70% of Taiwan's agricultural economic losses are caused by typhoons, and 27% are caused by rain hazards (including heavy rain). According to the Executive Yuan (2020), over the past 10 years, 90% of the damage to agricultural activities in Taiwan has been caused by floods, heavy rains and typhoons.

In view of the frequent extreme rainfall brought by typhoons, how to deal with the uneven distribution of hydraulic power and the application of resources in economic activities has an important impact on the efficiency of economic output (Frame et al., 2020). For example, how to effectively store precipitation and use it as an input for agricultural activities to drive product supply is very important for efficiency at the current or future output level. In contrast, excessive water supply, such as floods and heavy rainfall, will cause losses in agricultural activities such as undesired output value (Saeed et al., 2021; Sahana et al., 2021). Based on above discussion, this article uses Taiwan's agricultural statistical annual report, agricultural loss statistics, typhoon database, and rainfall distribution surveys, and uses the agricultural production of the counties and cities in Taiwan's main island from 2006 to 2019 as the research object, applying the Data Envelopment Analysis (DEA) and the concept of output efficiency analysis to explore the impact of typhoon over the years on the overall and inter-regional agricultural output and agricultural losses. This paper expected to find a positive correlation between agricultural losses and typhoon frequency and the significance of such correlation should have spatial differences, especially in ecologically fragile areas.

2 Literature review

Due to the characteristics of disaster statistics, part of the research uses input-output analysis for analysis (Yu et al., 2019; Lin et al., 2020). Shibusawa and Matsushima (2021) used the Japanese geographic environment data and the input-output table of each region to carry out the earthquake disaster economic evaluations based on the output value of each region. They estimated the direct losses of hazards based on natural hazards, population density, spatial distribution of economic sectors, and production profiles revealed by geographic data of every 500 square meters. The empirical results found that the degree of disaster loss isn't proportional to population density and inter-industry development. The study suggests that preventive measures or post-disaster reconstruction policies should consider more aspects to avoid overall economic losses. Lin et al. (2020) used the statistical data from agricultural annual reports to discuss the impacts of the natural hazards on climate change and crop losses on the regional economy. In their study, the regional input-output model combined with the Miller and Blair (2009) supply-side input-output model was applied. Due to the low ability of crops to resist hazards, the impact of the uncertain natural hazards on crop losses is the first to bear the brunt. They concluded that agricultural disaster losses have a great impact on income and employment effects, and the largest impact on domestic gross production is nearly 30%, resulting in an increase in unemployment and a decline in economic growth. They found that the input-output model can be used to estimate the effects of hazards on income and indirect effects. If combined with the social accounting matrix, the direct and indirect effects of disaster losses in various sectors can be estimated. Lee et al. (2020) and Lin et al. (2020) further analyzed the impact of single-day disaster events on agricultural losses and the economy. Their studies took Typhoons Morakot and Van Nabey as examples, using Input-Output Analysis to discuss. The empirical results found that: Typhoon Morakot and Typhoon Van Nabe caused damage to agriculture and industry. The multiplier effects of output reduction were 1.49 and 1.33, respectively, and the unemployment rate increased by .13 percentage points and .06 percentage points, respectively.

Natural hazards such as wind strikes not only affect agricultural losses, but also indirectly affect local employment issues (Qin et al., 2020). For example, after the passage of Typhoon Morakot in 2009, the labour force in the disaster area faced the problem of temporary unemployment, which caused the government to amend the law to help the laborers find employment. Sperling (2021) compared the employment situation of laborers in counties and cities hit and untouched by hurricanes and floods in Mexico after 2007. The study found that seasonal hurricanes invaded the region and caused the local labour population to migrate to avoid the hurricane in a short period of time, resulting in a decline in labour participation. As a result, the average salary in the hurricane-affected area was greatly reduced due to a large reduction in labour supply. Although the relatively neighbouring areas that weren't hit by the hurricane didn't suffer direct economic losses as a result, they included workers from areas affected by the hurricane, resulting in a drop in average wages. Chen et al. (2018) studied based on spatial database and geographic information system, integrating the original data of agricultural census, the current status of agricultural land use, and the potential of rainfall inundation. This assessment was based on Yunlin and Chiayi, which are important agricultural production areas in Taiwan. They explored the spatial distribution and spatial heterogeneity of potential agricultural losses when an extreme rainfall event occurs under rainfall scenarios with different flooding potentials. The results of the study showed that when the daily rainfall reaches 200 to 450 mm, the agricultural areas in central and southern Taiwan are threatened by flood, and the functions of water storage and drainage facilities will reach the upper limit of operation. If the scale of rainfall that will become more and more variable in the future, the formulation of measures such as hydraulic facilities and the use of hydraulic energy will have a key impact. Similar studies also have Liang et al. (2020a), Liang et al. (2020b), and Liang and Li (2020). By reviewing the literature, it is obvious that there is a lack of research on Taiwan in the existing studies, and most studies of typhoon focused on economic variables such as income and employment, and rarely explore specific agricultural losses. The study of Chen et al. (2018) is important as it gives us a good starting point and pointed out the spatial heterogeneity of agricultural losses caused by rainfall and floods. But the study is still county-based and doesn't explore Taiwan as a whole. This paper finds that DEA is a good method to solve the problem of multi-input and multi-output, and is effective in evaluating the effectiveness of multi-input and multi-output units (Basavalingaiah et al., 2022; Rehman et al., 2022). For example, Xie et al. (2019) pointed out in their study that since DEA is based on relative efficiency through linear programming, it isn't necessary to determine the weight of input and output indicators in advance during the application of the model, thus avoiding the influence of subjective factors. Therefore, DEA model will be used in this study to analyze the spatial difference of agricultural losses caused by typhoons in Taiwan. Meanwhile, Chen et al. (2018) is referred in the present study to visualize the losses by GIS platform. At the same time, considering the impact of massive rainfall brought by typhoon on agriculture, this paper combined with the changes of water conservancy facilities to discuss the impact of typhoon on agricultural water management in Taiwan.

3 Methodology

3.1 DEA

In traditional, the Data Envelopment Analysis (DEA) developed by Charnes et al. (1978) usually applies strong disposal reference technology:

$$P^S(X) = \left\{(x, y):\ y \le Y\lambda^A, x \ge X\lambda^A, \lambda^A \in R^+\right\} \tag{1}$$

In Eq. 1, x and y represent the input and output. Eq. 1 means the outputs are "desirable" when producer fabricates and therefore these outputs won't bring negative external effect. Färe et al. (1989) then constructed several efficiency measures according to the different ways of including desirable and undesirable outputs asymmetrically. Their weak disposal reference technology is as follows:

$$P^W(X) = \left\{(x, y^U, y^D):\ y^D \le Y^D\lambda^A, y^U = Y^U\lambda^A, x \ge X\lambda^A, \lambda^A \in R^+\right\} \tag{2}$$

In Eq. 2, define input, undesirable and desirable output as x, y^U and y^D. As Hsiao et al. (2012) pointed, region OFBCDE represents strong disposability, producer can yield the outputs freely or costless disposable if the outputs are "goods". However, if some outputs are "goods", and others are not, it is unreasonable to assume the production behavior under strong disposability assumption because it implies the "bad" outputs can be freely disposed. Therefore, the assumption of freely (strong) disposability of "bad" output is violated and we should use another approach which apply the concept of weakly disposability appropriately. Under the weak disposability assumption of undesirable outputs, moving (Y^U, Y^D) horizontally leftwards to the vertical axis on which $Y^U = 0$ is not possible unless $Y^D = 0$, and (Y^U, Y^D) can only be proportionally scaled down to ($\lambda^A Y^U$, $\lambda^A Y^D$), $0 \le \lambda^A \le 1$ (Li, 2020). The weak disposable assumption emphasizes the correlation of desired and undesired output. That is to say, the Decision Makers' Unit (DMU) performance rankings are very sensitive to whether or not undesirable outputs are included. Therefore, traditional models might produce a misleading indication due to their exclusion of undesirable outputs.

In our opinion, we consider the outputs of agriculture have a similar phenomenon. They also produce some "goods" (e.g., agricultural commodities and related economic productions) and some "bads" (e.g., pollution, production damage) that these outputs are desirable and undesirable. The "bad" outputs affect other outputs and take shape their whole performance indirectly in the industry. The evaluation of the agricultural industry efficient may calculates the results inaccurately if we measure under the assumption of strongly disposability. The reason is that when the outputs are undesirable, one can't assume that it is possible to produce less of that output keeping the other output and input fixed because these undesirable outputs are the byproducts of the remaining outputs.

Follow the concept of Färe et al. (1985) and Färe et al. (1989), we apply the methods of Cooper et al. (2007), Cooper et al. (2009) and measure the efficiency by solving the following equation:

$$\begin{aligned} min\ \rho &= \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^{S-}}{x_{ik}^{S}}}{1 + \frac{1}{q_1+q_2}\left[\sum_{r=1}^{q_1}\frac{S_r^+}{y_{rk}} + \sum_{t=1}^{q_2}\frac{S_t^{b-}}{b_{rk}}\right]} \\ & s.t. \\ & X\lambda + s^- = x_k \\ & Y\lambda - s^+ = y_k \\ & B\lambda + s^{b-} = b_k \\ & \lambda, s^-, s^+ \ge 0 \end{aligned} \tag{3}$$

In Eq. 3, x_k and y_k means the k -th input and output, X, y_{rk} and b_{rk} expresses the matrix of sample inputs, undesirable and desirable outputs.

3.2 Analysis process

The analysis process is as follows: First, through the above equations, the annual agricultural production efficiency of each county/city in Taiwan can be calculated. Then, the production efficiency value will be compared with the impact of typhoons on each county/city in each year to explore whether the frequency of typhoons is related to production performance. Our main results found that typhoons did have an impact on agricultural production efficiency in some counties, but did not necessarily have a comprehensive impact on production performance. Finally, in order to look for underlying reasons, our study enumerates data of water conservancy facilities in each county to explain why typhoons did not have a negative impact on agricultural production in some counties.

Accordingly, the input and output variables used in this article are summarized as follows:

Agricultural Outputs: Refers to the total agricultural output value (Unit: Thousand Taiwan dollars, Mean = 11,191,373, Variance = 10,771,685). $Output\ value = unit\ price \times output$.

Agricultural Loss: The agricultural losses in the area caused by the typhoon during the year. (Unit: Thousand Taiwan Dollars, Mean = 85,463, Variance = 363,122).

Labor: Refers to workers engaged in agricultural activities. (Unit: person, Mean = 38,672, Variance = 27,899).

Area = The area of land actually used as farming in agricultural activities also includes short-term leisure or fallow land. (Unit: hectares, Mean = 40,270, Variance = 27,866)

DT = The number of typhoons that have landed Taiwan each year (Mean = 2.786, Variance = 1.372).

It is worth noting that the variable DT is an environmental variable that counts the number of typhoons landed in Taiwan over the years. According to historical data, about 8–15 typhoons form in the Pacific Ocean every year. The average number of travel routes to Taiwan is 2.786. Due to the geographical area, every time a typhoon makes landfall, almost the entire island is surrounded. Therefore, we can analyze whether the typhoon will affect the agricultural activities of each county or city.

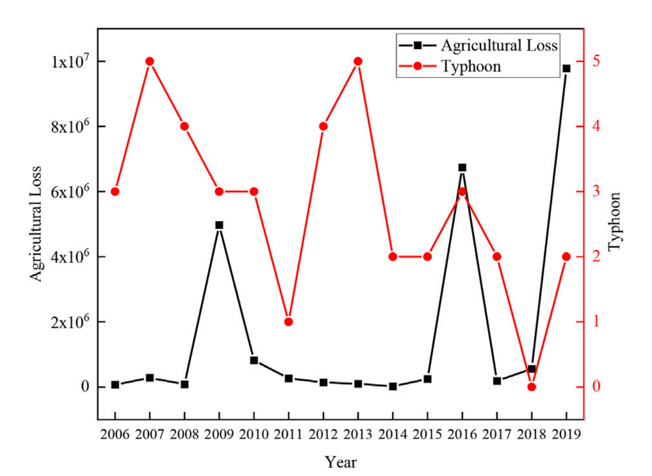

FIGURE 1
Agricultural losses and frequency of typhoons in Taiwan.

3.3 Data sources

The research data in this paper were manually collected from several official websites by referring to previous literatures on Taiwan, such as Su et al. (2010), Chang et al. (2019), and Yeh et al. (2021). The panel data of agricultural losses and related input and output variables related to typhoons from 2007 to 2019 were collected through the council of Agriculture. Meanwhile, in order to explain the findings of this paper, we also sorted out the variables of farmland water conservancy facilities in counties and cities of Taiwan from the executive Yuan in Taiwan, including the length of water storage pipelines and drainage pipelines. At the same time, the record of rainfall in Taiwan Meteorological Bureau were collected for helping explain the findings.

4 Results

4.1 Correlations between typhoon and agricultural loss

Figure 1 summarizes the statistics of agricultural losses which caused by typhoons and the number of typhoons landed Taiwan in 2009, 2013, 2016, and 2019. It can be found that the number of typhoons and agricultural losses are not necessarily positively correlated. For example, three typhoons in 2009 were less than five in 2013, but the scale of overall agricultural losses in 2009 was about 50 times that of 2013. Similarly, the number of typhoons in 2016 was three less than in 2013, but the agricultural losses in that year were 68 times that of 2013. The data shows that although typhoons are the main factor causing agricultural losses in Taiwan, there is no inevitable relationship between the number of typhoons and the scale of losses. Second, according to the Natural Disaster Yearbook (2019), the agricultural damage caused by the typhoon is concentrated in a specific area. For example, from 2006 to 2019, only three agricultural damages occurred in northern cities such as Taipei, New Taipei, Taoyuan, and Keelung. In contrast, there have been 20 agricultural hazards in southern cities such as Yunlin and Tainan. The most extreme is Chiayi County, where agricultural losses are still erupting every year even when there is no typhoon crossing the border in 2018.

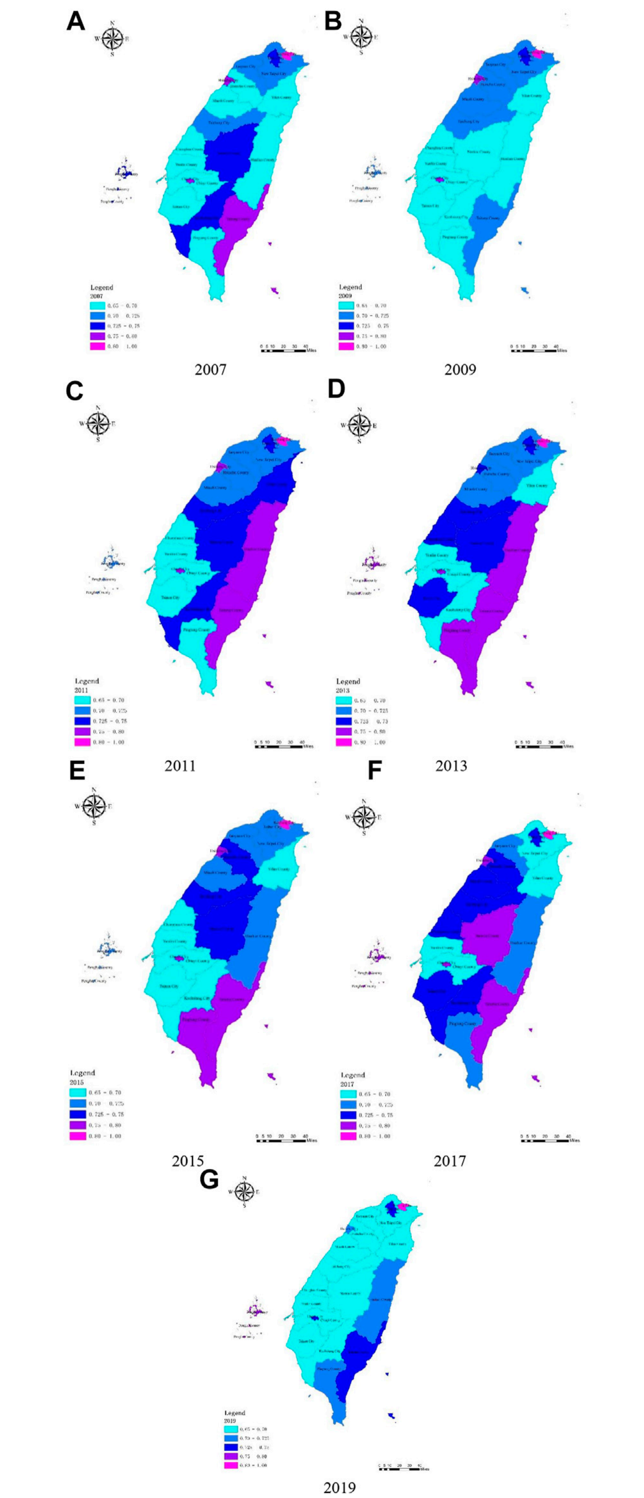

FIGURE 2
Agricultural production efficiency of various counties and cities in different years. **(A-G)** are, respectively, 2007, 2009, 2011, 2013, 2015, 2017, 2019.

According to the undesired output efficiency Eq. 3, this paper sorts out the average output efficiency of each city and region over the years (see full description in Supplementary Appendix SA1). The empirical results show that Keelung City has the highest output efficiency of

TABLE 1 Agricultural production efficiency.

Region	2007	2009	2011	2013	2015	2017	2019
New Taipei City	0.708	0.708	0.708	0.711	0.713	0.657	0.657
Taipei City	0.725	0.727	0.731	0.729	0.723	0.738	0.731
Taoyuan City	0.702	0.707	0.708	0.709	0.710	0.717	0.655
Taichung City	0.717	0.720	0.727	0.726	0.730	0.735	0.671
Tainan City	0.659	0.660	0.667	0.730	0.669	0.734	0.671
Kaohsiung City	0.733	0.672	0.733	0.676	0.677	0.738	0.675
Yilan County	0.678	0.686	0.742	0.680	0.686	0.688	0.687
Hsinchu County	0.656	0.718	0.724	0.721	0.727	0.730	0.666
Miaoli County	0.647	0.713	0.719	0.722	0.724	0.733	0.670
Changhua County	0.665	0.670	0.677	0.737	0.681	0.741	0.683
Nantou County	0.735	0.681	0.743	0.747	0.749	0.756	0.694
Yunlin County	0.676	0.684	0.691	0.689	0.693	0.698	0.698
Jiayi County	0.672	0.673	0.682	0.682	0.688	0.691	0.689
Pingtung County	0.694	0.692	0.700	0.759	0.760	0.706	0.703
Taitung County	0.759	0.704	0.770	0.770	0.775	0.780	0.725
Hualian County	0.682	0.688	0.752	0.754	0.703	0.713	0.706
Penghu County	0.731	0.709	0.711	0.766	0.717	0.778	0.770
Keelung City	0.966	0.994	0.993	0.996	0.955	0.947	0.964
Hsinchu City	0.792	0.784	0.780	0.735	0.765	0.770	0.721
Chiayi City	0.771	0.771	0.772	0.778	0.777	0.786	0.729
Mean	0.718	0.718	0.737	0.741	0.731	0.742	0.708

TABLE 2 Annual changes in water storage pipelines and drainage pipelines of farmland water conservancy facilities (unit: meters).

Region name	2005		2015		2018	
	Water storage	Drain	Water storage	Drain	Water storage	Drain
New Taipei City	23,000	314,051	23,000	314,051	23,000	314,051
Taipei City	60,742	75,858	60,742	75,858	60,742	75,858
Taoyuan City	69,465	306,416	69,465	306,416	69,465	306,416
Taichung City	21,809	163,077	24,642	167,542	25,028	403,345
Kaohsiung City	18,842	1,001,992	32,272	1,280,254	34,702	1,240,164
Yilan County	6,882	1,383,714	3,741	1,397,008	3,702	1,427,679
Hsinchu County	12,951	463,329	12,788	399,297	12,786	391,583
Miaoli County	5,963	981,705	5,438	315,746	5,186	325,861
Changhua County	64,329	2,983,042	51,851	3,587,046	47,577	3,557,697
Nantou County	5,279	184,679	5,279	184,679	5,297	292,758
Yunlin County	35,918	6,651,880	41,450	6,855,026	41,641	6,882,024
Jiayi County; Tainan	53,449	8,757,427	63,332	8,426,143	64,406	8,442,464
Pingtung County	10,210	285,266	5,500	2,330,739	5,500	2,331,842
Taitung County	5,601	42,861	5,601	42,861	5,601	42,861
Hualian County	15,526	115,936	16,191	118,701	17,108	127,988

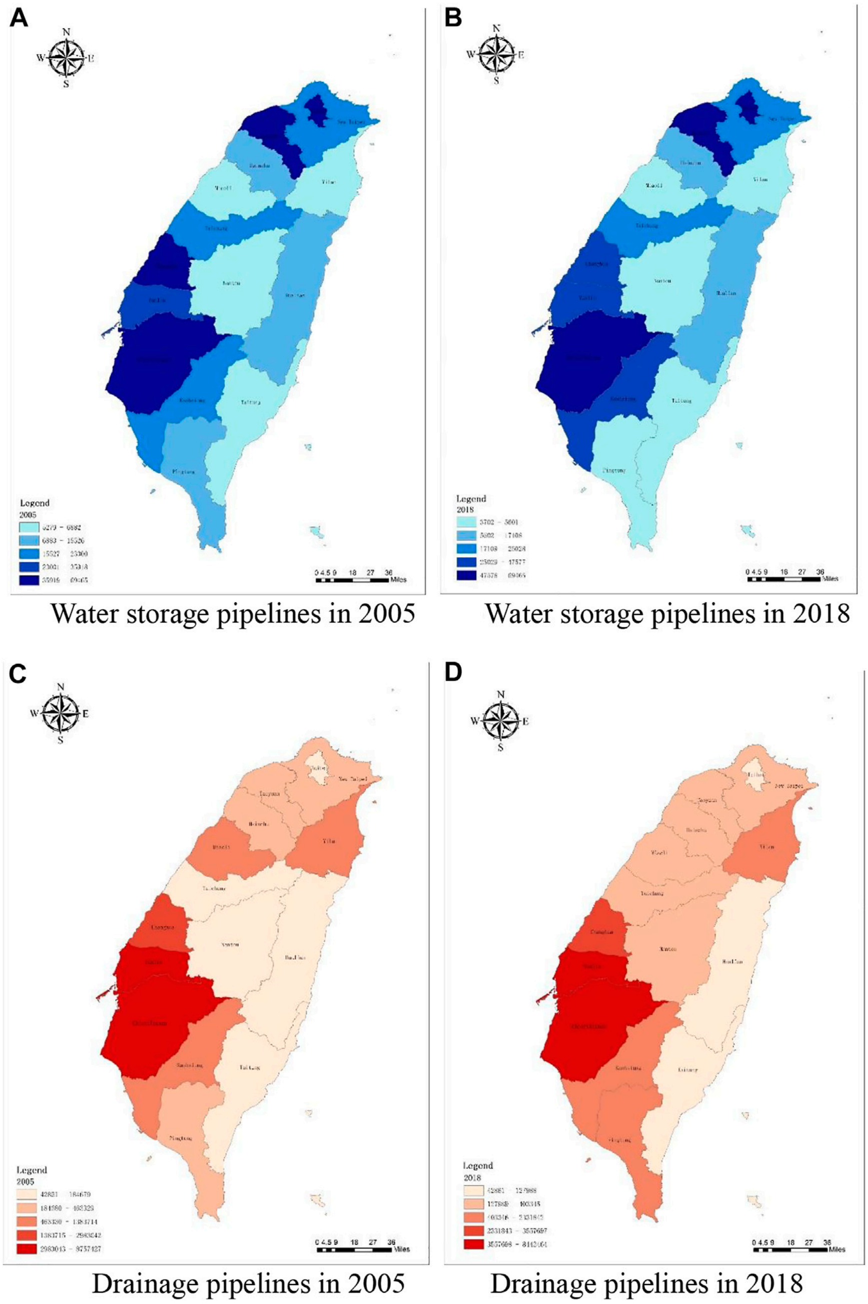

FIGURE 3
Annual changes in water storage pipelines and drainage pipelines of farmland water conservancy facilities (unit: meters). **(A)** Water storage pipelines in 2005; **(B)** Water storage pipelines in 2018; **(C)** Drainage pipelines in 2005; **(D)** Drainage pipelines in 2018.

.975 and Chiayi County has the lowest output efficiency of .682. From a regional perspective, the northern region has the highest performance at .778 and the southern region has the lowest performance at .700. Secondly, from the distribution of output efficiency samples, it can be found that the variance and standard deviation are between .003–.116. This result indicates that the fluctuation of agricultural output efficiency among regions, counties and cities is relatively low. From the perspective of areas where agricultural losses occur more frequently, the efficiency values of the southern and eastern regions are worse than other regions, but the fluctuations in the distribution of sample efficiency values are not as high as those of regions with better performance such as the northern region. The result reflects that when natural hazards such as typhoons strike, the impact on the efficiency of agricultural output in various regions of Taiwan will not fluctuate greatly.

Figure 2and Table 1 summarizes the output efficiency of Taiwan's counties and cities in 2007, 2009, 2011, 2013, 2015, 2017, and 2019. First of all, from the perspective of time trends, such as New Taipei City, Taoyuan City, Taichung City, Kaohsiung City, Hsinchu City and other regional production efficiency the output efficiency has shown a downward trend in recent years. Tainan City, Yunlin City, Chiayi County, Pingtung County and other regions showed a growth trend. It is worth noting that the main production areas of various crops in Taiwan are mostly located in Yunlin County, Chiayi County and Tainan City. However, Yunlin and Chiayi areas are prone to flooding due to low-lying terrain, while Tainan is due to the terrain. It can be seen from Figure 2 that 2009 and 2019 were the years when Taiwan's agricultural losses were relatively serious, but the output efficiency of these three regions did not significantly decrease in that year. The efficiency value of Chiayi County in 2019 was even the second of the 7 years. The high level indicates that in the event of a typhoon, regional agricultural output activities have a negative impact on the efficiency of disaster prevention and mitigation.

5 Potential explanation: Flood control construction differences

In order to explain our findings, past literature was referred. Among literature, Hung and Kao (2010) and Shiu et al. (2009) points out that the number of days of heavy rain and the frequency of heavy rain in Taiwan in the past 30 years have been significantly increasing, especially between 2000 and 2006, the frequency of heavy rain was significantly higher than that from 1970 to 1999. Due to the concentration of rainfall and the increased variance of variation, how to deal with sudden heavy rains and save water for the sustainable use of water resources during the subsequent dry season has become an urgent problem for Taiwan's agricultural development in recent years. From the perspective of Taiwan's overall agricultural activities, Yunlin, Chiayi, and Tainan are the few plain areas in Taiwan. The land is easier to cultivate and become the main agricultural economic area in Taiwan. However, some areas are low-lying, if there is no drainage pipeline. Drainage can easily cause flooding, mudslides and other hazards, which in turn makes agricultural activities stop.

According to agricultural statistics from the Council of Agricultural and Executive Yuan of the Taiwan Region, Table 2 and Figure 3 summarize statistics related to farmland water conservancy facilities in all counties and cities on the island in Taiwan from 2005 to 2018. As mentioned above, because Yunlin, Chiayi, and Tainan are the main agricultural production areas and are prone to flooding due to geographical factors, the establishment of local drainage measures is extremely important. In addition, due to the uneven distribution of rainfall in recent years, how to effectively store water is also an important policy issue. From Figure 3, it can be found that the length of agricultural water storage and drainage pipelines in Taiwan, such as Taipei, Taoyuan, and Taitung, remains unchanged for many years. For the average area, the construction of water storage equipment is increasing year by year. Figure 3 shows that when agricultural activities are in response to heavy rainfall and uneven rainfall, Tainan City, Yunlin City, and Chiayi County have effectively used flood storage and flood drainage channels to reduce flood risks and strengthen water resource utilization. by comparing the changes in agricultural losses in the areas where flood-control construction performed well, this paper believes that correlation exists, but it has not been able to achieve clear statistical verification. On the one hand, the economic data and the rainfall data of Taiwan have not been well integrated. For example, the regional rainfall data brought by the typhoon is not exist and the relevant definitions are not unified. Therefore, we believe that it is necessary to put forward relevant hypotheses and call on scholars to conduct relevant research in the future. This paper proposes the following hypothesis: The installation of storage and drainage equipment has made agricultural economic activities more sustainable in the face of the concentrated rainfall brought by typhoons.

6 Conclusion

This article takes the agricultural production of the counties and cities on the island of Taiwan from 2006 to 2019 as the research object, and applies the undesired output efficiency of Data Envelopment Analysis (DEA) to analyze the impact of typhoon on the overall and inter-regional agricultural output and agricultural losses. The results show that the performance in the northern region is the highest and the southern region is the lowest. Tainan City, Yunlin City, Chiayi County and other plain areas are vulnerable to hazards, especially the extreme rainfall brought by typhoons. However, the construction of flood storage and drainage facilities seems effectively slow down the impact of rainfall brought by typhoons. As some local governments have built drainage and water storage pipelines and other facilities in recent years, we propose a causal relationship that need to be further tested between the construction of water facilities and the agricultural damage caused by typhoons. Areas such as Taipei, Taoyuan, and Taitung that have made less efforts in flood control have notably failed to contain agricultural losses. Areas that actively build flood storage and drainage facilities, such as Tainan City, Yunlin City, and Chiayi County, are making their agricultural production more resilient and reducing losses in the face of hazards. Although this paper is a brief research report and not aim at proving this causal relationship, we believe this phenomenon is worth paying attention to in the future. This means that the construction of flood control facilities has gradually become more and more effective in making up for the agricultural losses caused by geographical disadvantages, which has important reference value for promoting local policies.

This study is based on the data of counties and cities on the main island of Taiwan. The analysis data still has macroeconomic characteristics. Therefore, it is needed to acknowledge our limitations. How to conduct more detailed analysis or micro-level discussions is the goal that must be paid attention to in the future. Due to the limitations of research data, future study can further integrate the spatial data of different crops in the geographic area, and further consider the actual conditions of various crops. After the spatial distribution of agricultural losses is clearly identified, the factors affecting the spatial distribution of agricultural losses can be further explored in future studies from the perspective of agricultural production factors to clarify the relationship between various production factors and the distribution of agricultural losses.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by WW, XQ, and QL. The first draft of the manuscript was written by WW, QL, QZ, L-CC and XC, and QL commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1055215/full#supplementary-material

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Analysis of groundwater ion abnormality and its cause of centralized drinking water sources in Jieshou City, China

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Groundwater provides drinking water to city and rural residents; which is also one of the chief water sources for commercial and agricultural activities in Jieshou City. We collected and analyzed the samples of 18 underground water source wells in Jieshou. We investigated whether the water was of acceptable quality and had characteristics that exceeded the standard. This study was conducted to determine the chemical characteristics of groundwater and abnormally high super-standard ions found in groundwater. The hydrogeological conditions of the study area were analyzed through data collection; through sample collection and sample testing, the characteristics and types of water chemistry were analyzed by means of mathematical statistics analysis and the Piper chart. The genesis of water chemistry was discussed using the Gibbs chart and correlation analysis; the proportional coefficient of ion molar concentration was used to judge the source, origin, and forming process of groundwater chemical composition. The results show that the groundwater is classified as marginally alkaline water, with a composition of Na-HCO_3. The cations are mainly Na^+, and the anions are mainly HCO_3^-. According to the III water standard of groundwater quality standard and comparing the content of each ion, Na^+ and F^- are the primary abnormal super-standard ions, and ions and compounds are the main occurrence states. The concentrations of Na^+ and F^- exceed the standard for class III water. There was a positive correlation between the abnormal Na^+ and F^-, and the concentration of F^- increased with the increase in monitoring depth. The causes of abnormal ions were mainly determined by the lithology of the aquifer in the study area, and most of them are fluorine-containing rocks, which are transferred into groundwater through leaching or hydration. The enrichment of Na^+ and F^- is influenced by the local primary geological setting, hydrochemical type, hydrogeological conditions, pH and artificial activities, and the primary geological setting is the main influencing factor.

KEYWORDS

centralized drinking water sources, abnormal ions, distribution characteristics, cause analysis, influential factors

1 Introduction

Groundwater resources characterized by wide distribution and stable water yield are vital water sources for agricultural irrigation, industries, and city life. In the northern part of China, groundwater as a crucial drinking water source for cities has been widely developed and utilized (Zhang et al., 2021). Epidemiological studies have shown that long-term high-fluoride intake from drinking water may lead to dental or skeletal fluorosis, which is suspected to be the leading cause of endemic fluorosis in some areas.

The water quality of the centralized underground water source directly affects the drinking water and the health of the residents. Hence, it is of great significance to study the water quality and its chemical characteristics for the rational development and utilization of underground water resources and the healthy drinking water of residents (Li et al., 2021; Xiao et al., 2021).

Several studies investigated the geochemical characteristics of groundwater under different climate conditions and geological background conditions and discovered that the groundwater in some areas shows high levels of salinity, nitrogen, fluoride, arsenic, etc., which can affect the groundwater quality (Lapworth et al., 2017; Adimalla, 2019), China (Wu and Sun, 2016; Yin et al., 2019; Li et al., 2021; Xiao et al., 2021). The geochemical characteristics of groundwater are closely related to factors such as the hydrogeological condition, the water-bearing media's lithology, the aquifer's hydrodynamic characteristics, and water–rock (soil) interactions (Liu et al., 2015; Kumar and Kuriachan, 2020). Some solutes in groundwater are gradually enriched under specific geological circumstances, reaching quantities that impair irrigation and drinking; this process is generally irreversible (Zhu et al., 2017).

Fuyang City is located in the northwestern part of Anhui province, with the most population in this province, and its industrial and agricultural water use is mainly sourced from groundwater. In recent years, despite a severe water shortage caused by water quality deterioration, serious groundwater resource pollution, and a lack of regulation and storage, the urban areas of Fuyang City, Taihe County, Linquan County, and Jieshou City have continued to exploit large amounts of groundwater to maintain average production and life, so groundwater quality and drinking water safety issues are significant concerns (Liu et al., 2012).

Jieshou is a county under Fuyang. The city has 23 centralized groundwater-type water sources, including one county-level source and 22 for villages, towns, and rural regions, supplying 729,500 people with 71,420 m^3 daily. Using the Groundwater quality standard GB/T14848-2017 class III standard (GB, 2017), samples of water that exceed the standard (1.0 mg/L) are called "over-standard."

According to the results of water quality testing conducted by local water source administrative departments, 13 of the 23 groundwater sources exceeded the standard for sodium content, and all 23 groundwater sources exceeded the class III groundwater standard of 1.0 mg/L for fluoride content, with some exceeding the standard by 1.12 times.

Fluoride is a crucial non-metallic halogen in the human body. Fluoride may fortify teeth and bones and minimize the occurrence of dental caries when administered in sufficient amounts. Nonetheless, if the human body consumes an excessive amount of fluoride, it will have negative effects on the bones and lead to conditions such as bone pain, rickets, and dental fluorosis (Zhang, 2014). High fluoride content in groundwater affects the exploitation and utilization of groundwater resources and the safety of drinking water for residents. Therefore, it has been studied worldwide (Karunanidhi et al., 2019; Yousefi et al., 2019; Haji et al., 2021).

This study evaluated county-level groundwater-type water sources from 18 drinking water source wells to analyze the hydrogeochemical characteristics and abnormal over-standard ions and also explored the cause of abnormal ions. Moreover, this study aims to 1) understand the geochemical characteristics of the groundwater in county-level water sources in Jieshou City, 2) determine abnormal over-standard ions, and 3) analyze the cause of abnormal ions.

2 Materials and methods

2.1 Study area

Jieshou is situated in the northwestern region of Anhui province, along the border between Anhui and Henan. It is at 115°15′ and 115°32′ east and 33°00′ and 33°30′ north. It borders Taihe County to the east, Fuyang City to the southeast, Linquan County to the south, Shenqiu County of Henan province to the west, and Dancheng County of Henan province to the north. Due to historic Yellow River floods, the administrative territory of Jieshou City shows the geomorphic characteristic of a deposition plain, linking the Yellow River flood plain and the Hejian Plain. The terrain along the Quan River is flat, high in the northwest and low in the southeast, and low-lying. On the majority of the planet's surface, a Cenozoic Quaternary sedimentary layer is covered by sandy soil. The city has a maximum width of 25 km from east to west and a maximum length of 58 km from south to north.

There is a semi-humid monsoon climate in a warm temperature zone in Jieshou City, with an annual average temperature of 15.4°C and an annual average precipitation of 886.5 mm. There are two major tributaries of the Huai River that flow from east to west: the Quan River and the Ying River.

2.2 Description of an aquifer

The groundwater in the region of study consists mainly of unconfined rock pore water. According to aquifer characteristics,

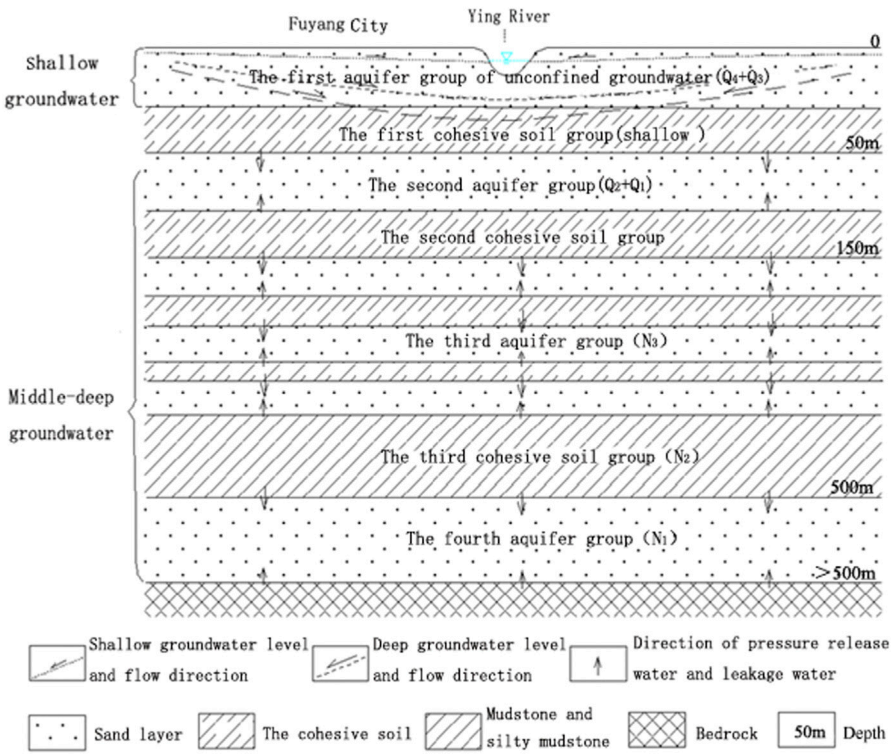

FIGURE 1
Diagram of aquifer structure in the research area.

groundwater's buried state, hydrodynamic properties, and the link between atmospheric precipitation and surface water, the unrestrained rock porous aquifer group is classified into the shallow porous aquifer group and the deep porous aquifer group.

The shallow groundwater exists in the 50 m shallow Holocene and Late Pleistocene layers and is directly tied to atmospheric precipitation and surface water. It may be referred to as the first aquifer group (shallow); the middle-deep groundwater exists in the stratum 50 m below the surface and is unrelated to precipitation or surface water. According to the hydrogeological structure and exploitation situation, the middle-deep groundwater of unconfined rock is divided into three aquifer groups, namely, the second aquifer group (buried depth of 50–150 m), the third aquifer group (buried depth of 150–500 m), and the fourth aquifer group (buried depth of 500–1,000 m) (buried depth greater than 500 m). The details of Fuyang's aquifer structure are given in Figure 1.

2.3 Sample collection and statistical analysis

In this study, 18 groundwater samples were collected from the confined aquifer through pumping wells during July 2021. The information on water source wells is shown in Table 1. Sampling locations were recorded using the RTK (real-time kinematic) device (Figure 2). All the wells were the primary sources of drinking and domestic water use for residents. The sampling processes followed national technical regulations. Before sampling, the wells were pumped for 10 min to avoid stagnant water in the pipeline. The containers were brown polyethylene plastic bottles, rinsed with deionized water in the laboratory, and washed again using the groundwater to be sampled before sampling. Two replicates of each sample were collected to ensure the reliability and validity of the data.

All samples were stored in a refrigerator at 4°C. All monitoring indicators for groundwater samples are shown in Table 2. The samples were mainly analyzed for pH, EC, total dissolved solids (TDS), total hardness (TH), main cations (K^+, Ca^{2+}, Na^+, and Mg^{2+}), main anions (HCO_3^-, CO_3^{2-}, Cl^-, and SO_4^{2-}), nitrogen pollutants (NH_4^+, NO_3^-, and NO_2^-), and F^-. Main cations were determined by ICP-OES (Avio 200, United States); Cl^-, SO_4^{2-}, and NO_3^- were determined by ion chromatographs (Eco IC and CIC-D100); F^- was determined by a thundermagnetic ion activity meter (PXSJ-216); NH_4^+ and NO_2^- were determined by a visible light spectrophotometer (L2); and

TABLE 1 Water source wells in county-level water sources of Jieshou city.

S/N	Sample no.	Well depth (m)	Exploiting layer and position	Static water level
1	JS-1–2	265	Confined aquifer, 104.5–265 m	73
2	JS-1–3	450	Confined aquifer, 240–444 m	72
3	JS-1–4	450	Confined aquifer, 292–442 m	73
4	JS-1–5	450	Confined aquifer, 282–438 m	70
5	JS-1–6	470	Confined aquifer, 282–458 m	72
6	JS-1–9	500	Confined aquifer, 290–444.4 m	69
7	JS-1–11	500	Confined aquifer, 317–448 m	73
8	JS-1–12	460	Confined aquifer, 290–444 m	71
9	JS-1–13	450	Confined aquifer, 290–444 m	69
10	JS-1–15	450	Confined aquifer, 319–448 m	72
11	JS-1–16	450	Confined aquifer, 317–448 m	72
12	JS-1–18	450	Confined aquifer, 317–448 m	73
13	JS-1–19	450	Confined aquifer, 317–448 m	70
14	JS-1–20	440	Confined aquifer, 317–440 m	95
15	JS-1–21	450	Confined aquifer, 317–448 m	95
16	JS-1–22	450	Confined aquifer, 317–448 m	95
17	JS-1–23	450	Confined aquifer, 317–448 m	73
18	JS-1–24	450	Confined aquifer, 317–448 m	72

TABLE 2 Sample testing and analysis indexes.

Index type	Index name
Conventional index	Turbidity, chroma, odor and taste, pH, TDS, oxygen consumption, and total hardness
Metal ions	Hg, Sb, Cd, Cu, Mn, Pb, Zn, Al, Be, Ba, Ni, Co., Mo, Ag, Ti, Na, K, Ca, Mg, Fe, Cr, and Cr (VI)
Other inorganic elements	Fluoride, carbonate, bicarbonate, silicic acid, boron, nitrate, nitrite, ammonia nitrogen, iodide, arsenic, and selenium

HCO_3^- and CO_3^{2-} were determined by titration. All indexes were measured strictly according to the Quality Standard for Groundwater of the People's Republic of China (GB/T 14,848–2017).

In this study, statistical andalyses were performed using Excel 2019. Correlation, factor analyses, and a graph of correlation were performed using SPSS 21.0. The diagram of the aquifer, the Piper diagram, and the Gibbs diagram were completed with the help of AutoCAD 2010 and Origin 2020. The proportional coefficient of ion molar concentration was used to assess the evolution process of groundwater chemical composition.

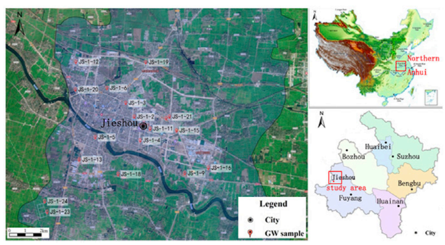

FIGURE 2
Distribution of sampling points of water source wells in Jieshou city.

2.4 Groundwater quality assessment

In this study, the single-factor evaluation method was used to evaluate groundwater quality. Single-index evaluation refers to the analysis and evaluation of a single index to reflect the situation of a single pollutant in groundwater. In the evaluation of a single index, the groundwater quality category is determined by referring to the level limits of each participating index. When the limit values of indicators in different categories are the same, the quality standard is preferred instead of the inferior one, that is, when a factor can be identified as both the quality standard and the inferior standard, the quality standard is the first choice. Finally, the worst factor category was selected as the water quality category for the group.

The evaluation formula is $I_i = C_i/C_0$; Ii is the water quality index of single factor i; C_i is the measured water quality value of a component; and C_0 is the standard value of class Ⅲ in the Groundwater Quality Standard (GB/T 14,848–2017). Ii ≤ 1 indicates that the water quality factor meets the corresponding water quality standards; Ii ≥ 1 indicates that the water quality exceeds the corresponding water quality standard. The single-factor evaluation method can clearly identify the main pollution factors (abnormal superscalar factor) by comparing the representative values of each pollution factor concentration with the evaluation criteria (Hu, 2015).

2.5 Analysis of available data

Based on the collected geological background and surface environmental data of the study area, the lithology and rock-forming minerals of groundwater aquifers were analyzed, and the source, precipitation, and migration mechanisms of abnormal ions were studied. Combined with the previous monitoring data, the causes of abnormal ions in the groundwater of the centralized drinking water source in Jieshou City were comprehensively analyzed.

3 Results and discussion

3.1 Hydrochemical characteristics

Using a mathematical statistic of the chemical indexes of county-level water sources in Jieshou City, the 18 groundwater samples collected this time have a pH value of 7.8–8.7, falling into the category of weak alkaline water. The major anion in the water is HCO_3^-, with an ionic concentration range of 338–422 mg/L, a mean value of 383.89 mg/L, a standard deviation of 23.706 mg/L, and a variable coefficient of 0.0618. The second major anion is SO_4^{2-}, with an ionic concentration range of 37.3–60.2 mg/L, a mean value of 50.678 mg/L, a standard deviation of 7.350 mg/L, and a variable coefficient of 0.1450. The third anion is Cl^-, with a content range of 38.1–47.8 mg/L, a mean value of 31.617 mg/L, a standard deviation of 5.661 mg/L, and a variable coefficient of 0.1505. The content variation trend of Cl^- shows a certain positive correlation with SO_4^{2-}. The major positive ion in the water is Na^+, with an ionic concentration variation range of 252–433 mg/L and a mean value of 343.83 mg/L, followed by Ca^{2+} and Mg^{2+}, with an average ionic concentration of 4.322 mg/L and 2.943 mg/L, respectively. Due to the similar physicochemical properties of magnesium and calcium, their contents in groundwater samples from water source wells show a positive correlation; the content of K^+ is minimal, with a mean value of 1.612 mg/L (Table 3).

The TDS concentration range is 563–714 mg/L, falling into the category of highly mineralized water. All samples were tested without Cu, Mn, Zn, Be, Ni, Co, Ti, Cr, or Cr(VI).

3.2 Hydrochemical type

Piper diagrams are widely used to study groundwater chemical types and can effectively reflect hydrochemical types and characteristics (Liu et al., 2020). The hydrochemical type can reflect the content proportion of the major anions and positive ions in the water body, which is usually represented by a piper trilinear chart. According to the proportion of different ions, the hydrochemical type is divided into 16 categories. For the water source wells in Jieshou City, the plot results are shown in Figure 3.

The plot results indicate that since most water source wells are concentrated in an urban area and their depths are very close, the hydrochemical types of groundwater samples from water source wells in Jieshou City are very similar, showing that Na^+ and HCO_3^- are dominant. Their hydrochemical type falls into the Na-HCO_3-Cl-SO_4 type, approximating the Na-HCO_3 type. There could be multiple reasons for the formation of the Na-HCO_3-Cl-SO_4 type, including the following: 1) when the runoff condition of deep groundwater is not good, the concentrations of $Cl^-$and Na^+ lead to the hydrochemical types of groundwater being the Na-HCO_3-Cl-SO_4 type and 2) the dissolution of gypsum and calcite resulted in the enrichment of $SO_4^{2-}$and Ca^{2+} (Gao et al., 2020).

3.3 Determination of abnormally enriched ions

With reference to the Quality Standard for Ground Water GB/T14848-2017, these research results are taken as the basis for determining whether the content of a hydrochemical constituent in the groundwater exceeds the standard. The groundwater whose indexes can meet the class III water standard can be taken as drinking water.

TABLE 3 Test results of groundwater hydrochemical ions.

Index sample	pH (dimensionless)	Na q (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Fluoride (mg/L)	Bicarbonate (mg/L)	Total dissolved solids (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Total hardness (mg/L)
JS-1–2	7.9	269	1.03	8.18	6.41	2.88	370	627	41.8	40	37
JS-1–3	7.8	252	1.18	7.01	5.23	2.75	384	647	42.1	50.3	31
JS-1–4	7.9	314	1.54	4.05	2.24	2.25	422	714	35.3	52.9	23.3
JS-1–5	8	305	1.33	3.39	2.29	2.12	385	650	31.8	48	23.7
JS-1–6	8.3	326	1.55	4.02	2.87	2.08	404	709	40.1	53.9	24.5
JS-1–9	7.9	343	1.34	6.58	4.05	2.62	379	636	37	44.5	35.4
JS-1–11	8.7	370	1.65	3.83	2.66	2.1	374	692	36.1	54.7	22.5
JS-1–12	8.3	412	1.52	3.49	2.44	2.16	405	708	39.8	53.1	23.3
JS-1–13	8.5	433	2.7	3.53	2.36	2.02	352	624	30.7	43.3	24.1
JS-1–15	7.8	383	1.76	3.89	2.64	2.16	414	669	40.9	60.2	21.7
JS-1–16	8.5	301	1.68	3.22	2.26	2.25	378	654	37.2	54.8	20.9
JS-1–18	8	304	1.35	3.63	0.82	2.17	367	606	34	49.6	25.8
JS-1–19	8.1	322	1.2	3.96	2.78	2.15	386	652	39	56.1	23.3
JS-1–20	8.1	384	1.85	4.06	3.03	2.12	381	673	47.8	56.3	25.8
JS-1–21	7.9	361	1.97	3.99	2.96	2.09	402	677	46.6	58.4	29
JS-1–22	8	377	2.04	3.55	2.58	2.37	418	701	40.9	60.7	25.5
JS-1–23	8.2	383	1.62	3.79	2.72	2.11	338	563	28.5	37.3	25.4
JS-1–24	8.1	350	1.71	3.63	2.63	2.03	351	565	27.5	38.1	23.7
Mean	8.11	343.83	1.61	4.32	2.94	2.25	383.89	653.72	37.62	50.68	25.83
SD	0.25	47.167	0.374	0.361	1.189	0.243	23.706	43.99	5.661	7.350	4.338
Variable coefficient	0.031	0.137	0.232	0.083	0.404	0.108	0.0618	0.067	0.1505	0.1450	0.168

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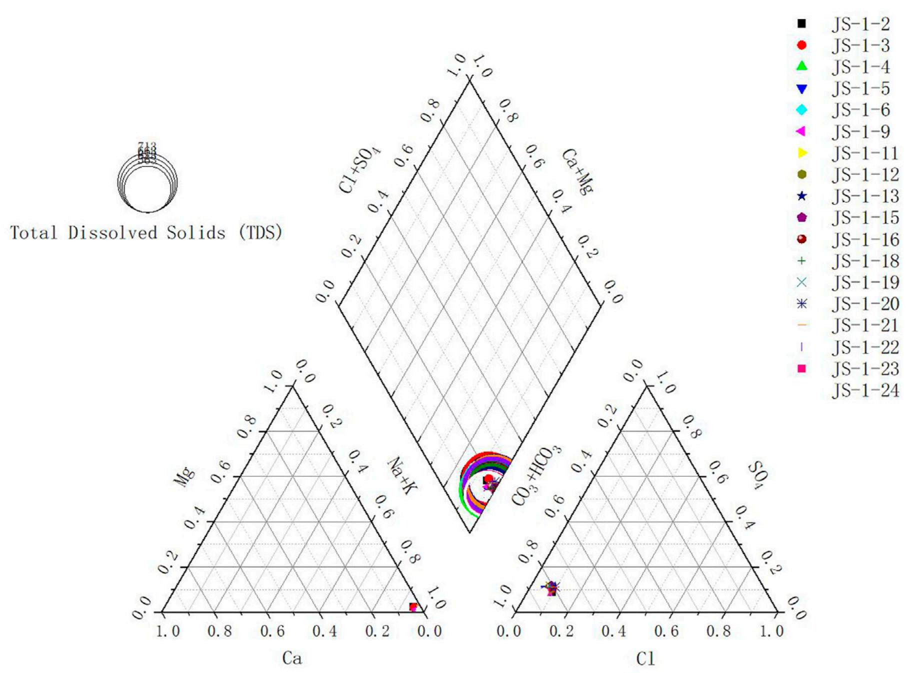

FIGURE 3
Piper trilinear chart of water source well samples.

From the determination results of the samples and the previously monitored data, it is discovered that the ions and chemical constituents, in the groundwater samples of Jieshou City, that exceed national standards can be divided into two categories. Only few samples contain such ions over the standard in one category. An occasional contingency or an error may arise in these ions during the test and cause their level to exceed the standard by a small extent. Hence, they are not the focus of this study. In the other category, according to previous and current monitoring data, some ions are generally enriched to an extent far greater than the limit specified in the National Quality Standard for Ground Water GB/14848-2017. In particular, in the results of water source wells, some groundwater samples fall into the hydrochemical constituent of class IV or even class V groundwater. Such a class of hydrochemical constituent is considered abnormally enriched ions.

In the test results this time, the major abnormal ions are Na^+ and F^-. In accordance with the Quality Standard for Ground Water GB/T 14848–2017, class III groundwater is required to contain sodium less than 200 mg/L. Still, in the water source well samples of Jieshou City, the sodium content range is between 252 and 433 mg/L, significantly exceeding the class III water standard, and some samples even exceed the class IV water standard of 400 mg/L. The abnormally enriched F^- is another significant feature. In the water source well samples collected this time, the fluoride content range was between 2.02 and 2.88 mg/L, which exceeds the admissible limit of 1 mg/L in the “Quality Standard for Ground Water GB/T 14,848–2017.” Most of the GW samples from the study area exceeded the standard. Therefore, Na^+ and F^- are determined as abnormally enriched ions (Kong et al., 2020).

3.4 Occurrence state of abnormal ions

3.4.1 Occurrence state of fluoride

Fluoride, a VII A group element in the periodic table of the elements with an atomic number of 9, belongs to the halogen element. Its simple substance has very strong reactivity, and it is easy to get an electron to form F^-. Fluoride mainly exists in the form of an ion or combined state in the water–soil system, in which migration and transformation are closely related to the occurrence state of fluoride. When the environmental conditions change, the occurrence state of fluoride will also vary accordingly.

It is known from the test results that fluoride exists in groundwater mainly in the forms of F^-, MgF^+, CaF^+, and NaF; the F^- in groundwater is evidently positively correlated to the content of TDS, HCO_3^-, and Na^+, while showing an unsharp negative correlation with Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}.

Most water source wells in the county-level water sources of Jieshou City are more than 400 m deep. The groundwater at this depth is middle-deep groundwater, with weak water flow, slow horizontal circulation, and mainly vertical alternating. The salinity in the water is not easy to migrate, forming a superior

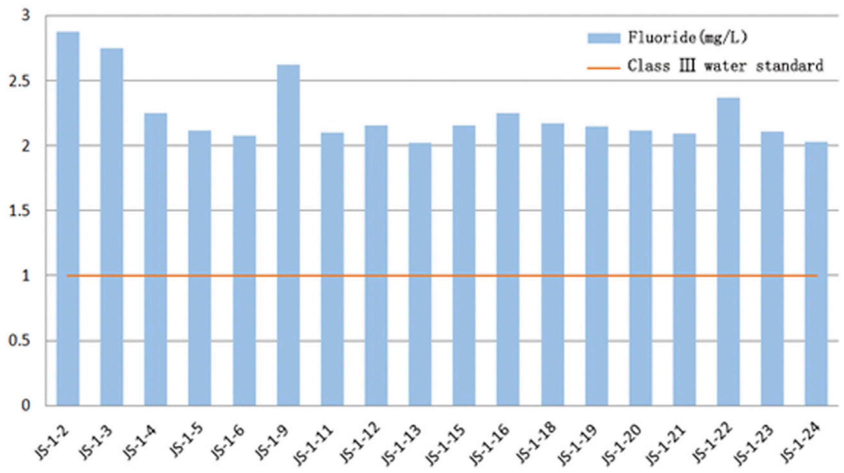

FIGURE 4
Fluoride content in county-level water sources of Jieshou city.

storage condition for F^-, and the hydrochemical action is dominated by evaporation and inspissation, facilitating the enrichment of fluoride and the formation of groundwater with high fluoride (Liu et al., 2015; Li et al., 2017).

3.4.2 Occurrence state of sodium

Sodium, an element of alkali metal with an atomic number of 11, can easily lose only one electron in the valence shell and form Na^+. Due to its high reactivity, there is no simple sodium substance in nature. Most of sodium exists in minerals in the form of a compound. The content of sodium element in the earth's crust is 2.27%, ranking it seventh in abundance in the earth's crust and fifth among metal elements, and its abundance in the ocean is 1.08 × 10^4 mg/L. The majority of sodium salt minerals are highly soluble, but some sodium minerals have poor solubility or do not even dissolve. The common sodium minerals are montmorillonite $[(Na,Ca)_{0.33}(Al,Mg)_2[Si_4O_{10}](OH)_2{\cdot}nH2O]$, hornblende $[(Ca,Na)_{2-3}[Mg,Fe(II),Fe(III),Al]_5[(Al,Si)_8O_{22}](OH)_2]$, albite $[Na_2OAl_2O_3.6SiO_2]$, etc (Rajmohan et al., 2021).

3.5 Distribution characteristics and change of abnormal ions

It can be known from the aforementioned test results that in the county-level water sources of Jieshou City, the Fe, Mn, and iodide levels conform to the class III water standard of groundwater, but the fluoride and sodium ions greatly exceed the standard by 1.88 times and 1.165 times, respectively. The over-standard fluoride and sodium ions show a positive correlation. The distribution of abnormal ions in the wells of water sources is shown in Figure 4, Figure 5.

1) Middle aquifer: JS-1–2 samples were collected from the aquifer (104.5–265 m) with a fluoride content of 2.88 mg/L at the maximum, which is 1.88 times the class III water standard of groundwater.
2) Deep aquifer: The rest of the samples were collected from the aquifer 280–448 m, with fluoride content between 2 and 2.4 mg/L, generally exceeding the standard by 1–1.4 times the class III water standard of groundwater.
3) The overall trend of vertical distribution shows that the fluoride concentration increases with the depth of monitoring wells, and the fluoride content is relatively higher in the deep aquifer. It is inferred that this relates to the calcium ion content in the groundwater to a certain extent.

The high fluoride content in groundwater has caused a great level of harm to human health (Liu et al., 2021). The analysis of fluoride distribution and its causes in groundwater can provide a basis for determining the source of fluoride and the safety of drinking water (Zhang et al., 2020; Liu et al., 2021).

3.6 Cause analysis of abnormal ions

3.6.1 Source of abnormal ions

1) Material source of fluoride

The main reason for high fluorion fluoride concentrations is the continuous dissolution of fluorinated minerals. The groundwater of the research area is unconfined pore water, and the middle-deep aquifer group is composed of Neogene–Early and Middle Pleistocene calcareous argillaceous glutenite and Quaternary system alluvial sand. According to the analysis of existing data, the fluoride released from the hydrolysis

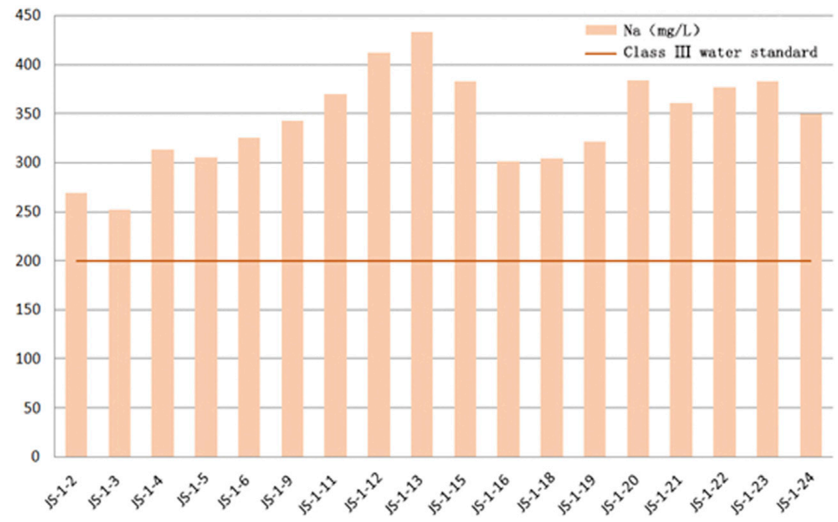

FIGURE 5
Sodion content in county-level water sources of Jieshou city.

and corrosion of hornblende, pyroxene, gneiss, biotite, granite, evaporite, albite, fluorapatite, and fluorinated mineral bedrock makes a significant contribution to the high fluoride levels in groundwater (Yang et al., 2017). Different types of rocks always have different fluoride contents, determining the differentiation of fluoride background values in different regions. In natural conditions, rocks or fluorinated minerals may release the fluoride into the water body, atmosphere, and soil under the combined effects of water–soil action, volcanic movement, and bedrock weathering and then integrate with the regional fluoride geochemical abnormality to form the fluorosis area. High-fluoride rocks and minerals are the ultimate sources of regional fluoride pollution or fluorosis.

2) Regional background features of sodium

The county-level water sources of Jieshou City belong to middle-deep groundwater, and its aquifer is mainly composed of silty sand, fine sand, and medium sand. The sandstone contains many sodium-bearing minerals such as albite, which enters the groundwater *via* ion exchange action, so the aquifer lithology is the primary source of sodium. In addition, the research area is located in the Huaibei Plain, one of the regions with a potentially wide distribution of soda saline-alkali soil in China. The salty soda soil formed by various causes is rich in all kinds of sodium salts. This part of the sodium salt can probably enter the groundwater under the action of rain eluviation, which is an essential source of sodium in groundwater as well.

In studying the chemical composition of groundwater, some hydrogeochemical issues can often be studied by using the proportionality coefficient of ion molar concentration between various components. The proportionality coefficient of ion molar concentration can be applied to determine the source, cause, and forming process of groundwater's chemical components; better describe the evolutionary process and characteristics of the hydrochemical component; and make a typical analysis of the hydrogeochemical evolution. rNa^+/rCl^- and rCa^{2+}/rSO_4^{2-} can reflect the source of main ions in groundwater. In the samples collected this time, the results of the rNa^+/rCl^- ratio in water source wells are far higher than 1 (Figure 6), indicating that the dissolving process of feldspar, niter, and other sodium-bearing

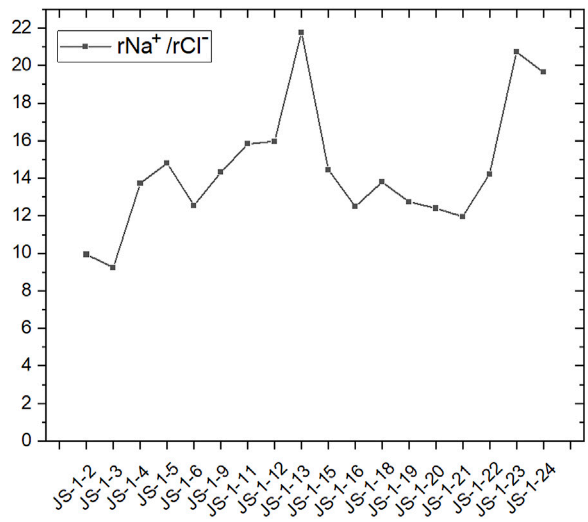

FIGURE 6
The results of rNa^+/rCl in groundwater of Jieshou city.

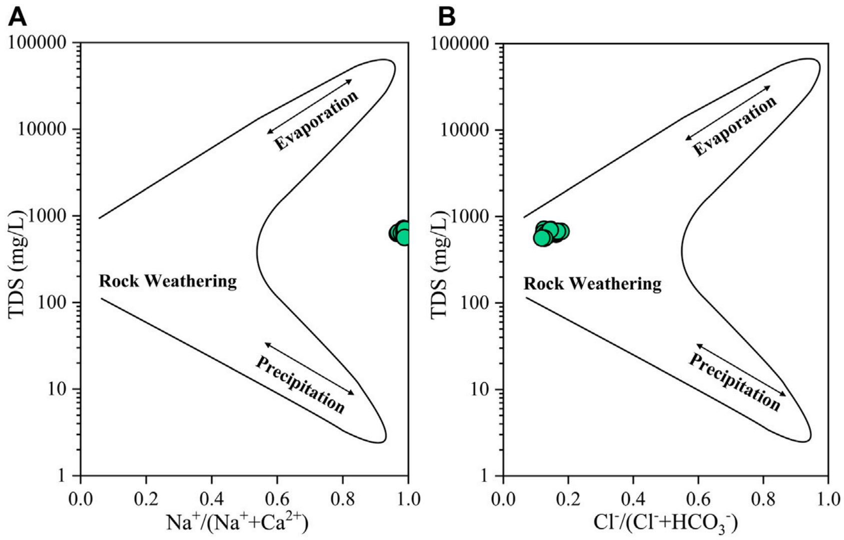

FIGURE 7
Gibbs chart for the groundwater in the North Anhui area.

minerals has happened; this further proves that feldspar and other sodium-bearing minerals are significant sources of sodium in the groundwater of Jieshou City (Zango et al., 2019).

3.6.2 Separation of abnormal ions

1) Groundwater formation mechanism

The soluble ions in the groundwater mainly originate from the weathering decomposition of rocks and soil and the atmospheric precipitation, so the Gibbs diagram (Gibbs, 1970) is often used to qualitatively assess the hydrochemical influence of regional rocks, atmospheric precipitation, and evaporation concentration on groundwater (Sunkari et al., 2020; Yu et al., 2020). The groundwater-tested hydrochemical data are projected into the Gibbs diagram. Rock weathering represents the rock weathering degree, precipitation represents the atmospheric precipitation degree, and evaporation represents the evaporation concentration degree. The results of this chart indicate that the main ion component of groundwater originates from the rock weathering process. In this weathering process, sodium-bearing minerals dissolve, allowing sodium to enter the groundwater (Hu, 2015).

The TDS content of the groundwater in Jieshou's concentrated groundwater source is generally high, and the ratio of $\rho(Na^+)/\rho(Na^+ + Ca2^+)$ is large (0.93–1.0), and the ratio of $\rho(Cl^-)/\rho(Cl^- + HCO_3^-)$ is small (0.1–0.28) (Figure 7). The results show that the ionic characteristics of groundwater in Jieshou City are influenced by rock weathering and evaporation, of which the latter is more notable. In addition, the ρ $(Na^+)/\rho$ $(Na^+ + Ca^{2+})$ ratio of water samples in most areas falls outside the Gibbs curve, indicating that the water may be affected by groundwater overextraction and other external factors, leading to the change of separation composition (Kong et al., 2020).

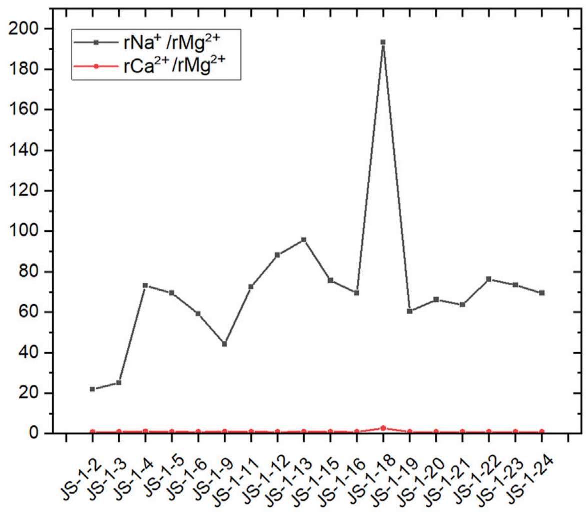

FIGURE 8
The rNa^+/rMg^{2+} and rCa^{2+}/Mg^{2+} of groundwater in Jieshou city.

2) Mineralization degree

rNa^+/rMg^{2+} and rCa^{2+}/Mg^{2+} can reflect the degree of mineralization of groundwater. In general conditions, the calcium ion is a dominant cation in low-mineralized water. As the mineralization degree increases, sodium gradually becomes the dominant cation. In the water source well results of Jieshou City, rNa^+/rMg^{2+} is far more abundant than rCa^{2+}/rMg^{2+} (Figure 8), showing that the degree of mineralization of the

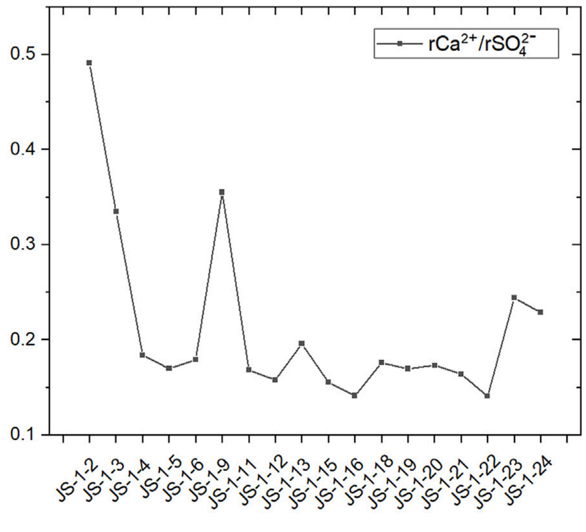

FIGURE 9
The $rCa^{2+}/rSO4^{2-}$ in groundwater of Jieshou city.

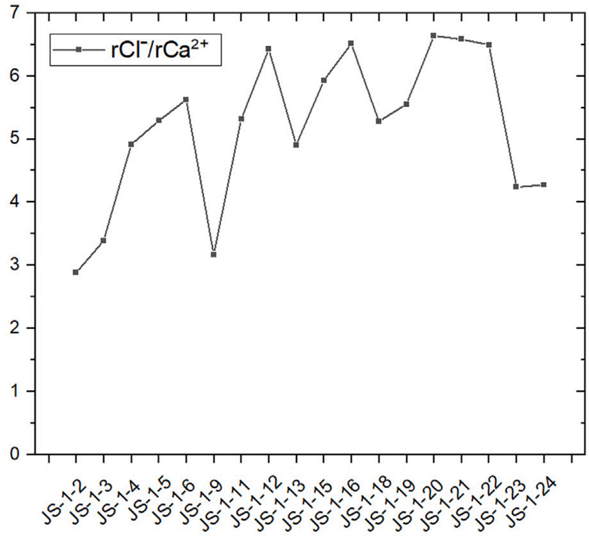

FIGURE 10
The results of in groundwater of Jieshou city.

deep well is significantly higher, leading to the enrichment of sodium. High salinity in groundwater is conducive to the dissolution of fluorite, allowing fluoride to enter the groundwater (Li et al., 2020). According to the molar ratios of rNa^{+}/rMg^{2+} and rCa^{2+}/rMg^{2+}, the dominant interactions between groundwater and rocks can be distinguished, which are evaporation, dissolution, and silicate weathering, respectively (Xiao et al., 2015; Olea-Olea et al., 2020).

3) Ion exchange

Ion exchange is one crucial approach for abnormally enriched ions to enter the groundwater. Affected by the ion radius and the electric charge of the ions, fluoride often enters the water body by exchanging hydroxide in water solution. At the same time, the sodium is more likely to exchange with the calcium ions in the water. In the research area, fluoride shows a significant correlation at a level of 0.059 (both sides), and the groundwater, with a pH value that is more alkaline, provides a good condition for the enrichment of fluoride. The adsorption capability and degree of the ions in groundwater relate to the ions' concentration in the groundwater. Suppose the pH value of groundwater is higher (to be alkaline), then the degree of mineralization of groundwater increases. In that case, the alternate adsorption of cations in the water will also be enhanced, and the calcium ions existing in the groundwater will displace sodium from the sodium salt (Frommen and Groeschke, 2021). With the increase of sodium in the water, the amount of fluoride will also increase. Typically, the calcium ions in the groundwater come from the dissolution of gypsum, so its ratio to sulfate is basically maintained at 1:1, while most rCa^{2+}/rSO_4^{2-} ratios in the water source well samples of Jieshou City are less than 1 (Figure 9). This proves the loss of calcium, which displaces the sodium in minerals through ion exchange with sodium-bearing minerals, thus separating from the groundwater system.

4) Hydrodynamic condition of groundwater

rCl^{-}/rCa^{2+} can be used to reflect the hydrodynamic properties and lixiviation of groundwater. The hydrodynamic condition of shallow groundwater in Jieshou City changes considerably (Figure 10), but on average, the lixiviation of a water source well is evidently higher than the results of a monitor well, which is consistent with the higher enrichment of sodium and fluoride in water source wells. The results revealed the lixiviation, and the hydrodynamic condition is one of the causes of abnormally enriched ions in the groundwater of Jieshou City.

5) Hydrochemical condition

Regarding fluoride, it is known from the groundwater test data of Jieshou City that as far as the distribution area of calcareous water in groundwater is concerned, the fluoride contained in it is lower. In comparison, the fluoride contained in the sodium water distribution area is high, but as far as fluoride is concerned, its calcium salt and sodium salt have different solubilities. In general conditions, the solubilities of calcium fluoride and sodium fluoride in water are 16 mg/L and 42×10^3 mg/L, respectively. When the sodium fluoride is hydrolyzed, the fluoride will exist in the groundwater as ions. Due to its low solubility, the calcium fluoride will exist in water as sediment. Thus, the groundwater shows the phenomenon of "high calcium

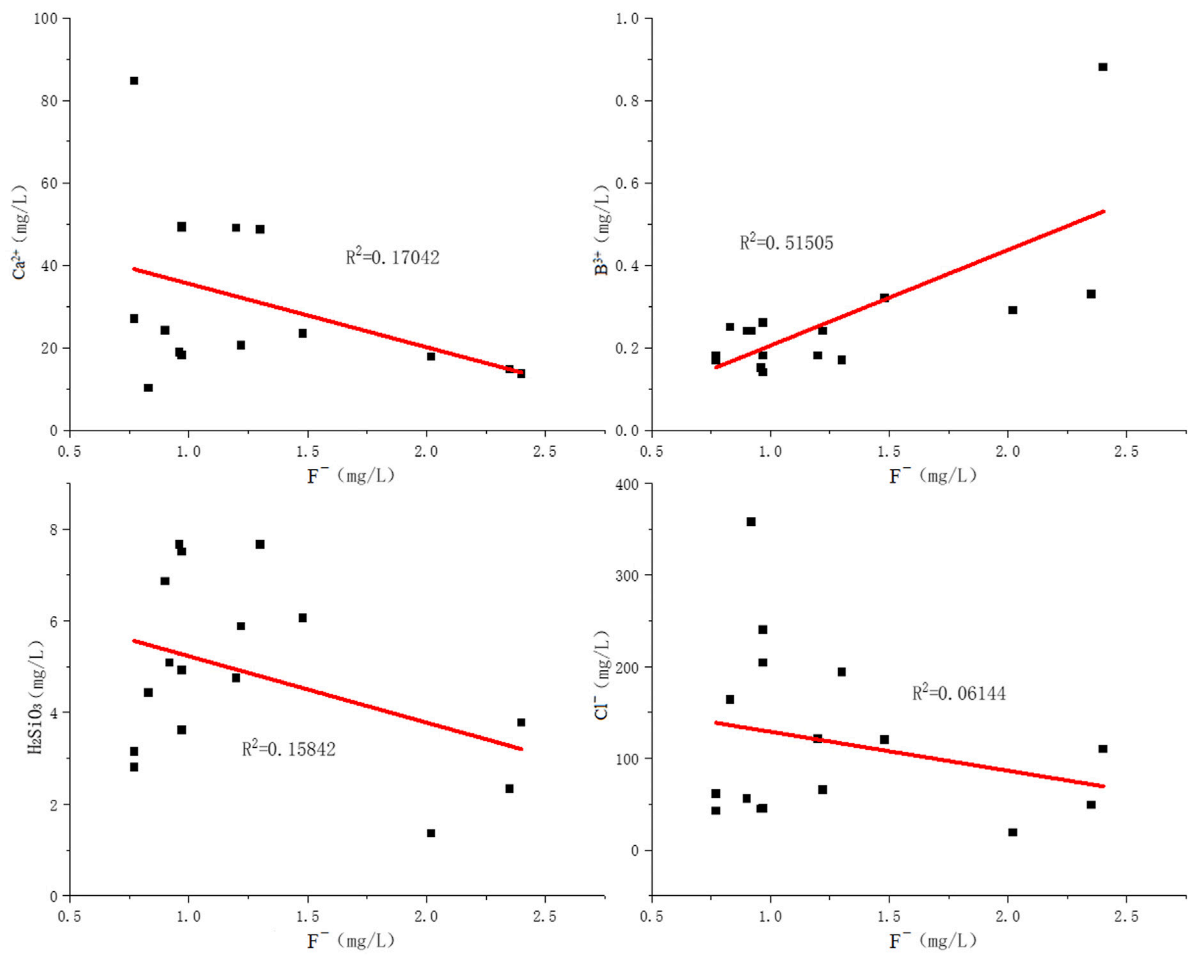

FIGURE 11
Relationship between fluoride and other ions or elements.

and low fluoride or high sodium and high fluoride" (Singh et al., 2020). In other words, if the cations in groundwater are mainly calcium ions, in view of the solubility of calcium fluoride, the groundwater will contain less fluoride; but when the cations in groundwater are mainly sodium, on account of the strong solubility of sodium fluoride, there will be significant fluoride enrichment. The relationship between fluoride and other ions or elements is shown in Figure 11. Furthermore, the bicarbonate and carbonate contained in groundwater could cause a chemical reaction with calcium fluoride to generate calcium carbonate or calcium bicarbonate, further accelerating its hydrolysis and thus increasing the fluoride content in groundwater (Yu et al., 2015; Zhang et al., 2020).

Regarding sodium, the hydrochemical component results of groundwater in Jieshou City also demonstrate some beneficial chemical conditions for the enrichment of sodium in groundwater or show other ions' content level features coupled with the sodium enrichment process. The details are as follows:

(1) Factor analysis was performed using IBSS 2021 statistical software, and it was discovered that the second major elements, sodium and potassium, contribute greatly to the extraction results, indicating that the alkali metals have a common source (natural mineral); meanwhile, other ions that show larger positive loads are boron, chloride, and sulfate; all these ions can be explained as the results of the lixiviation process of nature, and these provide a basis for the mineral source of sodium (Table 4).
(2) Correlation analysis shows that the sodion sodium content is strongly negatively correlated with calcium ions this time. This verifies that in the process of ion exchange, the increase of sodium content can restrain the calcium ion content; sodium has a positive correlation with boron, chloride, and sulfate ions; sodium has a weak positive correlation with pH value, indicating that the alkali environment is in favor of the dissolution of sodium. The groundwater of Jieshou City exactly shows weak alkali environment, providing a favorable condition for the

TABLE 4 Groundwater ion factor analysis component matrix of Jieshou city.

	Component			
	1	2	3	4
pH (dimensionless)	−0.481	0.535	0.185	−0.237
Sodium (mg/L)	−0.014	0.857	−0.275	0.092
Potassium (mg/L)	0.378	0.832	−0.054	0.091
Calcium (mg/L)	0.840	−0.011	0.345	−0.179
Magnesium (mg/L)	0.932	−0.138	0.012	0.010
Fluoride (mg/L)	−0.797	0.283	−0.132	0.096
Bicarbonate (mg/L)	0.082	−0.210	−0.654	0.579
Silicic acid (mg/L)	0.447	−0.316	−0.181	−0.214
Total dissolved solids (mg/L)	0.828	0.493	-0.004	0.095
Boron (mg/L)	−0.782	0.406	0.030	−0.089
Chloride (mg/L)	0.860	0.420	0.027	−0.011
Sulfate (mg/L)	0.822	0.515	−0.007	0.028
Ammonia nitrogen (mg/L)	0.660	−0.463	0.266	0.059
Oxygen consumption (mg/L)	0.177	−0.167	0.836	0.215
Total hardness (mg/L)	0.982	−0.051	−0.031	0.046
Total phosphorus (mg/L)	−0.224	0.060	0.446	0.740

enrichment of sodium in the water body. The correlation of sodion and other ions is shown in Figure 12.

3.6.3 Migration mechanism of abnormal ions

1.) Migration mechanism of fluoride

The formation lithology of the research area mainly includes the Quaternary silt, silty fine sands, and clay; the Neogene mudstone and siltite; the Paleogene sand shale and siltite; and the Cretaceous glutenite. The type of groundwater is unconfined rock pore water. The aquifer group's Earth shell generally contains a high content of fluoride minerals; the clay minerals are rich in kaolinite, montmorillonite, and hydromica, and the sand layer contains mica, apatite, fluorite, hornblende, etc. During weathering, eluviation, and pollution production, they are transferred to groundwater under lixiviation or hydration action and become an important source of natural groundwater. The main reactions are as follows:

1) The decomposition equation of biotite under alkaline conditions (high pH value) is as follows:

$$KMg_3[AlSi_3O_{10}]F_2 + 2OH^- \rightarrow KMg_3[AlSi_3O_{10}][OH]_2 + 2F^-. \tag{1}$$

2) The decomposition equation of hornblende under alkaline conditions is as follows:

$$NaCa_2[Mg, Fe, Al]_5[Al, Si]_8O_{22}F_2 + 2OH^- \rightarrow NaCa_2[Mg, Fe, Al]_5[Al, Si]_8O_{22}[OH]_2 + 2F^-. \tag{2}$$

3) The chemical reaction equation of CaF_2 (fluorite) is as follows:

$$CaF_2 + 2NaHCO_3 \rightarrow CaCO_3 + 2F + 2Na + H_2O + CO_2, \tag{3}$$

$$CaF_2 + H_2O + CO_2(g) \rightarrow CaCO_3 + 2F^- + 2H^+. \tag{4}$$

Equations (1) and (2) represent the replacement action, and Eq. (3) represents the hydrolysis reaction of fluorite. The relation between the solubility of fluoride-rich minerals (frequently observed in fluorite) and the pH value is shown in Figure 13 (Elrashidi and Lindsay, 1986), in which the solubility of fluorite and sellaite significantly increases with the pH value. According to the groundwater test results of Jieshou City, the pH value of deep water in county-level water sources is between 7.8 and 8.7, showing alkalinity. Therefore, the reaction described in Equations (2) and (3) is the main reaction of fluoride rise. Many domestic and international scholars have carried out a great deal of empirical research on this. Alkaline water is beneficial to the dissolution of F^--containing minerals (Lü et al., 2016). The Ca^{2+} concentration promotes further dissolution of F^--containing minerals such as fluorite, thus releasing F^- into groundwater (Liu et al., 2015; Li et al., 2019).

2.) Migration mechanism of sodium

In general, sodium exists as sodium in the water body. However, in addition to existing as ions in minerals, they may also be adsorbed on the surface of negatively charged clay particles through electrostatic interaction. Therefore, the process of sodium entering the water body mainly includes the sodium-bearing minerals dissolving, a part of the indissolvable minerals exchanging ions with other cations in the water body, and the sodium adsorbing on the surface of mineral particles de-adsorbing.

Within the administrative area of Jieshou City, there are some thick, unconfined Quaternary fluvial and lacustrine sediments deposits on the surface layer, which is also the leading development site of groundwater in the city (Hu, 2015). The sediments are rich in various sodium-bearing minerals such as feldspar, niter, and clay minerals and are easy to enter the water body through the aforementioned process, which provides a solid foundation for the source of sodium in the groundwater of Jieshou City (Figure 14). Some sodium-containing minerals such as fluorite and montmorillonite can absorb a cation in GW and release an intrinsic cation. The higher the concentration of cations in GW, the stronger its adsorption capacity (Frommen and Groeschke, 2021).

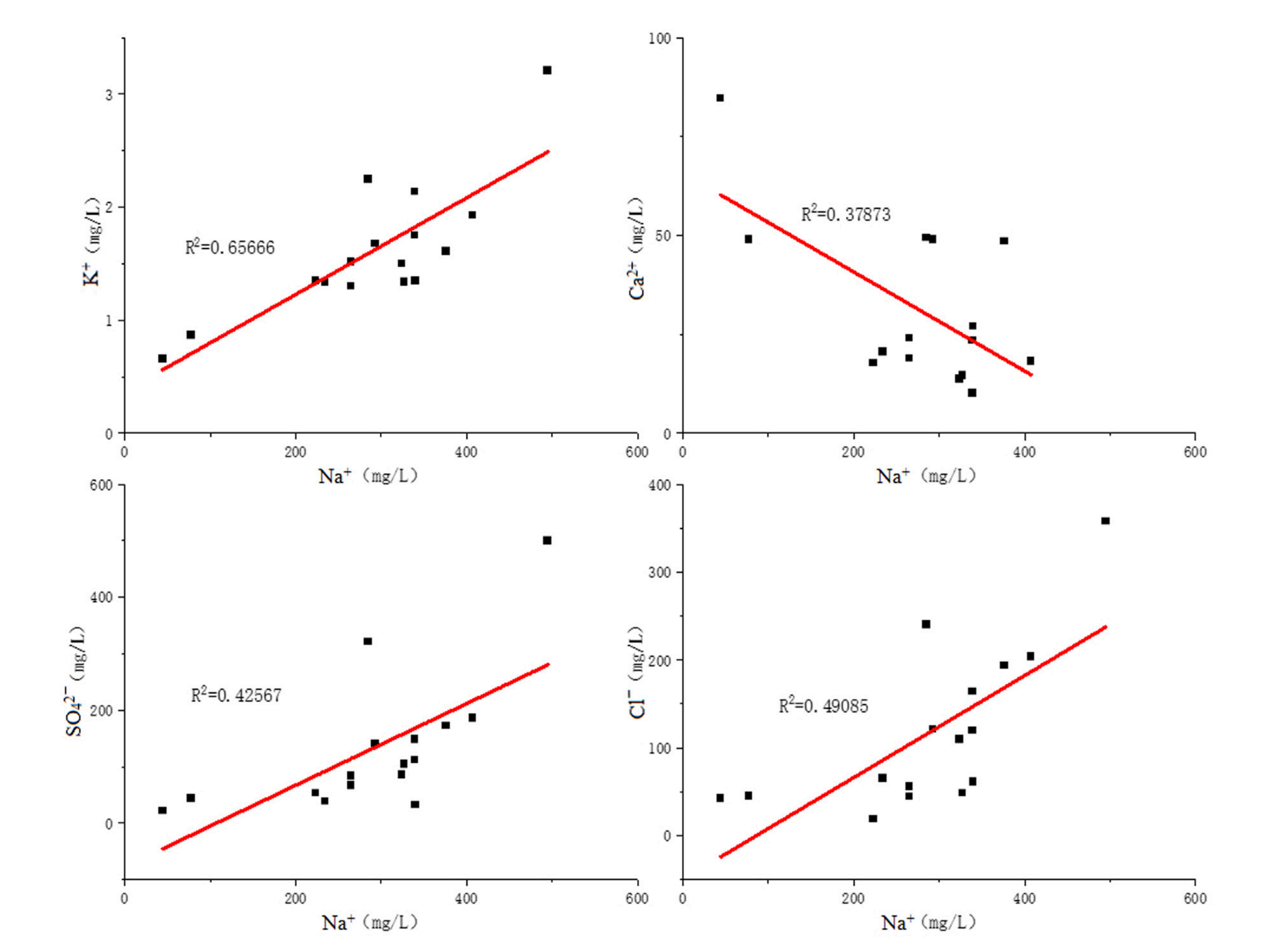

FIGURE 12
Correlation of sodion and other ions.

3.6.4 Influential factors of abnormal ion enrichment

1) Climate and hydrogeological conditions

The research area is located in a semi-arid region with low rainfall, high evaporation, and intense evaporation inspissation action. The shallower the groundwater depth is, the stronger the evaporation inspissation will be. When water is evaporated, the salinity will accumulate in the residual water, causing the total dissolved solids to rise. When evaporation inspissation occurs, the salts precipitate in order of increasing solubility. Because of the rising concentration of a chemical component in water and the precipitation of salts, the proportion of chemical components in water also changes. The evaporation inspissation causes the region to form a sodium carbonate distribution area and increases the fluoride and sodium content in the water.

Extensive literature research shows that the fluoride contained in the shallow groundwater of the north Anhui area exceeds the standard (Ding et al., 2009; Wu et al., 2011); the shallow regional groundwater has a certain hydraulic connection to deep groundwater; and leaking recharge from shallow groundwater to deep groundwater will bring chemical constituents to the latter. Some studies have demonstrated (Xu et al., 2009) that the fluoride content of groundwater is negatively correlated with runoff conditions. If the groundwater runoff condition is good and the circulation alternation is quick, the fluoride content will be lower; in contrast, if the groundwater runoff condition is poor and the circulation alternation is slow, fluoride is likely to enrich.

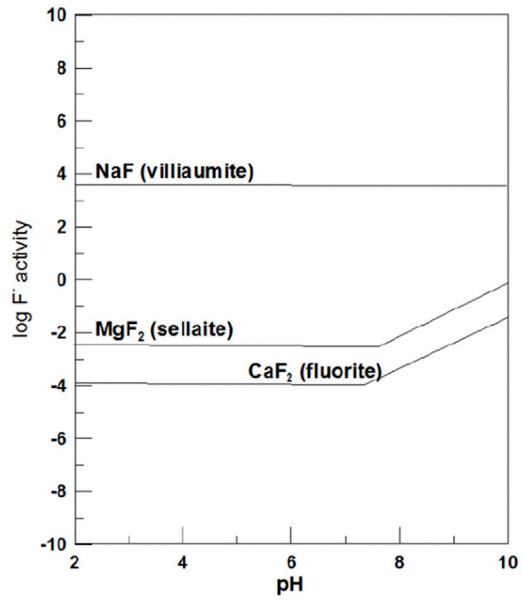

FIGURE 13
Relation between fluorinated minerals' dissolution and pH value.

2) Chemical type of groundwater

The fluoride concentration in groundwater can be affected by chemical constituents and the hydrochemical type of groundwater. It is known from the analysis that the hydrochemical type of research area is the Na-HCO_3 type. According to the test results, the samples with high Ca^{2+} concentrations have low fluoride concentrations. In conformity with existing research results, the regions with high fluoride concentrations in groundwater often have high concentrations of Ca^{2+}, HCO_3^-, and Na^+ (Guo et al., 2007; Su et al., 2013). This phenomenon occurs because when groundwater's water-bearing medium is calcium, Na^+ exchanges cations with Ca^{2+}, elevating the Ca^{2+} concentration in groundwater and increasing CaF_2 solubility; thus, fluoride content increases in groundwater. High concentrations of HCO_3^- and Na^+ is beneficial for the dissolution of CaF_2 (Xu et al., 2009).

3) pH

A large number of studies have indicated that the pH value of groundwater is positively correlated with fluoride concentration (Han et al., 2022; Su et al., 2009; He et al., 2010; Lu et al., 2014). This is mainly because when groundwater pH is high, the OH^- concentration rises in groundwater, and OH^- has a radius close to F^-. Also, equivalent electrovalence makes it easier to displace F^- in fluorinated minerals. In addition, the meta-alkaline groundwater is beneficial to the dissolution of fluorinated minerals.

4) Human factors

In the research area, the buried depth of the deep aquifer is considerable, generally greater than 200 m, and the upper aquiclude is a thick clay stratum with good water-proof performance. In natural conditions, shallow groundwater is evidently affected by climatic conditions and human factors, but deep groundwater is less affected.

However, human exploitation of deep groundwater can damage the aquifer structure, change the original hydrodynamic condition of groundwater, cause groundwater from high-fluoride aquifers to flow into a low-fluoride aquifer, and elevate its fluoride concentration. In some regions, the overexploitation of deep groundwater leads to groundwater depression cone and leakage recharge from the upper high-fluoride aquifer to deep groundwater, thus increasing the fluoride concentration of deep groundwater.

4 Conclusion

According to the regional data of the past and this sampling analysis, the groundwater is classified as marginally alkaline water with a composition of Na-HCO_3-Cl-SO_4; the cations are mainly Na^+, and the anions are mainly HCO_3^-. The fluoride and sodium in the groundwater from centralized drinking water sources in Jieshou City

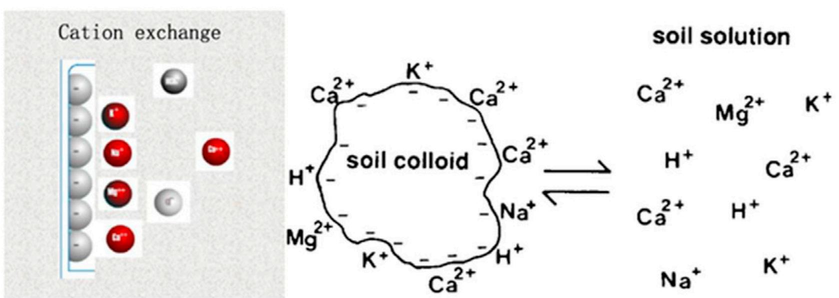

FIGURE 14
A common process of sodion migrating in water body.

are abnormally enriched ions. Their contents have exceeded the thresholds specified in the class III water standard of the National Quality Standard for Ground Water: sodium, 200 mg/L and fluoride, 1.0 mg/L. Some samples even exceed the class IV water standard.

The abnormal enrichment of ions in the centralized drinking water sources of Jieshou City is caused by natural geological factors, hydrogeological conditions, and groundwater's hydrochemical type. The primary geological setting is the main influencing factor, and human factors have little influence on it. The high content of F^- and Na^+ is caused by geological factors and hydrogeological conditions, while the aquifer group's Earth shell generally contains a high content of fluoride minerals, and the sand layer contains mica, apatite, fluorite, and hornblende, etc. During weathering, eluviation, and pollution, they are transferred to groundwater under lixiviation or hydration action and become a significant source of fluoride in natural groundwater. In addition, the high sodium ion content is also related to the type of water chemistry and ion exchange.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GS: sample collecting, experimentation, methodology, software, and writing—original draft. GL: conceptualization and review and editing. YL: investigation and sample collecting. GW: software and experimentation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Pakistan's water resource management: Ensuring water security for sustainable development

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Pakistan is blessed with abundant water resources but facing a critical water shortage due to a lack of storage facilities, poor water governance, and the adverse impacts of climate change. The burgeoning population at present 225 million, which is expected to cross 250 million by 2025 is creating an additional burden on water resources, as per capita availability is depleting sharply from 5,000 m3 in 1951 to 1,100 m3 in 2005, which is expected to fall to 800 m3 by 2025. Pakistan's water demand is increasing at an average yearly rate of 10% which in terms of the area will increase to 338 km3 by 2025, against the availability of 240–258 km3. Out of the available surface water, approximately 74% is extracted, while 83% of the groundwater is used for agricultural and other uses, which is an exceptionally high ratio for a water-scarce country like Pakistan. The adverse impacts of climate change are also causing extreme weather conditions, resulting in drought and floods almost every year. Inadequate water reservoirs, water wastage in agriculture and households, negligible wastewater recycling, and contamination of drinking water are causing health risks that have turned serious national security challenges for Pakistan. This research article argues that surface and subsurface water in Pakistan is depleting sharply, and if not addressed in time, has the potential of becoming the biggest national security problem. The article investigates the available water status in Pakistan covering surface and subsurface resources in detail, including reservoirs for storage, and sectoral utilization, to draw conclusions on water availability and usage requirement. The policy recommendations highlight the effective integration of smart technology in addressing multidimensional water issues and efficient water governance for ensuring water security for the sustainable development of Pakistan.

KEYWORDS

water scarcity, water management, sustainable development, human security, national security

1 Introduction

Pakistan is the world's fifth most populous country with an estimated population of 225 million and an average growth rate of 1.75% every year (World Bank, 2022b), it is 33rd country by area with 650 miles of coastline along the Gulf of Oman and the Arabian Sea and 340,590 square miles land area (UN, 2022). The geography, topography, and climate of Pakistan are diverse ranging from the high and glaciated mountains of Hindukush, Himalayan to the plains and deserts of Punjab and Sindh, mountain and semi-mountains of Baluchistan and Khyber Pakhtunkhwa (KPK) provinces. Starting from the north, Pakistan has three distinct geographical zones: The Northern highland containing Kashmir and Gilgit -Baltistan regions. The northern regions have famous

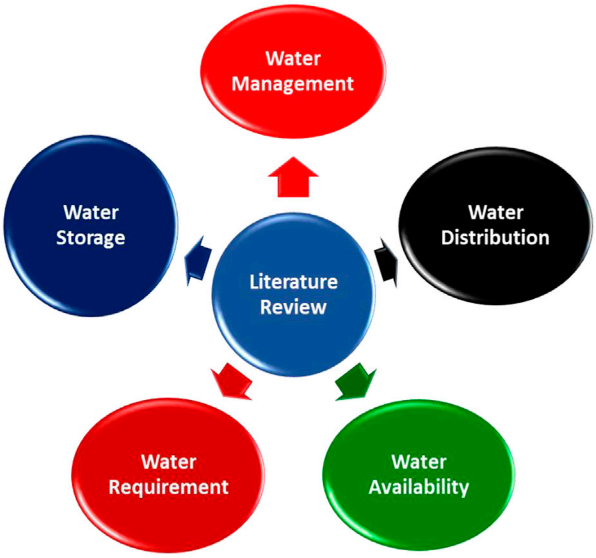

FIGURE 1
Literature review dimensions.

ranges of Hindukush, Karakoram, and the Pamir Mountains, where K2 and Nanga Parabt are also located. The Indus plain contains tributaries of the Indus River starting from Kashmir to the Arabian Sea. Baluchistan Plateau is in the west and the Thar Desert lies in the east of the country, which is contiguous to the Cholistan Desert of Punjab Province and the Rajasthan Desert of India. Pakistan is blessed with all four seasons, where climate varies from tropical to temperate and arid conditions in the coastal South. The northern and glaciated regions receive extreme cold and snowfall during winters, while the monsoon season is from July to September every year in the rest of the country, with some variations in the plains of Punjab and Sindh. Two extreme conditions of drought and flood are also common occurrences witnessed in a year as seen in the ongoing year 2022. Indus River System (IRS) is the major source of water supply for Pakistan (Pappas, 2011). However, the increase in demand for water due to increasing population, agriculture, and other household requirements has pushed Pakistan towards water scarcity (Khalid, 2017). There is also an asymmetry in the availability of water for drinking, irrigation, and other usages (Taimur, 2022). Pakistan is fortunate to be geographically located in rain favourable areas and varied temperature zones, ranging from four different climates to receiving rainfall throughout the year. As per the World Bank survey, Pakistan receives an average of 200 mm of rainfall from July to September (World Bank, 2021). Unfortunately, most of the rainwater ends up in the Arabian Sea, due to flooding and improper water storage and drainage channels (Briscoe et al., 2005). The research article has been developed considering the United Nations Sustainable Development Goals (SDGs) and the Millennium Development Goals (MDGs) on the provision of fresh drinking water across Pakistan, water storage, management, judicious distribution, and use of technology for recycling wastewater. As a policy input to the relevant government ministries in Pakistan, this research article provides a comprehensive set of recommendations to achieve SDGs by 2030.

2 Literature review

For a comprehensive literature review, the dimensions as shown in Figure 1 have been discussed in this part.

2.1 Pakistan's population and water requirements

Water being a necessity for life has always been a source of the establishment of great civilizations as can be witnessed since the dawn of civilization, e.g., by observing the ancient Egyptian and Mesopotamian Civilizations in the Middle East and the Indus Civilization in South Asia (Water From the Dawn of Civilization | Earth Sciences—UNESCO Multimedia Archives, n.d.). The water demand has been exponentially increasing with the increase in the global population. Approximately six times more water is needed worldwide due to the increasing world population as compared to the last century (Tehsin et al., 2019). Water availability has been gradually strained due to increasing demand and consumption of natural resources coupled with water mismanagement, particularly in the case of developing nations, where Pakistan is no exception. Pakistan has the Indus River System (IRS) as the principal source for irrigation that 'irrigates 80 percent of the 21.5 million hectors of agricultural land in Pakistan (Ministry of Finance, 2007) Pakistan Economic Survey 2006–07 Chapter 16 Environment. PDF, n.d.). Being the only major river system coupled with increasing population and decreasing snowfall over the Himalayas and Karakorum Mountain ranges puts increasing stress on the surface water resources in Pakistan. Underground water sources are also depleting at a fast pace due to unusually high withdrawals. The alarming decline in per capita availability of freshwater resources, i.e., from 5,300 cubic meters (m^3) at the time of inception of Pakistan in 1947 to about 1,000 cubic meters (m^3) in 2011 indicates many challenges, most significant one are the water resources management in Pakistan (World Bank, 2013). Pakistan is blessed with a unique mix of water resources in the form of glaciated mountains, the Indus Basin River Water System (IRS), and a network of canals and distributaries. However, with the rising population, lack of appropriate water resource management, and water distribution, and less emphasis to sensitize the public on water discipline, Pakistan is fast transiting from a water-stressed to a water-scarce country. It is highlighted that Pakistan is the fifth populous country in the world with an annual increase rate of 1.75%. At present, the population of Pakistan is estimated at approximately 225 million, which is likely to reach 250 million by 2025 (Yaqoob et al., 2021), where urban population alone is likely to increase by 52% by 2025 (Janjua et al., 2021). Due to this exponential increase in population, the water demand for agriculture and non-agriculture usage like; industrial and domestic will also increase by 8% in 2025 (Parry, 2016). It has been revealed through a literature review that in 1951, Pakistan had a per capita water availability of 5,000 m^3, which fell to 1,100 m^3 in 2005, and by 2025, it is expected to fall to 800 m^3 (Qureshi and Ashraf, 2019). The UN estimates that Pakistan's water demand is increasing at an average yearly rate of 10% (Connor, 2015), which means that the water demand in terms of the area will increase to 338 km^3 by 2025, but the total water availability will remain in the same range from 240 to 258 km^3 (Shaheen, 2010). Out of the available surface water, approximately 74% is extracted, while 83% of the groundwater is extracted for agricultural and other uses, which is an exceptionally high ratio for a water-scarce country like Pakistan (Laghari et al., 2012). The inadequate water resources management system is causing a demand and supply gap in the judicious utilization of available water due to the increase in population, and wastage of surface and groundwater. Water scarcity is emerging as a serious national security challenge for Pakistan. Apart from water-related disputes with India (Riaz et al., 2020), it is also causing inter-provincial disharmony and societal conflicts (Bhatti et al., 2019).

2.2 Water resources of Pakistan

Pakistan's water resources, like most of the South Asian nations, comprise surface water sources i.e., rivers, lakes, coastal basins, large and small water reservoirs, and underground water resources. Primary sources include rainfalls and falls leading to the formation of glaciers. Pakistan has 143 large and small water storage reservoirs, among which the Tarbela, Mangla, and Chashma are major ones with a collective storage capacity of 18.92 Million Acre Feet (MAF) (Tehsin et al., 2019). Over some time, a serious decline in the existing water resources of Pakistan has been witnessed, which can be attributed to several factors. The increased demand for freshwater supply can be related to the increasing population. The population growth has resulted in rendering more than 12% population without fresh drinking water as per the Human Development Report 2001 of the United Nations Development Program (UNDP) (UNDP and United Nations, 2001). Furthermore, a reduction in average annual rainfall has also contributed to stress on water resources due to less recharge on yearly basis (Naheed and Rasul, 2010). The phenomena of global warming have also affected Pakistan, with rising temperatures every year (Chaudhry et al., 2009), which results in the melting of glaciers at a rapid pace. The unregulated use of tubewells has also contributed to the water scarcity and depletion of subsurface water sources (Tehsin et al., 2019).

2.3 Water resources management in Pakistan

The institutional arrangements to manage and regulate the water resources in Pakistan are devolved to the provincial and further to the local governments since 2001 (Cooper, 2018). Some of the key challenges in water management in Pakistan emanate from the unequal per capita water consumption in urban and rural areas. Water supply and sanitation are underinvested by the public sector (Water and Sanitation, n.d.). In April 2018, the Ministry of Water Resources published the National Water Policy to address the water resources management issues prevailing in Pakistan and projected the key targets to be achieved by 2030. It emphasized more sustainable utilization of water resources and proposed the concept of "producing more crop per drop" (National Water Policy of Pakistan, 2018). Water expert and former diplomat Shafqat Kakakhel contends that Pakistan's new National Water Policy, despite significant gaps, represents a breakthrough moment (Opinion: Pakistan's new National Water Policy is historic, 2018). The water resource distribution between Pakistan and India is also managed through a bilateral water distribution accord called the "Indus Water Treaty (IWT)". The details are covered in the relevant part on water resources and distribution in subsequent paragraphs. The summary of literature review is given at Table 1.

3 Data and methodology

The study has been completed over the last 7 months covering a wide-ranging examination of Pakistan's topography, from the northern Himalayan areas of Gilgit and Skardu to the plains and deserts of Punjab and Sindh. The framework of Data and Methodology is given in Figure 2 below, which is explained in detail in the ensuing paragraphs.

FIGURE 2
Framework of data and methodology.

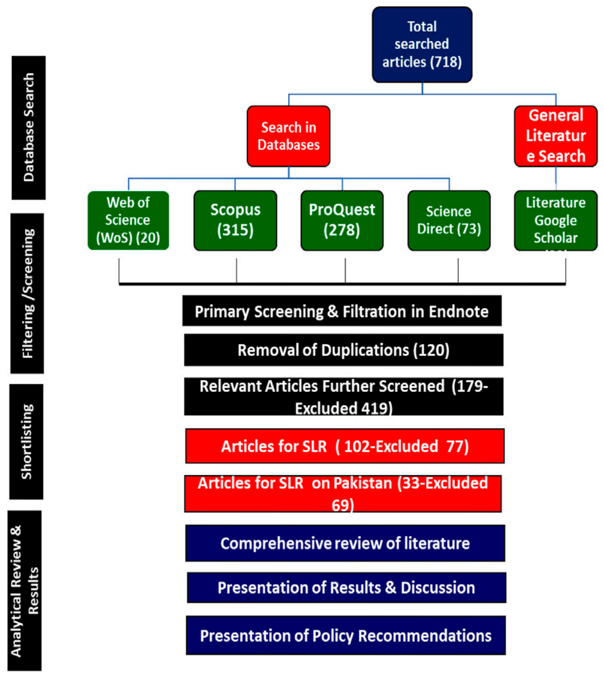

FIGURE 3
Process of systematic literature review (SLR).

3.1 Methodology of systematic literature review (SLR)

This SLR methodology is designed to systematically review the required literature to draw relevant conclusions from available data. More specifically, SLR helps to review the climate and water governance-related literature for the classification of key governance elements; enabling dynamics; significant gaps and challenges; and possibly an effective governance approach for the management of water resources of Pakistan. SLR is a preferred mode for researchers in reviewing various attributes of water governance and management. Based on the SLR strategies devised by prominent researchers, a five-step approach has been observed for undertaking the SLR, which broadly covers; scoping, planning for SLR, searching, screening, and presenting a literature review. The Systematic Literature Review (SLR) Methodology was adopted for the critical examination of available literature on Pakistan's water resources, utilization, and constraints. The excerpts of literature have been incorporated in Literature Review part above, however, details of the SLR methodology are given in Figure 3 below.

3.2 Implications drawn from literature review

The available literature mostly focuses on Pakistan's available water resources, distribution among the provinces and sectors of water utilization, that too in a compartmented fashion. Therefore, the current study has been designed in a way to cover the holistic investigation of water management in Pakistan which should take into account all forms of surface and sub surface water, its recharging, storage, distribution, and future vision for achieving water related SDGs by 2030. The implications of climate changes on water management in Pakistan have also been examined in detail and relevant conclusions have been incorporated in the policy recommendations.

TABLE 1 Summary of literature review.

References	Name of journal/Book	Context
Yaqoob et al. (2021)	Processes	Pakistan's population
Janjua et al. (2021)	Water Policy	Pakistan's urban Population
Parry, (2016)	International Institute of Sustainable Development (IISD)	Water demand and consumption in Pakistan
Khemka and Kumar, (2019)	Social Development and Sustainable Development Goals in South Asia	Pakistan's water availability and demand
Qureshi and Ashraf, (2019)	Water Resources Management	Pakistan's water availability and demand
Connor, (2015)	UN World Water Report 2015	Pakistan's water demand
Shaheen, (2010)	Institute of Regional Studies Islamabad	Pakistan's water availability and demand
Laghari et al. (2012)	Hydrology and Earth Sciences	Groundwater sources in Pakistan
Riaz et al. (2020)	NDU Journal	India -Pakistan water distribution
Bhatti et al. (2019)	Water	Water conflicts and Pakistani society
Water From the Dawn of Civilization (2010)	UNESCO Documentary Archives	Timeless significance of Water Resources
Tehsin et al. (2019)	Margalla Papers	Increased Water Requirements over the past century
Pakistan Economic Survey (2007)	Pakistan Economic Survey - Chapter 16: Environment	Indus River and irrigation of agricultural lands in Pakistan
Pakistan Water Supply and Sanitation Sector: Urban Water Supply and Sanitation (2013)	International Bank for Reconstruction and Development/The World Bank. (2013). (report). Pakistan Water Supply and Sanitation Sector: Urban Water Supply and Sanitation	The decline in *per capita* freshwater resource availability
UNDP and United Nations, (2001)	UNDP Human Development Report	2001 Stats for Pakistanis with no access to drinkable water
Naheed and Rasul (2010)	Pakistan Journal of Meteorology	Reduced annual rainfall is a contributory factor to the scarcity of freshwater resources
Chaudhry et al. (2009)	Climate Change Indicators of Pakistan. Pakistan Meteorological Department report	Global warming and scarcity of water resources
Cooper (2018)	Water management/governance systems in Pakistan. K4D Helpdesk Report. Brighton, United Kingdom: Institute of Development Studies	Hierarchy of Water Resource Management in Pakistan
Water and Sanitation (2018)	Ministry of Planning and Development, Government of Pakistan. Water and Sanitation. MTDF	Sector-specific challenges in Water Resource Management in Pakistan
National Water Policy of Pakistan, (2018)	National Water Policy 2018, Ministry of Water Resources, Government of Pakistan	Government of Pakistan's efforts in Water Resource Management in the upcoming decade
Opinion: Pakistan's new National Water Policy is historic (2018)	Opinion: Pakistan's new National Water Policy is historic. The Third Pole	A critical review of the National Water Policy of Pakistan2018

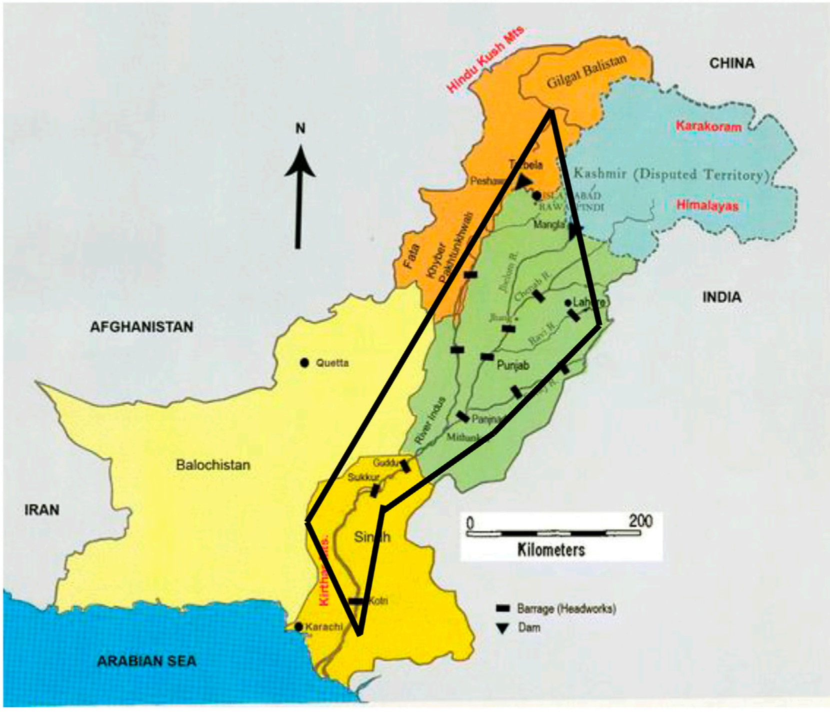

FIGURE 4
Field visits to the indus basin area.

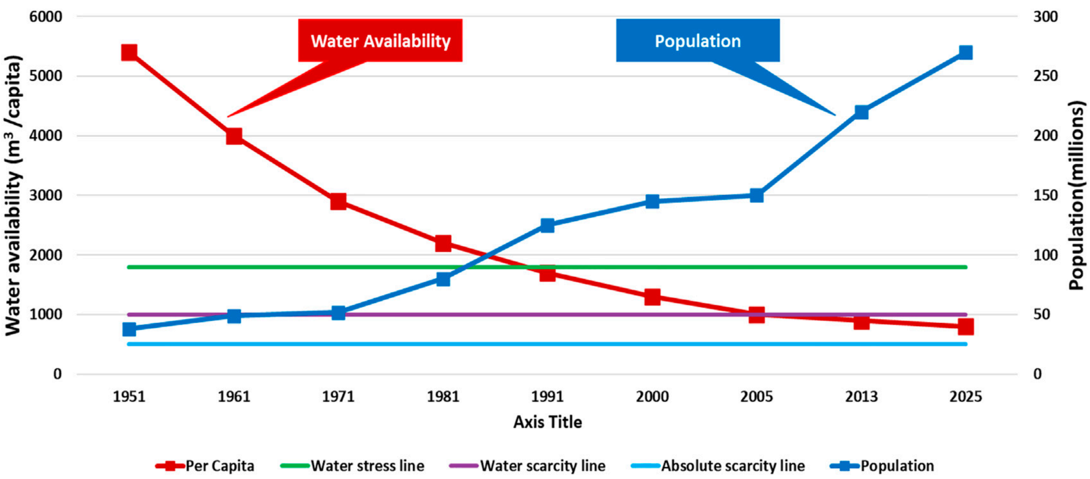

FIGURE 5
Pakistan's water availability and demand by 2025.

3.3 Model setting

Pakistan's available water resources, population, and water requirement for human consumption, agriculture, and non-agriculture consumption have been analyzed using primary data available from the Ministry of Energy Pakistan, Water and Power Development Authority (WAPDA), Indus River System Authority (IRSA), field visits to major dams of Mangla, Tarbela and Chashma, and review of different studies and findings conducted by national and international organizations on Pakistan. For the tangible outcome of the study, a comprehensive approach was adopted covering all regions of Pakistan for examination of the water situation. All headworks and barrages were physically visited for analyzing the water governance issues. Interviews were also conducted with regulatory staff, who agreed to respond based on anonymity and incorporating their views in the study without referring to them. Their privacy request has been given value and nowhere any identity to this effect has been divulged. Figure 4 below shows the area of field visits for examining the water situation.

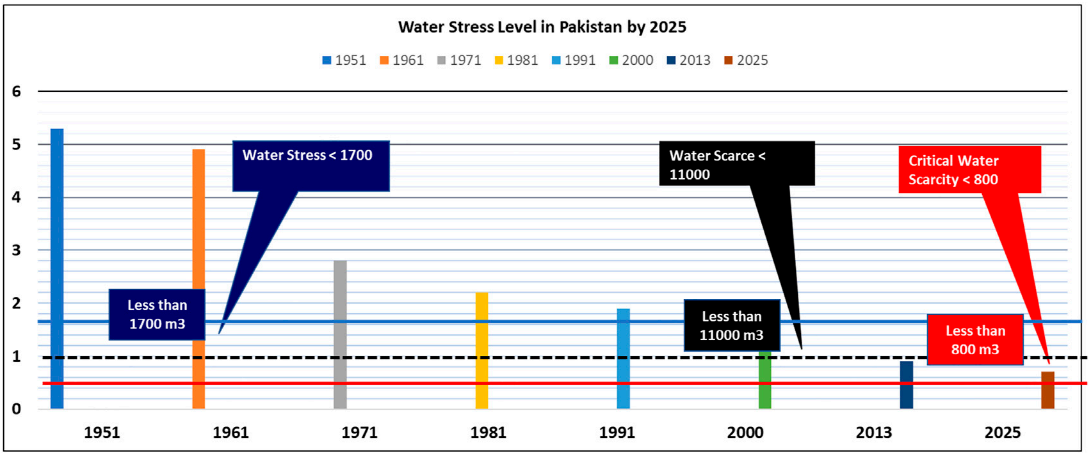

FIGURE 6
Water stress level in Pakistan by 2025.

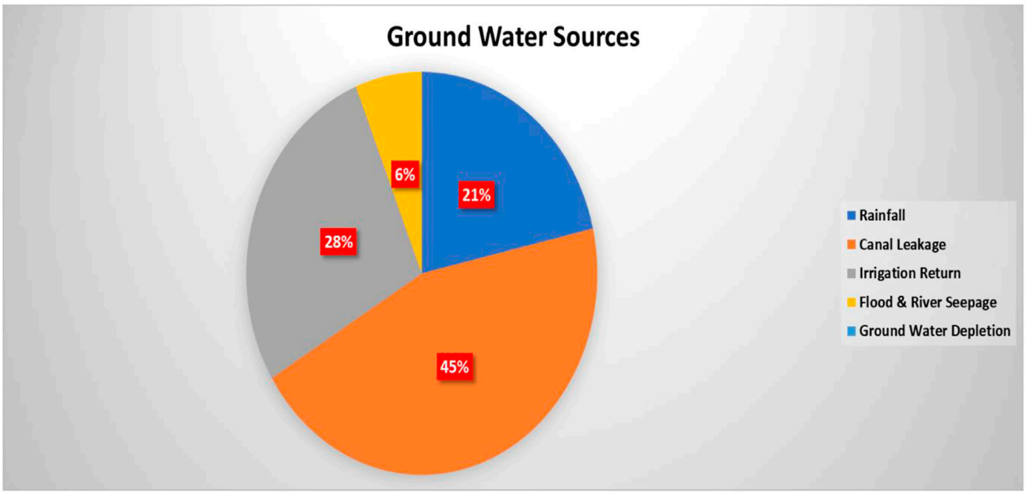

FIGURE 7
Groundwater sources in Pakistan (World Bank Report https://www.worldbank.org/en/news/feature/2021/03/25/managing-groundwater-resources-in-pakistan-indus-basin).

From the northern glaciated region of Skardu along the Indus River, the field visits followed the systematic route stretching from north to south of Pakistan, passing over the entire Indus Basin Delta and Indus River System, which provided a unique mix of natural resources, the climax of engineering expertise and colossal irrigation system in the form of canals and link canals for proportionate distribution of water to the entire country. The manifestation and implications of the Indus Water Treaty on water sharing between India and Pakistan since its implementation in the last 50 years have also been examined in detail. The inter-provincial water-sharing arrangements have been analyzed with their implications on national security. Pakistan's water management policy documents have been examined and referred to in the relevant parts of the study. In the last part, viable recommendations have been offered as policy input for relevant government ministries for optimization and conservation of available water resources, developing national consensus on the construction of additional water reservoirs for sustainable development of Pakistan and achieving water-related Sustainable Development Goals (SDGs) and Millennium Development Goals (MDGs) by 2030.

3.4 Data analysis

The study focuses on ensuring efficient water governance for sustainable development of Pakistan, therefore, the data collected from literature review, field visits, interviews and on-sight briefings have been analyzed using qualitative and quantitative research methods. The findings have been explained in results and discussion part, while policy recommendations have been proffered in the last part of the study.

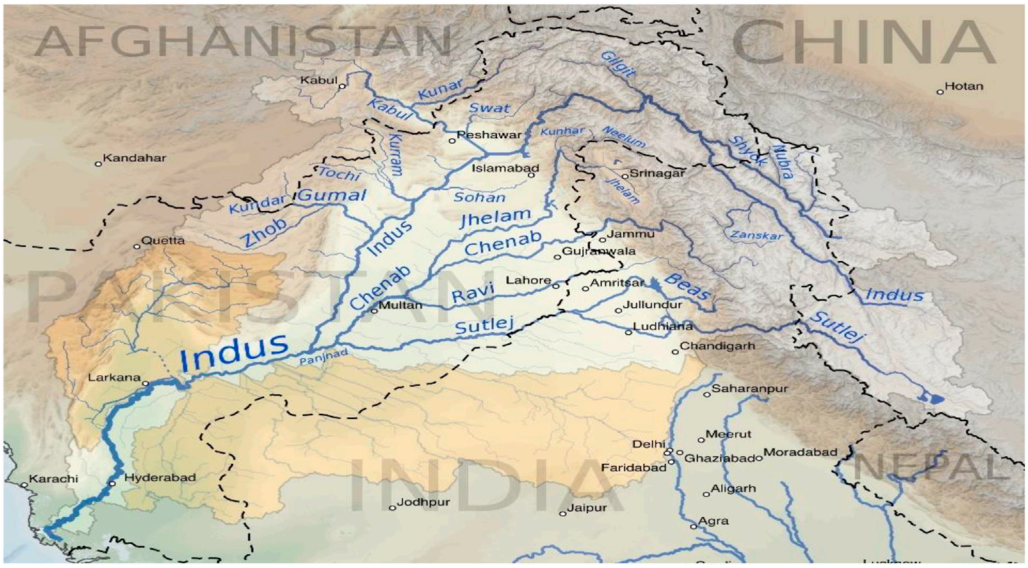

FIGURE 8
Indus rivers system in Pakistan.

4 Empirical results and discussion

4.1 Pakistan's water demand and availability

Water remains one of the critical issues in Pakistan since the time of its inception in 1947. Water is a main source of sustenance not only for humans but plants and animals as well around the globe. Pakistan remains scarce in terms of clean drinkable water availability to the masses. Indus River System (IRS) is the major source of water for the people and agriculture in Pakistan (Pappas, 2011). The population of Pakistan is increasing at a rapid pace due to which the average daily demand for water is also increasing, while availability is declining sharply. Another important aspect is that Pakistan is an agrarian country, where due to inadequate alternate sources of agricultural water, more than 95% of the surface and sub-surface water is consumed by agriculture and livestock sectors (Khalid, 2017). Pakistan is ranked 80 (Mehmood et al., 2013) among 122 nations in the world regarding drinkable water (Azizullah et al., 2011). Figure 5 below shows the graphical representation of water supply and demand status in Pakistan by 2025.

Pakistan is an underdeveloped country due to which it faces issues in many domains, where water scarcity has emerged as the most pressing national security issue. Pakistan not only faces a water shortage but also lags in clean drinkable water for the population. The construction of water reservoirs for storing and then systematically distributing water remains lopsided, despite the growing demand. Figure 6 below shows the systematic path towards water scarcity as year on year basis, the gap between water availability, storage, and sectoral consumption is widening and water security is emerging as a vital national security challenge for Pakistan if remedial measures are not initiated now as the time is running out and we are only 3 years away from the water-scarce line.

There is also an asymmetry in the availability of water for drinking, irrigation, and other usages (Taimur, 2022). Pakistan receives an average of 200 mm of rainfall from July to September (World Bank, 2021), but most of the rainwater ends up in the sea due to inadequate water storage and drainage channels.

4.2 Pakistan's water resources and management

4.2.1 The supply source of water resources

Pakistan's Northern areas which include the provinces of Gilgit-Baltistan (GB) and Azad Jammu and Kashmir (AJ&K) are blessed with abundant glaciers with an approximate area of 13,680 sq km, which is approximately 3% of the mountainous region of the upper Indus River Basin (Ahmed et al., 2007a). The winter season from October to March every year receives plentiful snowfall which is the main source of icing of the glaciers. The melting process starts in the summer, roughly from late May to August, which feeds adequate water to Indus River Systems (IRS). River Kabul is another source of water to IRS as it enters Pakistan through Unai Pass in Southern Hindukush to the North of Khyber Pass in Khyber Pakhtunkhwa (KPK) Province at an elevation of 3,000 m above sea level.

Rainfall is complimentary to the melting of glaciers in the summer and monsoon seasons of Pakistan, which provide profuse water to IRS. On average, the rainfall is more than 200 mm from July to September each year. More than 70% of the rain is witnessed from the monsoon and the western disturbances. In northern parts of Pakistan, a low-level rain cycle continues at frequent intervals even during winter.

According to the World Bank report, groundwater provides 90% of domestic water in rural areas and 70% at the national level with its share of approximately 50% for agriculture (World Bank, 2022a). The main sources of recharging of groundwater are the seepage from IBIS, which sits as a freshwater layer even on saline water in desert regions of Pakistan and is considered the main source of drinking and irrigation. Similarly, rainwater also finds its way through the layers to submerge in groundwater. The percentage-wise sources of groundwater recharge are given in Figure 7 below. Due to the unpredictability of canal water supplies, farmers across Pakistan have resorted to groundwater pumping, which is going on in a highly unregulated manner. The agriculture areas in the Indus Basin Irrigation System (IBIS) have installed approximately 500,000 tube wells, which are estimated to pump water of approximately 50 Billion Cubic

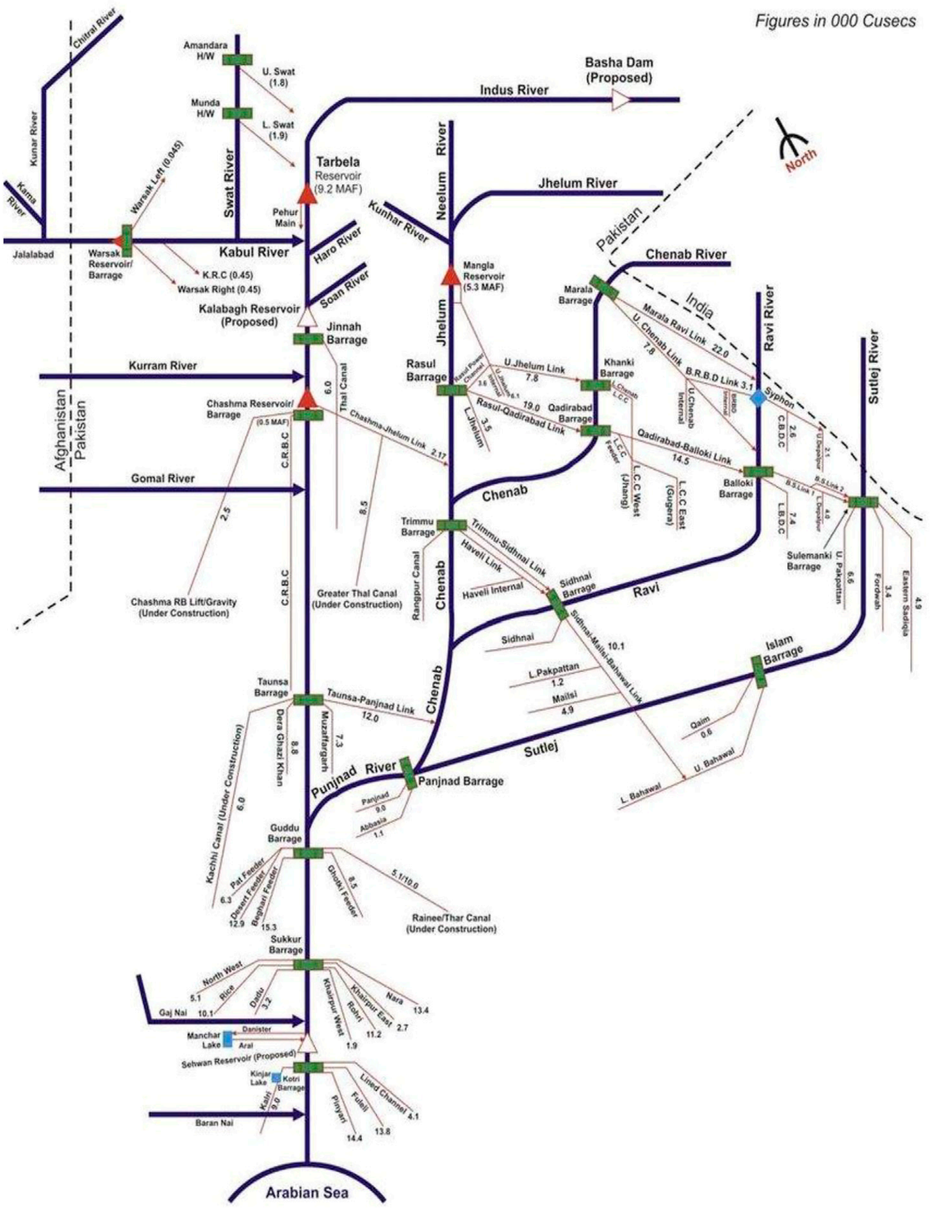

FIGURE 9
Indus basin irrigation system (IBIS) of Pakistan. Source ministry of planning and development (Iqbal, 2013) https://www.pc.gov.pk/uploads/plans/Ch20-Water1.pdf.

Meters (BCM) (Ahmed et al., 2007b), whereas, the groundwater potential in Pakistan is approximately 55 MAF (Ebrahim, 2018). Even in the domestic sector, unmonitored groundwater misuse is on the rise, which is sharply decreasing the most precious commodity of nature.

The primary source of surface water in Pakistan is through Indus River System (IRS) which is based on the river inflows and is measured at predesignated rim stations. The rim stations are control measures in the shape of dams, barrages, and other such reservoirs. The significant rim stations on Indus River System are at Mangla and Tarbela Dams, Marala at Chenab River, Marala reservoir at River Jehlum, Sulemanki Headworks at Sutlej River, and Baloki at Ravi River. Figure 8 shows the alignment of different rivers in the Indus River System.

Pakistan's 70% of the land is drained by the IRS accounting for almost 566,000 $km^{2,}$ which is spread to all four provinces of Khyber Pakhtunkhwa (KPK), Punjab, Sindh, and Baluchistan originating from Gilgit -Baltistan and Azad Jammu and Kashmir (AJ&K) except Kabul River which enters in KPK Province at Khyber Pass (Winston et al., 2013). The stretch of IRS is approximately 2,900 km with an elevation of 18,000 ft from the Himalayas to the lower riparian areas of Sindh Province leading it to the Arabian Sea (Janjua et al., 2021). The IRS is among the leading irrigation system in the world. Around 150,000 km^2 of agricultural land out of 190,000 km^2 is irrigated by the Indus Basin Irrigation System (Ahmed et al., 2007a). The IRS contains a network of 16 barrages, three dam, three Headworks, two siphons, 44 canal systems, (23 in Punjab, 14 in Sindh, five in KPK, and two in Balochistan), while 12 link canals and more than 107,000 small water courses (Hassan and Ahmad Khan, 2002).

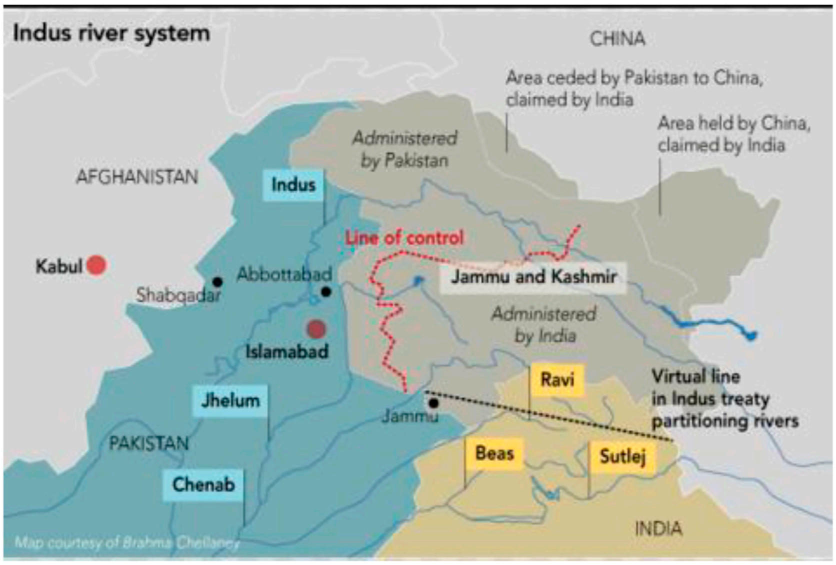

FIGURE 10
Indus water treaty and distribution of rivers between India and Pakistan.

4.2.2 Water resource management system

The IRS is a lifeline for Pakistan's survival as majority of the agricultural production is dependent on the river water. The Indus Basin contributes more than 25% of Pakistan's GDP, as it provides a critical water supply to almost 90% of the food production crops in Pakistan. The Indus Basin Irrigation System (IBIS) of Pakistan is among the world's leading contiguous irrigation systems, which contains six major rivers which are, the Sutlej, Ravi, Jhelum, Chenab, Indus, and Kabul rivers. The IBIS has an annual flow of 146-million-acre feet (MAF), while 106 MAF of water is diverted to canals. Pakistan receives about 50%–80% of average river flows from glacial melt, while the remaining is from the yearly monsoon rains. The three Western rivers, ie., Indus, Chenab, and Jhelum contain 144.91 MAF of water, and the two Eastern rivers ie., Ravi and Sutlej contain 9.14 MAF of water. From the available water, 104.73 MAF is used for irrigation purposes, 39.4 MAF usually flows to the Arabian sea due to limited storage capacities, and around 9.9 MAF is expended through the system losses like evaporation, seepage, and spill during floods. Figure 9 shows the excellent network of IBIS, which is unique in South Asia and the world at large.

The current water storage capacity is insufficient as the three main reservoirs, i.e., Mangla (1967), Tarbela (1978), and Chashma (1971), have a designed capacity of 15.75 MAF, however, sedimentation has reduced it to 13.1 MAF. Therefore, these reservoirs can hardly store water for 30 days against global standards of at least 120 days. The usual flow to the Arabian Sea during floods has also increased significantly as witnessed during the recent floods of the year 2022, which instead of storing and then reusing at the time of need has been wasted causing enormous men and material losses to the tune of 30 million people affected and financial losses of US$ 30 billion (Haidar and Dilawar, 2022). Moreover, the canals and link canals have an Earth surface which also results in the seepage of a substantial amount of irrigation water. Another important aspect is the traditional approach to farming and the use of irrigation water through flooding instead of using a drip irrigation system. Such a lavish wastage of water has created serious demand and supply gap, and depleted the limited storage capacity, especially during the critical harvesting seasons.

Pakistan is a lower riparian country and all the rivers less than Kabul flow to Pakistan from India. During the early days of partition

TABLE 2 Pakistan's water resource management organizations

MOWR	Ministry of Water Resources	PIDs	Provincial irrigation dept
WAPDA	Water and Power Development Authority	PADs	Provincial Agriculture dept
PMD	Pakistan Metrological Dept	PIDAs	Provincial Irrigation and Drainage Authority
SUPARCO	Space and Upper Atmosphere Research Commission	OFMW	On Farm Water Management
IRSA	Indus River System Authority	LG&CD	Local Govt and Community Development Dept
FFC	Federal Flood Commission	WASAs	Water and Sanitation Agencies
IWC	Indus Water Commission	AWBs/FO	Area Water Boards/Farmers Organization
PCRWR	Pakistan Council of Research on Water Resources	WUA	Water Users Association

TABLE 3 Pakistan's water resource management laws

1960	Indus water treaty between Pakistan and India
1983	Pakistan Environmental Protection Ordinance (PEPO), the first regulation regarding the protection of continuously decreasing environmental sources in Pakistan
1983	Pakistan Environmental protection agency (PEPA), a proper working body to regulate PEPO 1
1984	Pakistan Environmental Protection Council (PEPC) in 1984, more specifically working on environmental protection
1991	Water Apportionment Accord
1992	Pakistan National Conservation Strategy (NCS) with a clear enough implementation plan for sustainable development in Pakistan
1993	National Environmental Quality Standards (NEQS) to provide safe limits for municipal and liquid industrial effluents released to water bodies, industrial gaseous emissions, and motor vehicle exhaust and noise
1997	Pakistan Environmental Protection Agency (PEPA), under Section 2 the term environment was defined to include water and various forms of pollution like discharge
2000	Millennium Development Goals (MDGs), goal 7 is to ensure environmental sustainability with target 10 to Halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015
2001	National Environmental Action Plan (NEAP), a clear plan for sustainable development approved by PEPC
2005	National Environmental Policy to protect, conserve and restore Pakistan's environment to improve quality of life
2008	National Drinking Water Policy to provide access to safe and sustainable drinking water and protection of water resources and related issues
2015	Sustainable Development Goals (SDGs) goal 6 is to ensure the availability and sustainable management of water and sanitation for all, with target 6.1 to achieve universal and equitable access to safe and affordable drinking water for all by 2030 (PCWR, 2021)

on 01 April 1948, India stopped the rivers flow to Pakistan, which gave a devastating blow to the agriculture sector and a serious national security issue emerged. After hectic diplomacy by the great powers and the World Bank, Indus Water Treaty (IWT) was formalized on 19 September 1960. According to the treaty, India was granted exclusive rights to two eastern rivers (Beas/Sutlej and Ravi), while Pakistan was given the rights to three Western rivers (Jhelum, Chenab, and Indus) (Riaz et al., 2020). Despite three major wars and two standoffs with India, the IWT has proved its resilience and robustness. This is a highly successful treaty of the South Asian region. Despite some reservations over its interpretation and implementation by way of constructing dams on a run of the rivers flow by India in Indian Occupied Kashmir, it has largely prevailed (Ishaque and Shaikh, 2017). Figure 10 shows the river's distribution under IWT between India and Pakistan.

Pakistan has elaborate organizations at the federal and provincial levels for managing water resources as given at Table 2. The organizational framework, institutional capacity, and bureaucratic mindset have made the horizontal (within institutions) and vertical (among institutions) coordination, synchronization, and execution of work extremely challenging and often fragmented. The institutional responsibilities for climate and water governance are dreadfully demarcated between federal and provincial institutions, and other associated organizations (Yasin et al., 2021). This functional ambiguity often creates overlaps and conflicts of interest. As a result, mistrust prevails among and between the provinces on issues of water governance like; water availability and flows, water allocations, and data sharing.

In the recent years, the water availability and quality have become the most critical issues in Pakistan (Soomro et al., 2011). The increasing population, industrialization, and food demand have intensified these problems during the last few decades. The government of Pakistan from time to time has enacted several laws and regulations for the availability, storage, distribution, and use of water. Realizing the impact of climate change, limited storage capacity, and achieving water-related SDGs of provision of safe and clean drinking water to all by 2030, the regulations are in place which have been promulgated with the consensus of all the provinces and economic coordination council (ECC). The details of promulgated laws and regulations for governance of water in Pakistan are highlighted at Table 3. however, their implementation in the right spirit appears to be a daunting task for federal as well provincial governments.

4.2.3 Impact of climate change on water sustainability

The United Nations Secretary-General Mr. Antonio Gutters paid an official visit to Pakistan on 9–10 September 2002 to show solidarity to flood victims and assess the devastations through field visits and official briefings. He stated that "nature, has attacked Pakistan, which contributes less than 1% of global emissions" (Guterres, 2022b), while facing the consequences of developed countries' emissions and pollution of climate. He further added that "it was outrageous that action to reduce greenhouse gas emissions was being put on the back burner, today it is Pakistan, and tomorrow, it could be your country" (Guterres, 2022a), pointing toward industrialized countries. The Global Climate Index (GCI) 2021 has also vindicated Pakistan's vulnerabilities to climate risks, where Pakistan stands at number 8 (Eckstein et al., 2021) in the vulnerability Index. The analysis presented highlights the severe impacts of climate change on Pakistan ranging from extreme heat and drought to dreadful floods. Therefore, long-term water sustainability in Pakistan is highly susceptible to changes in weather patterns.

4.2.4 Recycling and management of wastewater

The sustainable use of recycled wastewater for agriculture, washing, cleaning, and other uses less drinking is on the rise in developed countries and developing countries are also catching up. In Pakistan, neither adequate regulations nor any such public-private partnership is in place for the smart use of wastewater. The problems of wastewater disposal tend to stem from distortions due to the failure of environmental policies and the lack of institutional capacity for monitoring and management (Bashir, 2012). The biggest challenge faced by the policymakers is the efficient use of technology and the realization for the masses to recycle wastewater. The rural population is disconnected from mainstream national policies and international good practices, and hardly any mechanism exists to address this vital issue at the national and provincial levels. Therefore, as Pakistan approaches the water scarcity line in the next 3 years, the situation will be further exacerbated and complicated.

4.2.5 Water scarcity an evolving national security challenge

According to Rao Irshad Ali Khan, Chairman Indus Water River Authority (IRSA), the water availability in Pakistan has declined tremendously since 1947 (Islam, 2011). At the time of independence, the per capita water availability was 5,600 cubic meters. This percentage has decreased from over 5,260 cubic meters in 1951 to 1,038 cubic meters in 2010. If the same situation continues, then by 2022, the water availability in Pakistan will further decrease to 877 cubic meters per annum and by 2025 to 660 cubic meters, and by 2050 it will touch 575 cubic feet (Daud et al., 2017).

Another important factor is the availability of river water, viz a viz the requirement of sub-surface water to meet human consumption and agriculture needs. However, these wells due to the improper level of maintenance get dried up and people in rural area start looking for alternative sources which in most cases is full of health hazards. Rural areas lack proper infrastructure due to which there are no proper water storage areas for storing rainwater, resulting in flooding and wastage of rainwater.

5 Policy recommendations

5.1 Proposed policy framework

After critically examining Pakistan's available water resources, storage, distribution, governance and management, promulgation of laws and regulations, and future water demand and supply gap, certain recommendations are offered, which shall provide the policy input for Pakistan's relevant ministries and organizations. The thrust lines of the proposed framework given in Figure 11 involve strong policy implementations for efficient water governance, to achieve water-related SDGs and MDGs by 2030 for the sustainable development of Pakistan.

The efficient water governance model suggested in Figure 12, considers the synergistic coordination with key stakeholders, relevant institutions, policy framework, and unfathomable commitments of leadership at all levels for achieving the optimum results. The important elements of the proposed water governance model include; political commitment and leadership for policy formulation and implementation. Capacity building of relevant institutions, stakeholders' engagement, and use of technology for efficient resource management.

The terms of reference for each of the elements of the proposed water governance model are highlighted in self-explanatory Figure 13 below.

5.2 Drip water and recycling of wastewater for irrigation

Due to a lack of smart irrigation water management, each province consumes its water quota at a very early stage. While main cash crops remain deprived of water at critical stages of the year. A drip system is suggested to be encouraged in a phased manner to judiciously use available water. Sindh is often found complaining about the discriminatory distribution of water by the federal government. The Sindh Information Minister Sharjeel Memon even appealed to the federal government to take notice of the grave water shortage in Sindh province (Alvi, 2019). He even brought to the attention of the government the 1991 water accord, which ensured judicious water distribution to all provinces. The Pakistan Water Apportionment Accord 1991 was established to dispense water share to all provinces. However, the accord doesn't give an exact proportion of the amount of water being allocated to the provinces (Irsa, 1991). For this purpose, IRSA was established to address, regulate, and develop standard operating procedures regarding water allocation to the provinces. Unfortunately, each

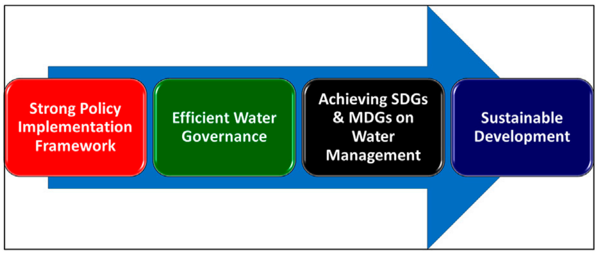

FIGURE 11
Proposed policy framework.

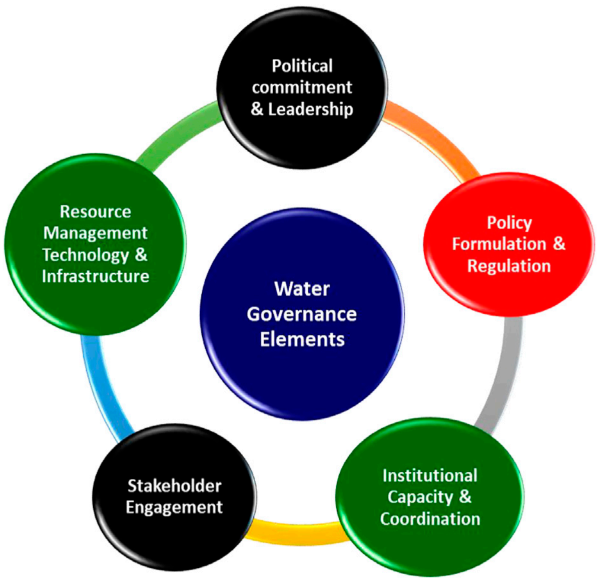

FIGURE 12
Elements of the proposed water governance model.

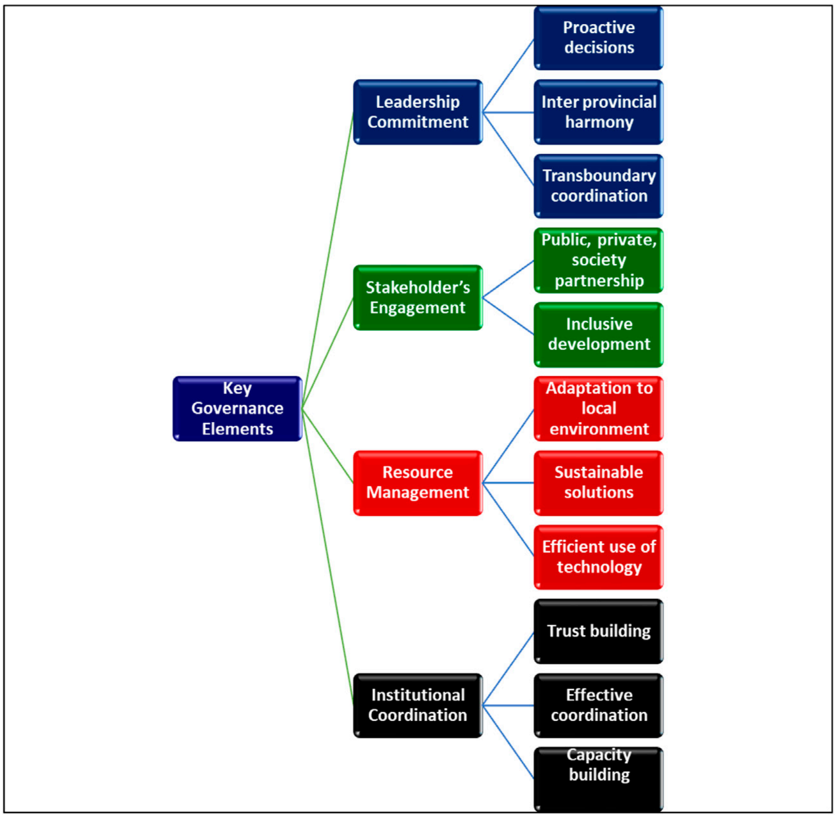

FIGURE 13
Suggested terms of reference for water governance elements.

province has its unique features in terms of agricultural needs and population, thus making the interpretation and implementation of the accord even more difficult. Therefore, it is suggested that smart irrigation systems be installed as a priority for the judicious use of agricultural water. Similarly, wastewater recycling plants should be introduced in a phased manner commencing from provincial capitals and gradually extending to all urban and rural areas. This water should be diverted for cleaning, agriculture, and other non-drinkable usage. Modern housing societies like Bahria Town Islamabad have already installed such plants, which can be replicated in other parts as well.

5.3 Enforcement of legislations

While Pakistan has promulgated multi-dimensional legislation for the storage, distribution, and use of water, however, there are several coordination and management issues at federal and provincial levels, which have been amply discussed in the analysis part. It is, therefore, suggested that appropriate dispute resolution forums be established through consensus so that the stakeholders can debate and find solutions to evolving water challenges instead of press briefings. The recent floods have also exposed Pakistan's extreme vulnerability to climate change, therefore, appropriate laws and Standard Operating Procedures (SOPs) should be revisited and re-adjusted to meet future challenges in a befitting manner.

5.4 Construction of more reservoirs on an urgent basis

The need for the construction of more dams has been realized in the last 4 decades, however, the trivial political mileages created fissures among the federating units, which provided an excuse for not constructing dams. Now that Pakistan is at a critical juncture of its survival, hardly 3 years away from being declared as water scarce country, therefore, all elements of national power (ENP) should be mobilized for building consensus, arranging resources, and fast-paced completion of more dams. The speed of the ongoing projects of Diemer and Bhasha should be expedited and while China-Pakistan Economic Corridor (CPEC) is more focused on infrastructure development, a part of it should be renegotiated for the construction of water reservoirs. A comprehensive road map for at least 15–20 years should also be prepared by the Ministry of Planning Commission in consultation with all the stakeholders for the development, conservation, and judicious use of water. The existing capacity of Mangla, Tarbela and Chashma has been eroded to a large extent due to silting, which should be restored at priority.

5.5 Rationalizing groundwater and crop patterns

The installation of tube wells should be subject to the issue of a no objection certificate (NOC) by the local government after all the technical evaluations of water availability and sustainability, coupled with the monitoring mechanism for avoiding the wastage of groundwater. Instead of an individual-level water supply, a community-based tube well system is proposed to conserve groundwater and ensure effective monitoring. Similarly, in short term, water-intensive crops should be discouraged and replaced by high-yield crops requiring less water.

5.6 Refurbishment of canals and tributaries

To preserve the water seepage and unusual waste, it is strongly recommended that all water channels should be cemented. This practice was initiated in Punjab province some 20 years ago and has proved highly successful in the preservation of water. This should be extended across Pakistan over a phased program. This long-term investment would be beneficial for ensuring water security on a sustainable basis.

5.7 Integrated water management system (IWMS)

The "whole of government" and "whole of nation" approach is recommended for dealing with water crises holistically. The proposed approach should be able to handle the existing and evolving challenges like; the impact of climate change, surface and groundwater use, urbanization, industrialization, and pollution impacting the water quality.

6 Conclusion

Today Pakistan is confronting ever-increasing water security issues, which are likely to compound further due to the burgeoning population, negative impacts of climate change, and inefficient management of available water resources. The prevailing mistrust among the federation and federating units, inadequate implementation of policies, and lack of storage capacity attribute to ongoing friction and disputes. Addressing interprovincial disputes, predominantly between Sindh and Punjab, is a challenge for the federal government as such issues arise every cropping year. It is, therefore, imperative that the government should introduce policies that help in addressing equity, storage issues, environmental sustainability, and sustained economic development while ensuring water security. Regulating and altering water-use comportment, along with adopting modern irrigation technologies, can limit water shortages in the short term and pave the way for improved economic growth and development in the long term.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

WI designed the study, and contributed results parts. MM contributed literature review, while RT contributed policy recommendations and proof reading.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The layout and the spatio-temporal evolution of water-polluting enterprises in Zhejiang under regulation

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Water pollution is closely related to the development of water pollution-intensive industries, but there is a lack of relevant research, and few studies to verify the existence of "pollution heaven." This paper aims to study the layout and the spatio-temporal evolution of water-polluting enterprises. Taking Zhejiang Province, China as an example, this study visualized the spatial distribution of water pollution enterprises under the "Five Water Treatment" regulations during 2018–2022. At the same time, based on the Mann-Whitney *U* test, this paper verifies the hypothesis of pollution paradise in Zhejiang Province. The results show that the distribution of water pollution enterprises in Zhejiang is clustered, and water pollution control has been realized to a certain extent. However, water pollution enterprises still tend to be located in areas with lower environmental standards and weak environmental regulations. In view of this, the government should optimize the industry structure, strengthen the supervision of suburban water pollution enterprises.

KEYWORDS

spatial analysis, water polluting enterprises, industrial agglomeration, blue development, regulation, Zhejiang, pollution heaven

1 Introduction

Water is regarded as the source of human life. Together with land and energy, water provides the basic conditions for the development of human society and plays a vital role in the development of human society. Water resources is an important foundation for national economic and social development, and an important guarantee for improving ecological environment. Xia et al. (2011) pointed out that the three challenges facing the world are resources, population and environment. Water resource is a national strategic resource and a key factor affecting ecological civilization. As a complex systematic engineering, water resources management plays a strategic role in promoting sustainable economic development (Fu, 2022). Therefore, serious attention is needed to the water pollution problem (Liu et al., 2021; Sawyer et al., 2021). In recent years, China has witnessed rapid growth in its economy and population. Meanwhile, the large demand for water resources and serious water pollution problems have hindered the rapid economic development in China. The problem of water pollution is closely related to the development of water pollution-intensive industries. In particular, an important reason for the serious water pollution problem in China is the unreasonable planning and layout of water pollution-intensive industries (Chang, 2017). The so-called pollution-intensive industries refer to industries characterized by high-intensity pollution emissions. The spatial transfer of pollution-intensive industries is considered to be an important reason for the diffusion and transfer of pollution. Relatedly, the regional spatial distribution and evolution

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of pollution-intensive industries is an important issue for sustainable economic development. Hence, as a response to environmental problems brought by economic activities, it is necessary to investigate the spatial layout and driving factors of polluting industries, and it can also provide important implications for policymaking, such as enacting effective strategies to transfer polluting industries in the regional transition period, to promote the sustainable regional development (He, 2017).

Previous researchers have conducted theoretical and empirical studies on the influence of different patterns of industrial spatial agglomeration on the ecological environment (He et al., 2022). For example, Fang et al. (2021) looked at the mining industry at different development stages of urban agglomerations and did a dynamic evaluation of the impacts of the mining industry on the atmosphere, soil, rivers, and other ecological environment elements at different stages. Bonnet et al. (2021) included industrial agglomeration as an indicator to assess sustainable development and combined it with indicators such as externality and social welfare, to build a more comprehensive model for evaluating urban sustainable development. In recent years, China has strengthened the intensity of industrial adjustment, and as a result, related research has incorporated industrial economic elements to a certain extent. For instance, Song et al. (2022) analyzed the spatial change of urban agglomeration land and its ecological environment effects. Liu et al. (2020) evaluated the impact of industrial structure on the environment by estimating the ecological environment impact coefficient of different industry types and the overall ecological environment impact index of regional industrial structure. These studies have confirmed that industrial spatial agglomeration has a certain impact on the ecological environment.

With the development of geospatial technology, scholars have conducted extensive research on spatial-temporal pattern mining, in which spatial analysis played an important role (Yu et al., 2017; Yin et al., 2022). Previous research has shown that for spatial analysis, data collection is relatively easy and can be applied widely (Chen et al., 2022; Zhu et al., 2022). This method can not only allow access to accurate statistics but also can present the results in an intuitive way and visualize the results. Furthermore, spatial analysis can improve the spatial accuracy of urban research, so as to implement spatial governance at a more refined level. At present, many researchers have carried out research on spatial distribution characteristics of geographical objects and the factors that might influence the distribution. For example, Gao et al. (2014) used spatial analysis methods such as cluster analysis to analyze the distributional characteristics of air pollution areas in various provinces and cities and divided 73 cities into 6 clusters. Zhang et al. (2016) used Spatial Clustering and other methods to examine the clustering of production service industries in Hangzhou. They have found that when the production service industry clusters were located in areas and adjacent areas with higher levels of urban function, the scope and scale of the cluster area would increase. Wang et al. al. (2019) used the spatial autocorrelation analysis method to study the spatial relationship of the ecological pressure of water resources, and provided decision-making suggestions for the government on how to use water resources sustainably; Yuan (2019) use regression analysis to study the relationship between the income and expenditure of urban residents in Gansu province, based on which policy-making suggestions were provided for the government to increase the discretionary income of residents. Li et al. (2018) employed special analysis and concluded that the spatial distribution of industries in Lanzhou has shown the characteristics of being dense in urban areas and sparse in county areas. Hence, this paper argues that the application of geospatial technology and big data to the study of the spatial distribution of water-polluting enterprises will help to enhance the understanding of the economic value of the spatial layout and temporal and spatial evolution of water-polluting enterprises in Zhejiang Province.

The theoretical basis of this paper is based on the “pollution haven” hypothesis, also known as the “pollution refuge” hypothesis, which was proposed by Walter and Ugelow (1979). The basic idea behind the “pollution haven” hypothesis is that firms that aim to maximize profits will reconsider their production decisions if strict environmental regulations increase their production costs. By now, one idea is that the “pollution haven” hypothesis is only partially true. That’s because environmental regulations affect FDI location choices, but they’re not the key factor. They believe FDI still focuses on the traditional factors (Musah et al., 2022). Another idea says there’s insufficient evidence for the “pollution heaven” hypothesis. Therefore, this paper will take Zhejiang Province as an example, based on the background of “five water treatment” scientifically reveal the distribution law of water pollution-intensive industries in Zhejiang Province, explore its influence mechanism, and confirm whether the “pollution haven” hypothesis exists in cities. Our findings may have important theoretical and practical significance for finding the balance in the relationship between development and environmental protection and for realizing green and high-quality development.

2 Methodology

2.1 Zhejiang Province and the “five water treatment” regulation

In 21 century, Norman E. Borlaug again, advocated the so-called “Blue Revolution” to fight for water resources (Shevah, 2019). Hence, Blue Revolution also represents a water revolution. In China, the Blue Revolution has also been clearly enacted in coastal provinces. Zhejiang Province is located on the southeast China and its economy has grown steadily and rapidly in the past decades. Rapid economic growth means increased demand for resources, which has raised concerns about water environment. In particular, major rivers and lakes in the province were seriously polluted. For example, the water pollution event of the Qiantang River has aroused public concerns (Li et al., 2019). To improve the water environment, on 29 November 2013, at the Fourth Plenary session of the 13th CPC Central Committee of Zhejiang Province, it was clearly proposed to take the “five water treatment” as a major strategic guideline to construct a blue future. The “five water treatment” consists of five aspects: sewage treatment, flood drainage, flood control, water supply protection and water conservation. The aim is to solve the problem of sustainable development caused by water problems. This has also led to the discussions on the influence of “five water treatment” and industrial effects in Zhejiang. In this context, the objective of this paper is therefore to explore the development of water pollution enterprises under the background of “five water treatment.”

Zhejiang Province includes 11 prefecture-level cities, covering the area between 118°01′-123°10′east longitude and 27°02′-31°11′north latitude (Figure 1). There are eight major water systems including the Qiantang River, Oujiang River, and Aojiang River. According to the Statistical Yearbook of Zhejiang Province, the GDP of Zhejiang

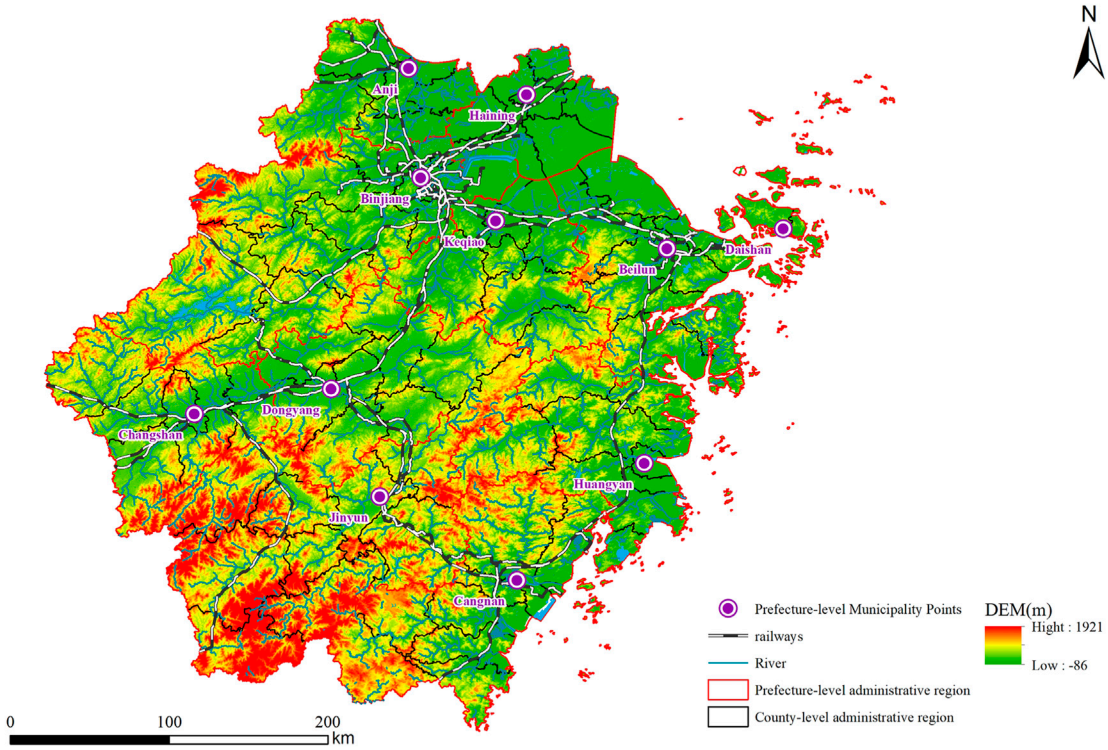

FIGURE 1
The map and overview of Zhejiang province.

Province in 2021 reached 7.35 trillion yuan, with an increase of 8.5% over the previous year. In terms of industries, the added value of the primary, secondary, and tertiary industries was 220.9 billion yuan, 3,118.9 billion yuan, and 4,011.8 billion yuan, respectively, with an increase of 2.2%, 10.2%, and 7.6% over the previous year. The industry in Zhejiang is relatively developed. According to the list of key polluters in 2022 by the General Office of the Ministry of Ecology and Environment, Zhejiang province identified 6,117 key polluters in 2022, and water pollution is dominated by the manufacturing industry.

2.2 Research methods

According to previous literature, in order to test the "pollution heaven" hypothesis (Xu et al., 2022), it is necessary to have a corresponding understanding of the spatial distribution of pollution points in the study area. The intuitive visual observation method is the kernel density, and the convenient way to judge the concentration of polluting enterprises in urban and rural areas is the nearest neighbor index method. On this basis, Ma et al. (2022) also proposed Mann-Whitney U test as a non-parametric test method, which can detect whether there is a significant difference in the distribution of two or more observed variables, which plays a complementary role in the presentation of differences in this paper.

2.2.1 Nearest neighbor index

The nearest neighbor index method uses the distribution of random patterns as a standard to measure the spatial distribution of point elements (Bai et al., 2021). The nearest neighbor distance is a geographic index that indicates how close the points are to each other in geographic space. This method measures the distance between each point and its nearest neighbors r_1, and takes the average of these distances $\overline{r_1}$, which is the average nearest neighbor distance that characterizes the degree of proximity. The calculation Eq. 1 is:

$$R = \frac{\overline{r_1}}{r_E}$$
$$r_E = \frac{1}{2\sqrt{n/A}} \tag{1}$$

In the formula, R is the nearest neighbor index. $\overline{r_1}$ represents the average distance between each actual water-polluting enterprise and the nearest point and r_E refers to the theoretical nearest neighbor distance. n represents the number of water-polluting enterprises, and A shows how large the research area is. In general, there are three distributional types: uniform type, random type, and cluster type, for which the nearest neighbor distance decreases successively. When $R = 1$, the distribution of point elements is random; when $R > 1$, the distribution of point elements tends to be uniform; when $R < 1$, the distribution tends to be clustered; $R = 0$ means complete agglomeration (GENG et al. ., 2019).

2.2.2 Kernel density estimation

Kernel density analysis is a method that uses each point or line element to model a smooth conical surface based on the kernel function. The kernel density at the center is the sum of the densities in the entire window (Chen et al., 2013). This method is widely used in the simulation of pollution spatial distributional

TABLE 1 Nearest neighbor index of water pollution enterprises in Zhejiang Province from 2018 to 2022.

Year	Average observed distance (m)	Expected observed distance (m)	Nearest neighbour index	Distributional pattern
2018	1300.3488	4000.1079	0.325078	Agglomerated
2019	1280.5896	4026.6783	0.318026	Agglomerated
2020	1215.3492	3745.9502	0.324443	Agglomerated
2021	1025.8629	3209.536	0.31963	Agglomerated
2022	991.6706	3102.3663	0.31965	Agglomerated

characteristics (Liu and Du, 2016). The present study uses kernel density analysis to examine the clustering characteristics of points in space (Zhu et al., 2018), and Eq. 2 is as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \quad (2)$$

In the formula: $f(x)$ is the estimated value of kernel density; h represents the search radius; n is the number of water-polluting enterprises; $k(\cdot)$ is the kernel function; $x - x_i$ represents the distance from the evaluation point to the output grid.

2.2.3 The Mann-Whitney *U* test

The Mann-Whitney *U* test is a non-parametric test that can be used to test whether two independent samples come from a population with the same mean, or whether the relative frequency distribution of two populations is the same. In the present study, the 30 county-level administrative units in Zhejiang Province were divided into urban areas and suburban areas. We hypothesized that water-polluting enterprises tend to locate in areas with relatively low environmental standards and weak environmental regulations. The calculation Eqs 3, 4 are as follows:

We first calculated U_A and U_B, where:

$$\begin{aligned} U_A &= n^2 + (n^2 + n)/2 - T_A \\ U_B &= n^2 + (n^2 + n)/2 - T_B \\ U_A + U_B &= n^2 \end{aligned} \quad (3)$$

In the next step, we selected the smaller value of U_A and U_B as the U value, so that the Mann-Whitney *U* test statistic can be obtained as:

$$Z = (U - n^2/2)/\sqrt{n^2(2n+1)/12} \quad (4)$$

At the level of $\alpha = 0.05$, when the number of border counties or the number of inner counties ≤10, and U is greater than its corresponding critical value $U_\alpha = 15$, or when the number of border counties and the number of inner counties is both greater than 10, the U distribution tends to be Normal distribution, $-1.96 < Z \leq 1.96$. As a result, the null hypothesis H_0 cannot be rejected, and otherwise, the null hypothesis H_0 is rejected.

3 Results

3.1 Types of the spatial distribution of water polluting enterprises in Zhejiang Province

We used the average nearest neighbor tool in ArcGIS 10.2 to get the nearest neighbor index of water-polluting enterprises in Zhejiang Province from 2018 to 2022 (see Table 1). The results showed that the average nearest neighbor index of water-polluting enterprises in Zhejiang Province from 2018 to 2022 was around 0.32, and the overall distribution showed a clustered characteristic. In the past 5 years, the nearest neighbor index of water-polluting enterprises in Zhejiang Province was less than 1, and the *p*-value flagged a significant test result at the 0.01 level. Among them, the nearest neighbor index of water-polluting enterprises in Zhejiang Province in 2022 decreased compared with the nearest neighbor index of water-polluting enterprises in 2018, indicating that the spatial distribution of water-polluting enterprises in Zhejiang Province gradually became increasingly agglomerated during this period, whereas the difference in distribution pattern was not significant.

3.2 Spatial agglomeration pattern of water polluting enterprises

The kernel density estimation method is used with ArcGIS 10.2 to further identify the spatial agglomeration area of water-polluting enterprises in Zhejiang Province. After several times of exploration, the optimal search radius was decided to be 100 km. The results showed that from 2018 to 2020, water-polluting enterprises in Zhejiang Province in general tended to be agglomerated in an area in the north (Figure 2 and Figure 3). Among them, the first-level agglomeration area was mainly located in the area with a relatively high level of network development in Zhejiang Province, that is, on the northern line of "Hangzhou-Haining-Shaoxing." This area is an important part of the urban agglomeration along the Qiantang River in Zhejiang Province. There were four secondary agglomeration areas as the cores of four central cities or sub-central cities, namely, Fuyang District of Hangzhou City, Liandu District of Lishui City, Beilun District of Ningbo City, and Jiaojiang District of Taizhou City. From 2021 to 2022, (Figure 2) water-polluting enterprises in Zhejiang Province were still mainly concentrated in the northern region. Among them, the first-level agglomeration area was located on the "Hangzhou-Haining-Shaoxing" line. The surrounding cities gathered significantly, and the agglomeration phenomenon was especially obvious in three subcentral cities: Xiaoshan District of Hangzhou City, Shangyu District of Shaoxing City, and Xiuzhou District of Jiaxing City.

3.3 Differences in the number of water-polluting enterprises between urban and suburban areas in Zhejiang Province

In 2018, the number of water-polluting enterprises located in the suburban area of Zhejiang Province was 1,643, which was

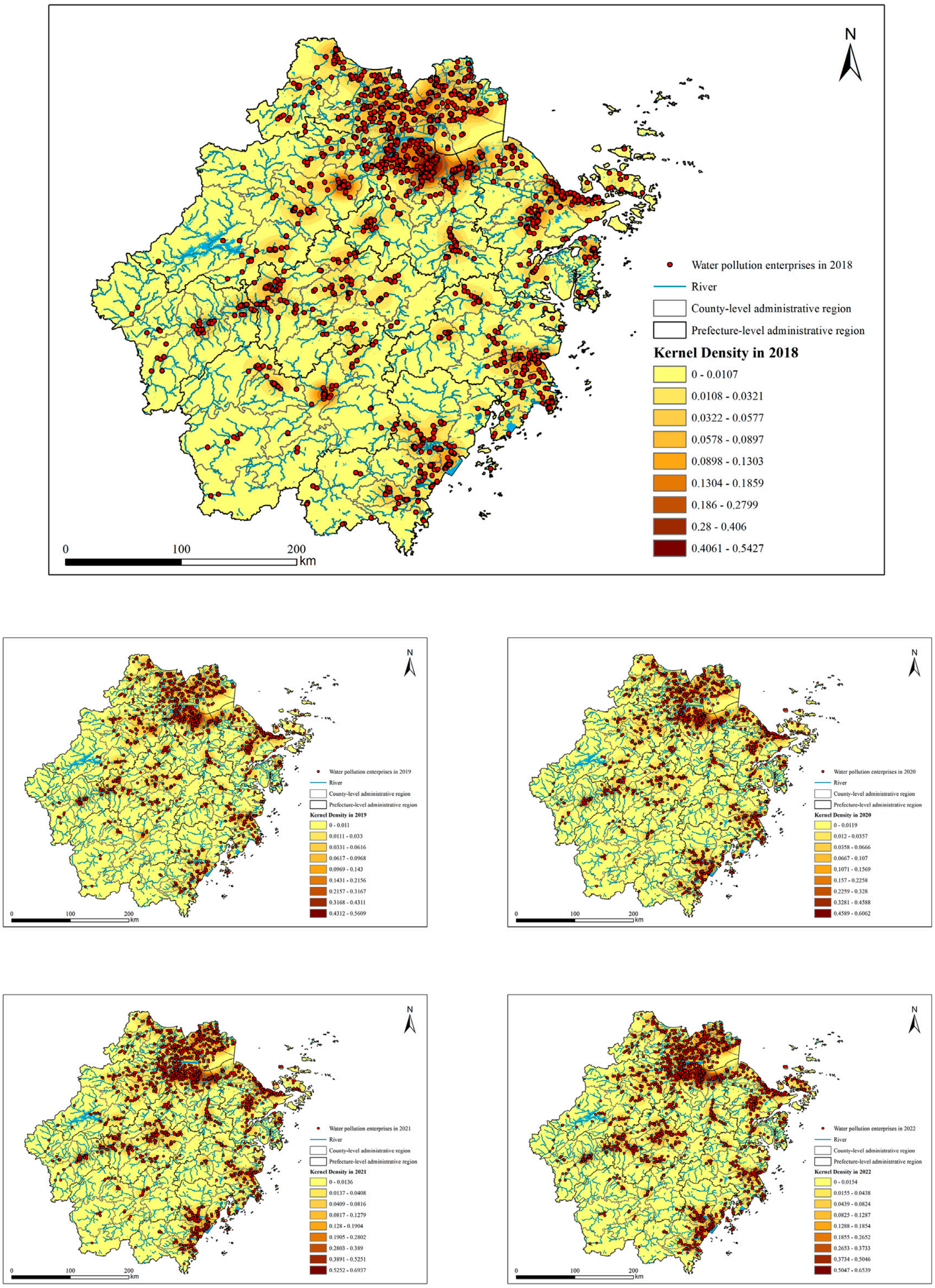

FIGURE 2
Estimation of the kernel density of water-polluting enterprises in Zhejiang province from 2018 to 2022.

3.61 times that of urban areas (see Figure 4). In 2019, the number of major water-polluting enterprises clustered in suburban areas was 3.28 times that of urban areas; in 2020, the number of major water-polluting enterprises clustered in suburban areas was 3.14 times that of urban areas; in 2021, the number of major water-polluting enterprises clustered in suburban areas was 3.18 times that of urban areas, and in 2022, the number of major water polluting enterprises clustered in suburban areas was 3.32 times that of urban areas. It can be seen that in the past 5 years, in terms of the layout of water-polluting enterprises in Zhejiang Province, most

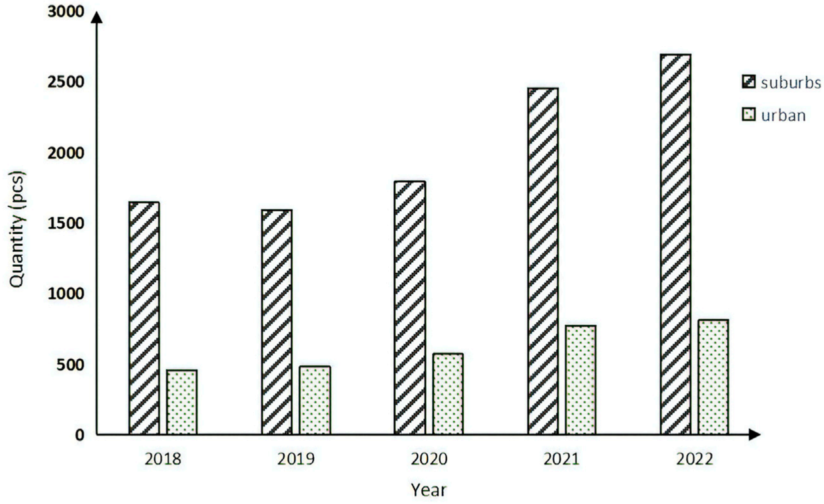

FIGURE 3
Difference in the number of water-polluting enterprises in Zhejiang Province between urban and suburban areas from 2018 to 2022.

enterprises have shown a preference for suburban areas. Unexpectedly, the tendency of "urban centralism" that is commonly seen in the field of environmental protection has not yet been observed for water-polluting enterprises in Zhejiang province.

3.4 Differences in spatial agglomeration characteristics between urban and suburban areas

Results of the analysis of the nearest neighbor index showed that from 2018 to 2022, the water-polluting enterprises in Zhejiang Province were clustered both in urban and suburban areas. For urban areas, land use is often intensive and thus the level of agglomeration of water-polluting enterprises in these areas was significantly higher than that in suburban areas. In terms of the characteristics of agglomeration, the agglomeration of polluting enterprises in urban and suburban areas showed differentiated spatial performance and location patterns (Figure 4). In 2018, the first-level agglomeration cores of urban water-polluting enterprises were located in the central area of Xiaoshan District, Hangzhou, and showed a clear pattern of distributing along rivers and lakes. There were three secondary agglomerations, with the Wuxing District of Huzhou City, Xiuzhou District of Jiaxing City, and Beilun District of Ningbo City as the core respectively. The distribution of water-polluting enterprises in the suburban area was relatively scattered. So far, five first-level agglomeration areas have been formed: Liandu District of Lishui City, Jiaojiang District of Taizhou City, Xiangshan County of Ningbo City, Dongtou District of Wenzhou City and Fuyang-Xiaoshan-Yuyao. Furthermore, secondary agglomeration areas formed large-scale contiguous areas in the areas of "Jiande-Lanxi-Longyou" "Zhuji-Pujiang-Yiwu" "Wenling-Yuhuan" and "Fenghua-Haining" In 2022, the agglomeration cores of water-polluting enterprises in urban areas were still mainly distributed in Xiaoshan District, Hangzhou City, and there was a tendency to spread eastward. However, compared with the number of cities in 2018, the secondary agglomeration areas have increased, mainly concentrated in the Gongshu District of Hangzhou City and Yinzhou District of Ningbo City. The tendency of large-scale spreading to surrounding cities has not been observed yet. Compared with 2018, the distribution of water-polluting enterprises in suburban areas tended to be more dispersed in 2022. By comparing the distribution across years, it can be found that the layout of urban regional polluting enterprises was not only closely related to the attributes of individual cities (e.g., city size and industrial structure) but was also linked with the connection level of regional element circulation networks. The distribution of water-polluting enterprises in suburban areas showed a strong dependence on local resources, and the agglomeration areas were all areas rich in rivers and lakes.

3.5 "Institutional space-boundary weakness" in the location of polluting enterprises

According to the "pollution haven hypothesis" polluting enterprises tend to locate in areas with relatively low environmental standards and weak environmental regulations (Tian et al., 2018). Within the regional system, areas far from the administrative center or at the border are often weak in environmental regulation (Wang et al., 2019). In order to test whether the "cross-border location preference" in the "pollution haven hypothesis" can be supported in Zhejiang Province, we looked at descriptive statistics and used the Mann-Whitney *U* test (Mann-Whitney *U* test) to analyze the distribution and quantity of water-polluting enterprises in urban and suburban areas. Descriptive statistics showed that the average number of water-polluting enterprises in the suburbs of Zhejiang Province was 3.29 times that of the urban areas, and the indicators such as the range and coefficient of variance in the urban areas are much larger than those in the suburbs, indicating that there were significant differences within the urban areas (Table 2).

For the Mann-Whitney *U* test, we adopted an alpha level for significance test $\alpha = 0.05$, and employed a two-sided quantile test, The results showed that there were no significant differences, and

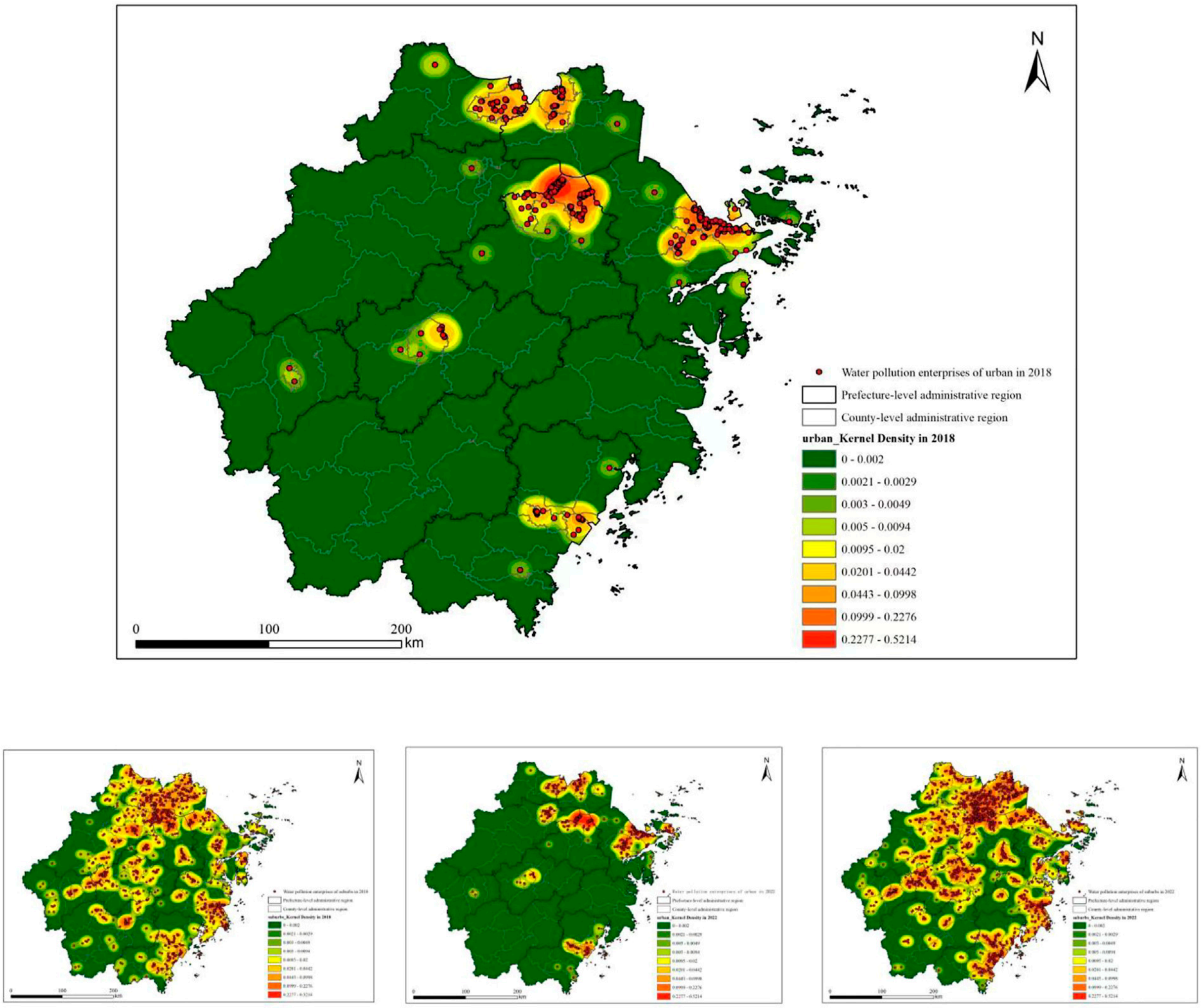

FIGURE 4
Estimation of Kernel density of water-polluting enterprises in urban and suburban areas in Zhejiang Province in 2018 and 2022.

TABLE 2 Descriptive statistics of the number of water-polluting enterprises in urban and suburban areas.

Area	Number of polluting enterprises	Range	Standard deviation	Mean	Coefficients of variance (CV)
Suburban	89.20	530	97.82	107.04	0.91
urban	27.11	718	191.56	162.63	1.18

thus H0 cannot be rejected (Table 3). However, there were still differences in the number of enterprises in urban and suburban areas from 2018 to 2022. In 2018, the average number of water-polluting enterprises in the suburbs of Zhejiang Province was 3.61 times that of the urban area, which was the year with the largest difference. The year with the second largest difference was 2020, the average number of water-polluting enterprises in the suburbs was 3.14 times that of the urban area. However, the difference was not significant at an alpha of 0.05 level. Hence, there was no significant difference between the number of water-polluting enterprises in the urban and suburban areas this year.

4 Discussion

It can be seen from the findings that the period from 2020 to 2022 is the rapid agglomeration stage of water pollution enterprises in Zhejiang Province. This phenomenon is particularly evident in the southern cities of Zhejiang, among which the prominent cities such as Wenzhou. In 2019, Wenzhou and other cities released the policy effectiveness of the “five water treatment” for 2015–2019 respectively, and made it clear that the current water pollution enterprises have made phased progress in treatment. In Wenzhou, for example, a survey found that 87.5% of water quality was at I-III class, reaching the annual provincial target of 75%. The proportion of I-III class water

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TABLE 3 The number of water-polluting enterprises in urban and suburban areas and the results of the Mann-Whitney *U* test.

Year	Suburban	Urban	Mann-Whitney *U* test			
	The average number of polluting enterprise	The average number of polluting enterprise	U value	Z value	*p*-value	Decision
2018	1643	455	500	−2.309	0.21	H0 was not rejected
2019	1590	484	620	−1.216	0.11	H0 was not rejected
2020	1792	570	612	−0.309	0.15	H0 was not rejected
2021	2453	771	1121	−1.202	0.09	H0 was not rejected
2022	2691	810	1321	−0.309	0.06	H0 was not rejected

quality in the provincial control section reached 83.3%, reaching the annual provincial target of 75%. The water quality of drinking water source reaches 100%. After consulting the policy documents, it is found that most areas in Zhejiang have strictly implemented the "one river one policy" regulation measures for key river courses since 2020, which has greatly promoted the effectiveness of the "five water treatment," accelerated the rapidagglomeration of water pollution enterprises and improved the water treatment effect. However, according to Mann-Whitney *U* test, the current distribution of water pollution enterprises in Zhejiang Province has initially shown the location preference of settling in suburban areas. This largely corroborates what previous scholars have found. Lei et al. (2017) once found that there was a pollution heaven in their study on the relationship between import and export trade and carbon emissions, which they thought was caused by the rapid development of import and export trade in the Yangtze River Economic Belt. The findings of this paper on water pollution enterprises are largely the same as those of them. Zhejiang, though a province, is a different, smaller area than the one they studied. But the phenomenon also exists. That's because Zhejiang province is rich in ports and waterways. Trade liberalization moved polluting industries to areas with lower environmental regulations, which damaged the environment in suburban areas and increased sewage discharge. In view of this, Zhejiang Province should optimize the industrial structure and implement relevant policies to suburban water pollution enterprises to prevent more serious water pollution in the suburbs.

5 Conclusion

This paper employed the nearest neighbor index, kernel density estimation, and Mann-Whitney *U* test to analyze the temporal and spatial evolution characteristics of water pollution-intensive industries in Zhejiang Province. The main findings from the present study include:

1. At present, the distribution of water-polluting enterprises in Zhejiang Province showed an agglomerated characteristic. The first-level agglomeration areas were all located in areas with a relatively high level of urban network development. The second-level agglomeration areas were all centered on central cities or sub-central cities. In general water-polluting enterprises were mainly concentrated near rivers, lakes, and seas. In terms of the developmental trend, 2020–2022 is the stage when a rapid concentration of water pollution enterprises occurred in Zhejiang Province.

2. The suburban location represents the overall difference in the existence and succession of water-polluting enterprises in suburban areas. At present, the layout of water-polluting enterprises in Zhejiang Province has initially shown the location preference of settling in suburban areas. The first-level agglomeration cores of polluting enterprises were concentrated in areas where the urban network is relatively developed and has good water connections such as easy reach to rivers, lakes, and seas. These findings showed that enterprises paid special attention to the circulation network of elements. However, the distribution of water-polluting enterprises in suburban areas was relatively scattered, whereas the number of enterprises was increasing year by year, showing dependence on local water resources.

3. The suburban location also represents the regional differences in the layout of polluting enterprises in the institutional space based on the blue development system. At present, water-polluting enterprises in Zhejiang Province do not show an obvious cross-border agglomeration for seeking the overflow of environmental externalities, whereas the comparison of the number of water-polluting enterprises in the suburban and urban areas shows that water-polluting enterprises were more inclined to be located in areas with relatively low environmental standards and environmental conditions.

The unreasonable layout of water-polluting enterprises in Zhejiang Province will lead to prominent contradictions in the use of water resources, aggravate water environment pollution, and increase the risks of water ecological damage. A scientific and reasonable industrial layout is the basis and prerequisite for the effectiveness of water resources protection in Zhejiang Province, especially for water pollution-intensive industries. Therefore, in the context of the Blue Development strategy, the spatial evolution of water-polluting enterprises in Zhejiang Province is actually cutting-edge and relevant.

The present study also has some limitations that need to be accounted for. At present, polluting enterprises are spreading all over the country, given the differences in economic levels and environmental systems across regions, different industrial developmental patterns may exist in different regions. Due to the lack of relevant data, the present study did not compare the distributional patterns in different areas of China. Future studies may further carry out research on different types of polluting enterprises in Zhejiang Province, and find out the economic value of the spatial layout and temporal and spatial evolution of polluting enterprises in Zhejiang Province. In addition, this paper only studies the water pollution enterprises. Other polluters such as air pollution and soil pollution have not yet been discussed, which will also be the focus of our future work. Liu et al., 2015, Sun, 2022.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by XX and LW. The first draft of the manuscript was written by XX, LW, and YZ commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Empirical study on green development of marine economy driven by marine scientific and technological innovation and its influencing factors

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In this study, the green development of marine economy driven by marine scientific and technological innovation is empirically studied and the influencing factors are analyzed. The results show that the development of marine science and technology is significantly positively correlated with the green development of marine economy as a whole, and each input variable has a promoting effect on economic development, but with varied degree of effect. The analysis on the growth models of "Circum-Bohai Sea Economic Zone," "Yangtze River Delta Economic Zone" and "Pearl River Delta Economic Zone" shows that at present, science and technology in each marine economic zone play an obvious role in promoting economic development, and each input variable plays a different role in promoting the green development of regional marine economy. With the help of threshold panel model, the influences of five factors, namely opening to the outside world, government investment, financial development, human capital and technology investment, on the green development of marine economy driven by marine scientific and technological innovation are investigated, and it is concluded that all kinds of external influencing factors will interfere with the role of marine scientific and technological innovation and achieve the effect of promoting or restricting it.

KEYWORDS

marine scientific and technological innovation, green development of marine economy, threshold model, influencing factors, technological innovation

Introduction

As the future development is more about the development of marine industry, the construction of first-class seaports is imminent. Only by establishing a perfect modern marine industry system, effectively improving the marine ecological environment and achieving green and sustainable development can contributions be made to the development of our country for truly becoming a powerful marine nation. Marine economy is closely related to national construction, effectively improve the quality of marine economy, make full use of this treasure house, obtain continuous resources, make contributions to national economy, and occupy a certain position in international competition. The research results on marine science and technology innovation and green development of marine economy can be divided into four aspects. First, the marine science and technology innovation and the marine economy green development correlation Research (Chen and Ma, 2020; Cu, 2020; Wang et al., 2021). Second, the research on coordinated development of marine science and technology innovation and Marine

TABLE 1 MEC evaluation indicator system.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Weights
MEC	Total marine economy	Proportion of added value of marine industry in the whole country	0.1634
		Per capita marine GDP	0.0453
		The proportion of total investment in fixed assets of marine industry in total investment in fixed assets of China	0.0240
		The proportion of the number of sea-related employees in the number of sea-related employment in the country	0.1606
	Marine economic structure	The ratio of the added value of the marine primary industry to the regional marine GDP	0.0236
		The ratio of the added value of the marine secondary industry to the regional marine GDP	0.0555
		The ratio of the added value of the marine tertiary industry to the regional marine GDP	0.1036
		Optimization index of marine industrial structure	0.0758
	Marine economic effect	The proportion of the added value of the marine industry to its regional GDP	0.0659
		Elastic coefficient of national marine GDP growth to regional growth	0.0317
	Marine ecological civilization	Exhaust emission per unit GDP	0.1250
		Wastewater discharge per unit GDP	0.1250

Economy green development. In recent years, the level of coordination between marine science and technology innovation and green development of marine economy has been increasing year by year, and is now in a good coordination stage (Wang et al., 2020; Zhao et al., 2022). Third, the impact of marine science and technology innovation on the green development of marine economy. Marine science and technology innovation can promote green development of the local marine economy by promoting the green Total factor productivity of the marine economy (Ning and Song, 2020; Qin and Shen, 2020). Fourth, the efficiency measure of marine science and technology innovation to marine economy green development. The three-stage DEA method shows that the overall efficiency of scientific and technological innovation to the growth of marine economy is not high, and the level of innovation efficiency still has great room for improvement (fan et al., 2019). In the existing research, only the mechanism of marine scientific and technological innovation driving green development of marine economy is analyzed, but no research is conducted on whether regional differences and influencing factors can affect and restrict the green development of marine economy driven by marine scientific and technological innovation. It is necessary to fully discover and understand the influence of these different factors on the green development of marine economy driven by marine scientific and technological innovation, attach importance to marine scientific and technological innovation, optimize the relevant environment and make it play its full role, so as to promote the development of marine economy and achieve all-round progress. As the influence of external conditions does exist, if the impact on the green development of marine economy driven by marine scientific and technological innovation is ignored in future work and the emphasis is put on improving marine scientific and technological innovation, it is likely to run counter to the purpose of promoting the green development of marine economy. In this study, based on panel data, the econometric model is introduced to make an in-depth study on this topic, and the countermeasures and suggestions for optimizing marine scientific and technological innovation to drive the green development of marine economy are discussed.

Data and variable description

The data in this study are from China Ocean Statistics Yearbook (2009–2018), China Statistics Yearbook (2009–2018) and China Financial Yearbook (2009–2018). The main variables are selected as follows:

Explained variables

Green Development of Marine Economy (MEC). Referring to the previous literature results (Li, 2011; Wang, 2013a; Cheng, 2013; Yin, 2013), in view of the availability and comparability of data, the indicator system is this study is mainly constructed from the total marine economy, marine economic structure, marine economic effect and marine ecological civilization, and the weights are determined by using principal component analysis method based on the previous research results (Table 1).

Core explanatory variable

Marine Scientific and Technological Innovation (MST). With reference to previous research results (Yin, 2008; Ni, 2010; Ma, 2012; Jing and Zhang, 2014), the principal component analysis is used in this study to determine the weight based on the previous research results. (Table 2).

Control variable

Opening to the outside world (OPEN)

Referring to the previous research results (Sun and Wan, 2011; Zhang et al., 2013; Dong and Yan, 2015a), in this study, the proportion of the total import and export volume in GDP of each region is used to measure the regional opening up.

TABLE 2 MST evaluation indicator system.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Weights
MST	Basic marine research	Number of marine scientific research institutions	0.0570
		Total number of marine professional and technical personnel	0.0975
		Total number of talents with senior titles	0.0995
		Proportion of professional and technical personnel in marine scientific research institutions with senior professional titles	0.0397
		Total investment of marine scientific research institutions (1,000 yuan)	0.1037
	Marine application research	Number of marine scientific papers published	0.0843
		Number of marine scientific and technological patents accepted	0.0933
		Number of patents granted for marine scientific and technological	0.0955
		Number of marine scientific and technological projects	0.0915
	Marine research and development	Number of achievement application projects	0.0797
		Transformation rate of scientific and technological achievements	0.0176
		Total output value of industrialization of marine scientific and technological achievements	0.0831
		The proportion of the total output value of industrialization of marine scientific and technological achievements to the total output value of marine industry	0.0571

TABLE 3 FD comprehensive indicator system.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Weights
FD	Scale of financial development	Gross output value of financial industry in each province/GDP in each province	0.3560
	Structure of financial development	The proportion of on-the-job personnel in the financial industry to the total employed personnel	0.3211
	Efficiency of financial development	Loan-deposit ratio of financial institutions	0.3229

TABLE 4 Descriptive statistics of main variables.

Variable	Obs	Mean	Std. Dev	Min	Max
MEC	110	5.6268	0.7318	3.6063	6.6164
MST	110	9.2285	2.8631	1.1500	13.1774
OPEN	110	0.0901	0.0606	0.0004	0.2291
FD	110	0.3342	0.0532	0.0616	0.5396
HC	110	11.2074	0.9737	9.5539	13.8637
GI	110	0.5640	0.3561	0.0392	1.6028
TI	110	0.4699	0.0937	0.0493	0.6389

Financial development (FD)

Referring to previous research results (Huang et al., 2014; Yang, 2014; Geng et al., 2015; Xin and Liu, 2015; Zhan and Shan, 2016), in this study, the indicator system is mainly constructed from three aspects: financial development scale, financial development structure and financial development efficiency, and the weight is determined by using principal component analysis based on the previous research results (Table 3).

Human capital (HC)

The level of human capital is directly related to the final result, which can be measured by many methods, but various factors should be fully considered in the selection, such as the availability of data first, because the follow-up research can be completed only if the relevant data are easily obtained, and then the feasibility of operation, which is also the technology for completing the research. In view of the above two factors, the method of Barro and Lee (2000) (Barro and Lee, 2000) is finally determined, that is, it is measured by the years of education of local residents. In this study, the proportion of employed people who are illiterate and semi-literate in China *1.5 + employed people who receive primary education *7.5 + employed people who receive junior high school education *10.5 + employed people who receive high school education *13.5 + employed people who receive junior college or above *17 is adopted.

Government investment (GI)

Referring to the previous research results (Wang, 2013b; Yu and Yang, 2018), in this study, the proportion of science and technology expenditure to GDP is measured by the methods commonly used in most literatures.

Technology input (TI)

Referring to the previous research results (Dong and Yan, 2015b; Sheng and Xu, 2018), in this study, most of the methods commonly used in the literatures are used to measure the proportion of technology transactions in GDP. The descriptive statistics of the mainindicators are shown in Table 4.

Model setup

Basic model setup

Solow model (Lewis, 1996) is the representative of the neoclassical economic growth theory model in the specific form of

$$Y_t = Af(K_t, L_t) \tag{1}$$

$$MEC_{it} = A_{it} MST_{it}^{\alpha} \mathrm{HC}_{it} \tag{2}$$

where,

MEC = green development of marine economy; M.

ST = marine scientific and technological innovation;

A = technical efficiency;

α = output elasticity of marine scientific and technological innovation;

i = the province; t = the year.

Technical efficiency A of green development of marine economy consists of financial development FD, government investment GI and technical input TI, expressed as

$$A_{it} = e^{\phi T_i} \bullet FD_{it}^{\alpha} \bullet GI_{it}^{\beta} \bullet TI_{it}^{\lambda} \tag{3}$$

$$\begin{aligned} \mathrm{In}MEC_{\mathrm{it}} = \gamma_1 \mathrm{In}FD_{it} + \gamma_2 \mathrm{In}GI_{it} + \gamma_3 \mathrm{In}TI_{it} + \gamma_4 \mathrm{In}MST_{it} + \gamma_5 \mathrm{HC}_{\mathrm{it}} + \xi_i \\ + \varepsilon_{it} \end{aligned} \tag{4}$$

Taking the neoclassical economic growth model (Yu and Yang, 2018) as an example, the regression equation is set as follows:

$$\begin{aligned} \mathrm{In}MEC_{\mathrm{it}} = \gamma_0 + \gamma_1 \mathrm{In}FD_{it} + \gamma_2 \mathrm{In}GI_{it} + \gamma_3 \mathrm{In}TI_{it} + \gamma_4 \mathrm{In}MST_{it} \\ + \gamma_5 \mathrm{HC}_{\mathrm{it}} + \xi_i + \varepsilon_{it} \end{aligned} \tag{5}$$

Threshold model setup

$$MEC_{it} = A_{it} MST_{it}^{\alpha} \tag{6}$$

Therefore, with reference to Hansen threshold regression model (Wang and Han, 2017; Xu and Li, 2022), a double-threshold regression model of marine scientific and technological innovation and green development of marine economy is established based on formula (5).

Opening to the outside world as a threshold variable

Technical efficiency A of green development of marine economy consists of financial development FD, human capital HC, government investment GI and technical input TI. Therefore, technical efficiency A can be expressed as:

$$A_{it} = e^{\phi T_i} \bullet FD_{it}^{\lambda_1} \bullet HC_{it}^{\lambda_2} \bullet GI_{it}^{\lambda_3} \bullet TI_{it}^{\lambda_4} \tag{7}$$

$$\begin{aligned} \ln MEC_{it} = \lambda_1 \ln FD_{it} + \lambda_2 \ln HC_{it} + \lambda_3 \ln GI_{it} + \lambda_4 \ln TI_{it} \\ + \alpha_1 \ln(MST) \bullet I(\ln OPEN \le \theta_1) \\ + \alpha_2 \ln(MST) \bullet I(\theta_1 < \ln OPEN \le \theta_2) \\ + \alpha_3 \ln(MST) \bullet I(\ln OPEN > \theta_3) + \phi T + \varepsilon_{it} \end{aligned} \tag{8}$$

Financial development as a threshold variable

Technical efficiency A of green development of marine economy consists of opening to the outside world OPEN, human capital HC, government investment GI and technical input TI. Therefore, technical efficiency A can be expressed as:

$$A_{it} = e^{\phi T_i} \bullet OPEN_{it}^{\lambda_1} \bullet HC_{it}^{\lambda_2} \bullet GI_{it}^{\lambda_3} \bullet TI_{it}^{\lambda_4} \tag{9}$$

$$\begin{aligned} \ln MEC_{it} = \lambda_1 \ln OPEN_{it} + \lambda_2 \ln HC_{it} + \lambda_3 \ln GI_{it} + \lambda_4 \ln TI_{it} \\ + \alpha_1 \ln(MST) \bullet I(\ln FD \le \sigma_1) \\ + \alpha_2 \ln(MST) \bullet I(\sigma_1 < \ln FD \le \sigma_2) \\ + \alpha_3 \ln(MST) \bullet I(\ln FD > \sigma_3) + \phi T + \varepsilon_{it} \end{aligned} \tag{10}$$

Human capital as a threshold variable

Technical efficiency A of green development of marine economy consists of opening to the outside world OPEN, financial development FD, government investment GI and technical input TI. Therefore, technical efficiency A can be expressed as:

$$A_{it} = e^{\phi T_i} \bullet OPEN_{it}^{\lambda_1} \bullet FD_{it}^{\lambda_2} \bullet GI_{it}^{\lambda_3} \bullet TI_{it}^{\lambda_4} \tag{11}$$

$$\begin{aligned} \ln MEC_{it} = \lambda_1 \ln OPEN_{it} + \lambda_2 \ln FD_{it} + \lambda_3 \ln GI_{it} + \lambda_4 \ln TI_{it} \\ + \alpha_1 \ln(MST) \bullet I(\ln HC \le \sigma_1) \\ + \alpha_2 \ln(MST) \bullet I(\sigma_1 < \ln HC \le \sigma_2) \\ + \alpha_3 \ln(MST) \bullet I(\ln HC > \sigma_3) + \phi T + \varepsilon_{it} \end{aligned} \tag{12}$$

Government investment as a threshold variable

Technical efficiency A of green development of marine economy consists of opening to the outside world OPEN, financial development FD, human capital HC and technical input TI. Therefore, technical efficiency A can be expressed as:

$$A_{it} = e^{\phi T_i} \bullet OPEN_{it}^{\lambda_1} \bullet FD_{it}^{\lambda_2} \bullet HC_{it}^{\lambda_3} \bullet TI_{it}^{\lambda_4} \tag{13}$$

$$\begin{aligned} \ln MEC_{it} = \lambda_1 \ln OPEN_{it} + \lambda_2 \ln FD_{it} + \lambda_3 \ln HC_{it} + \lambda_4 \ln TI_{it} \\ + \alpha_1 \ln(MST) \bullet I(\ln GI \le \sigma_1) \\ + \alpha_2 \ln(MST) \bullet I(\sigma_1 < \ln GI \le \sigma_2) \\ + \alpha_3 \ln(MST) \bullet I(\ln GI > \sigma_3) + \phi T + \varepsilon_{it} \end{aligned} \tag{14}$$

Technical input as a threshold variable

Technical efficiency A of green development of marine economy consists of opening to the outside world OPEN, financial development FD, human capital HC and government investment GI. Therefore, technical efficiency A can be expressed as:

$$A_{it} = e^{\phi T_i} \bullet OPEN_{it}^{\lambda_1} \bullet FD_{it}^{\lambda_2} \bullet HC_{it}^{\lambda_3} \bullet GI_{it}^{\lambda_4} \tag{15}$$

$$\begin{aligned} \ln MEC_{it} = \lambda_1 \ln OPEN_{it} + \lambda_2 \ln FD_{it} + \lambda_3 \ln HC_{it} + \lambda_4 \ln GI_{it} \\ + \alpha_1 \ln(MST) \bullet I(\ln TI \le \sigma_1) \\ + \alpha_2 \ln(MST) \bullet I(\sigma_1 < \ln TI \le \sigma_2) \\ + \alpha_3 \ln(MST) \bullet I(\ln TI > \sigma_3) + \phi T + \varepsilon_{it} \end{aligned} \tag{16}$$

Theoretical analysis and research hypotheses

In reality, it is difficult to show a simple linear relationship in the process of marine scientific and technological innovation driving the green development of marine economy in eleven coastal provinces and cities in China, and many factors may have an impact on the driving process, that is, there may be certain "threshold" characteristics in the process of marine scientific and technological innovation driving the green development of marine economy. When the marine scientific and technological innovation ability of the region reaches a certain threshold, the green development of marine economy develops significantly under the influence of factors. Considering that there is little research on the threshold characteristics of marine scientific and technological innovation driving green development of marine economy in the existing literature, this study reviews the relevant literature and finds that the green development of marine economy driven by marine scientific and technological innovation is likely to result from the differences of five factors, i.e., local opening to the outside world, financial development, human capital, government investment and technology investment.

Opening to the outside world

With the continuous acceleration of the process of economic globalization, marine scientific and technological innovation and marine economic development are all affected to varying degrees by the external impact brought by the opening to the outside world, especially when China's marine scientific and technological development starts later than that of western developed countries, some of the marine high-end technological innovation still rely on the replication and transformation of imported technologies. Therefore, the higher the degree of opening to the outside world, the easier it is for all scientific and technological innovation subjects in the industry to come into contact with the world's most cutting-edge and top-notch technologies and products, so as to help each subject better understand the global technology market trends and enhance the effectiveness and timeliness of scientific and technological innovation (Leamer, 1995). At the same time, the improvement of opening to the outside world can effectively accelerate the flow of innovative elements such as domestic marine scientific and technological talents, promote the optimization process of innovative resource allocation (Lai et al., 1995), and further enhance the level of industrial economic development (Wang, 2018). Thus, the following hypothesis is made.

H_1: The degree of opening to the outside world has a positive impact on green development of marine economy driven by marine scientific and technological innovation.

Financial development

The process of marine scientific and technological innovation is a high-investment, high-risk and high-return technological research and development process, which relies on the support of sufficient research and development funding resources in addition to hidden resources such as knowledge and technology. At present, there are three main sources of R&D funds: government investment, investment from innovative subjects such as enterprises, and investment from financial institutions. Compared with the former two kinds of investment, financial institutions have a larger amount of capital investment, which has a more severe impact on the overall innovation process. The researches have shown that new technological innovation needs a large amount of long-term and continuous R&D funding, and it is far from meeting the needs of technological innovation only relying on government special funds investment and innovation subject's own R&D funding support. However, even enterprises with rich innovation resources and huge financial support have external financing in the process of technological innovation. Based on the intervention of financial institutions, enterprises can effectively transfer innovation risks, at the same time, increase R&D capital investment, ensure the continuity and effectiveness of R&D expenditure investment, and further promote innovation efficiency. Thus, the following hypothesis is made:

H_2: Financial development has a positive impact on the green development of marine economy driven by marine high-tech innovation.

Human capital

Human capital, as an indispensable element in marine scientific and technological innovation activities, is also an important foundation for marine economic development, and plays an important driving force in the process of marine economic development driven by marine scientific and technological innovation. In essence, marine scientific and technological innovation activities are the innovation activities of knowledge and foundation, while the main carrier of tacit resources such as knowledge is the talents with knowledge and skills in related fields. Therefore, it can be considered that the investment of human capital is in essence the input of knowledge and technology, as well as the basic elements in scientific and technological innovation activities. The direct influence in the process of technology-driven industrial economic development is reflected in the impact of technological innovation products on economic development. Fundamentally, the scientific and technological innovation products are formed depending on the input of knowledge and technology, that is, the input degree of human capital in the process of marine scientific and technological innovation. Previous studies have proved that the intensity of human capital investment has a direct and significant impact on the process of scientific and technological innovation to promote industrial economic development, and the degree of impact increases with the increase in intensity of human capital investment (Aigner et al., 1977).Thus, the following hypothesis is made.

H_3: Human capital input has a positive impact on the green development of marine economy driven by marine scientific and technological innovation.

Government investment

In the process of marine scientific and technological innovation driving the green development of marine economy, government departments play the role of guiding, promoting and guaranteeing macro-control. First of all, marine scientific and technological innovation activities are the process of effective integration of relevant innovation resources. The flow process of knowledge, technology and R&D funds needs to be carried out under the policy and legal framework, and any resource flow beyond the framework is invalid. In addition, the government's influence on scientific and technological innovation is also reflected in funding. As mentioned above, the current financial support for marine scientific and technological innovation activities mainly comes from three aspects, among which financial investment is one of the important sources of innovation funds. Secondly, the green development of marine economy cannot be separated from the investment and support of government departments. On the one hand, government departments provide goal orientation and

TABLE 5 Panel data, fixed effect and random effect model estimation.

Provinces and cities	Variables	Panel data			Test result
		Ols	Fixed effect	Random effect	
Eleven coastal provinces and cities	MST	0.1681*** (4.55)	0.1221*** (4.81)	0.1294*** (5.27)	Wald test of fixed effect: F (10,92) = 48.32 Huasman test of random effect: chi2(4) = 21.58
	FD	0.0465* (1.87)	0.0642* (1.76)	0.0522* (1.66)	
	HC	0.0420** (1.98)	0.0127* (1.86)	0.0645** (2.16)	
	GI	−0.1687* (−1.81)	0.1304* (1.66)	0.1660* (1.79)	
	TI	0.0185* (1.75)	0.0423** (2.05)	0.0127* (1.66)	
	Coefficient	0.1583*** (3.11)	0.5069*** (6.10)	0.5713*** (5.66)	
	R^2	0.6832	0.6955	0.6242	
Circum-Bohai Sea Economic Zone	MST	0.4192*** (5.53)	0.3609* (1.85)	0.1491*** (3.42)	Wald test of fixed effect: F (3,29) = 37.42 Huasman test of random effect: chi2 (4) = 43.66
	FD	0.1470 (0.78)	0.0391* (1.71)	0.1592 (0.55)	
	HC	0.1294* (1.77)	0.0106* (1.68)	0.0619 (0.98)	
	GI	−0.3027*** (−3.32)	0.3016*** (3.23)	0.2172*** (3.04)	
	TI	0.0103* (1.66)	0.1065* (1.72)	0.0101 (1.32)	
	Coefficient	0.3316** (2.31)	0.4383*** (3.66)	0.4587*** (3.84)	
	R^2	0.6186	0.6596	0.6015	
Yangtze River Delta Economic Zone	MST	0.6485** (2.15)	0.1413*** (3.14)	0.3465* (1.69)	Wald test of fixed effect: F (4, 39) = 47.42 Huasman test of random effect: chi2 (4) = 51.36
	FD	0.0633* (1.74)	0.0646 (0.37)	0.0363* (1.67)	
	HC	0.1021* (1.64)	0.0474* (1.70)	0.1821* (1.90)	
	GI	−0.2212** (−2.14)	0.2591* (2.25)	0.2424* (2.20)	
	TI	0.0641** (2.14)	0.1990* (1.90)	0.0447* (1.68)	
	Coefficient	0.4521* (1.93)	0.4371* (1.81)	0.4472* (1.83)	
	R^2	0.6320	0.6822	0.6105	
Pearl River Delta Economic Zone	MST	0.2006** (2.64)	0.0975* (2.17)	0.2620** (2.44)	Wald test of fixed effect: F (3, 20) = 20.42 Huasman test of random effect: chi2 (4) = 16.48
	FD	0.0569** (2.14)	0.0656** (2.37)	0.0616** (2.21)	
	HC	0.1659** (2.39)	0.0573** (2.31)	0.1251** (2.10)	
	GI	−0.1845** (2.26)	0.2860** (2.60)	−0.0875* (2.09)	
	TI	0.0652** (2.37)	0.1266** (2.12)	0.0544** (2.27)	
	Coefficient	0.5872*** (4.87)	0.4308*** (3.65)	0.4231*** (3.44)	
	R^2	0.6413	0.6609	0.6302	

overall planning for the green development of the marine economy, and promote all economies in the marine industry to move forward in the direction of government planning through policy input, project establishment and other means, and strive to promote the green development of the marine economy. At the same time, the market's own mediation ability can no longer meet the needs of green development of marine economy due to the complex effect of the green development of marine economy and its variability, so it is necessary to rely on the government's macro-control ability to maintain the steady, rapid and high development of marine economy. On the other hand, government investment can effectively ensure the steady progress of green development of marine economy, and provide a healthy external environment guarantee for green development of marine economy through policies, regulations and other measures. Thus, the following hypothesis is made.

H_4: Government investment has a positive impact on the green development of marine economy driven by marine scientific and technological innovation.

Technical input

The intensity of technical input is one of the important indicators to measure the level of investment in marine scientific and technological innovation resources. Generally speaking, the higher the intensity of technical investment, the stronger the innovation ability of marine science and technology, and the more obvious its driving effect on the green development of marine economy. Relevant studies have shown that green development of marine economy driven by scientific and technological innovation is largely affected by the intensity of technical input. The different intensity of technical input leads to significant differences in the effect of green development of marine economy driven by scientific and technological innovation in different regions. The stronger the intensity of technical input, the stronger the driving ability, and the more obvious the result. Thus, the following hypothesis is made.

H_5: The intensity of technical input has a positive impact on the green development of marine economy driven by marine scientific and technological innovation.

Empirical analysis

Model results and analysis

According to Table 5, among the estimation results of OLS, fixed effect and random effect models in eleven coastal provinces and cities of China and Circum-Bohai Sea Economic Zone, Yangtze River Delta Economic Zone and Pearl River Delta Economic Zone divided by marine economic belt, Wald F test value of fixed effect and LM test value of random effect model show that the original hypothesis of OLS should be rejected and alternative hypothesis of fixed effect and random effect model should be accepted.

The test results in Table 5 show that according to R^2, the fitting degree of fixed effect of panel model is the best among the three models, followed by OLS method of panel data. Since the possible "pseudo-regression" problem of the series is not considered in the OLS method for panel data, the fixed-effect model is selected as the optimal one in terms of volume test and economic significance.

By analyzing the panel data of green development of marine economy driven by marine scientific and technological innovation in 11 coastal provinces and cities from 2008 to 2017, the regression equation is obtained as follows:

$$\begin{aligned}\mathrm{In}MEC_{it} &= 0.5069 + 0.0642\mathrm{In}FD_{it} + 0.1304\mathrm{In}GI_{it} + 0.0423\mathrm{In}TI_{it}\\ &+ 0.1221\mathrm{In}MST_{it} + 0.0127\mathrm{HC}_{\mathrm{it}}\end{aligned} \tag{17}$$

Equation 17 shows that in the whole regression model, government investment contributes the most to the high-quality development of marine economy, with a coefficient of 0.1304, followed by marine scientific and technological innovation, with an action coefficient of 0.1221 and a technology input coefficient of 0.0423, which is slightly higher than the contribution of human capital. The regression model accords with the hypothesis of neoclassical economic growth model and the current situation of marine economic development. Firstly, the neoclassical economic growth model holds that labor and capital can be replaced each other under perfect competition. With the development of science and technology, the contribution of single labor force to economy is far less than the force of science and technology to economic development. Furthermore, with the continuous development of the Internet and artificial intelligence, the functions of science and technology products are constantly being improved and gradually developing in the direction of replacing human resources. The model has shown that the contribution of technical input to the high-quality development of marine economy is greater than that of human capital, so the model is considered reasonable. Secondly, as far as the current situation of marine economic development is concerned, the development of marine economy mostly depends on the guidance of the government that the government fundamentally affects the development priorities of various industries of marine economy by adjusting the policies and the direction of capital investment, so as to further improve the quality of marine economic development. From the perspective of marine science and technology, most marine scientific and technological projects come from the government, so it can be considered that the government plays an essential role in promoting the development of marine science and technology. In the model, the strong collinearity of government investment to the high-quality development of marine economy has been shown. In conclusion, the model is reasonable.

According to the division of marine economic regions, the regression equation is divided into "Circum-Bohai Sea Economic Zone," "Yangtze River Delta Economic Zone" and "Pearl River Delta Economic Zone" for analysis one by one.

(1) Regression model for Circum-Bohai Sea Economic Zone

$$\begin{aligned}\mathrm{In}MEC_{it} &= 0.4383 + 0.0391\mathrm{In}FD_{it} + 0.3016\mathrm{In}GI_{it} + 0.1065\mathrm{In}TI_{it}\\ &+ 0.3609\mathrm{In}MST_{it} + 0.0106\mathrm{HC}_{\mathrm{it}}\end{aligned} \tag{18}$$

(2) Regression model for Yangtze River Delta Economic Zone

$$\begin{aligned}\mathrm{In}MEC_{it} &= 0.4371 + 0.0646\mathrm{In}FD_{it} + 0.2591\mathrm{In}GI_{it} + 0.1990\mathrm{In}TI_{it}\\ &+ 0.1413\mathrm{In}MST_{it} + 0.0474\mathrm{HC}_{\mathrm{it}}\end{aligned} \tag{19}$$

(3) Regression model for the Pearl River Delta Economic Zone

$$\begin{aligned}\mathrm{In}MEC_{it} &= 0.4308 + 0.0656\mathrm{In}FD_{it} + 0.2860\mathrm{In}GI_{it} + 0.1266\mathrm{In}TI_{it}\\ &+ 0.0975\mathrm{In}MST_{it} + 0.0573\mathrm{HC}_{\mathrm{it}}\end{aligned} \tag{20}$$

The comparison of the regression models of "three major economic zones" shows that the coefficients of each influencing factor in different regression models have little change, and the results are the same as those of the coastal zone model as a whole. Among them, the financial development and human capital in the Pearl River Delta region contribute more to the high-quality development of marine economy than other regions, reflecting two major characteristics: First, the Pearl River Delta Economic Zone has a better financial financing environment. Considering that Shenzhen and Guangzhou have a good foundation for financial development, they can communicate and cooperate with a wider range of financial institutions in the operation of the marine economy, thus enhancing the contribution of financial development to the high-quality development of the marine economy; Secondly, marine aquaculture, tourism and other

TABLE 6 Self-sampling test results of threshold effect of each threshold variable.

Threshold variables	Threshold types	F	p	Times of BS	Critical value			Threshold value	95% confidence interval
					1%	5%	10%		
Opening to the outside world	Single threshold	9.868*	0.092	300	16.799	10.741	7.338	0.54	[0.500,0.793]
	Double threshold	10.622	0.174	200	39.479	15.041	11.047		
	Triple threshold	−20.425	0.864	200	10.487	1.784	−3.518		
Government investment	Single threshold	13.471**	0.02	300	17.314	12.692	9.298	0.562	[0.559,0.572]
	Double threshold	19.7	0.155	200	50.361	37.973	30.106	0.979	[0.832,1.127]
	Triple threshold	0	0.2	200	0	0	0		
Financial development	Single threshold	15.537***	0.005	300	13.049	9.352	7.029	0.574	[0.532,0.618]
	Double threshold	23.449**	0.037	200	24.150	22.436	16.544	0.812	[0.804,0.859]
	Triple threshold	0	0.194	200	0	0	0		
Human capital	Single threshold	13.524***	0.003	300	12.068	10.828	8.808	0.534	[0.518,0.614]
	Double threshold	20.308**	0.048	200	23.234	18.732	16.557	0.743	[0.707,0.753]
	Triple threshold	0	0.227	200	0	0	0		
Technical input	Single threshold	13.613	0.242	300	21.033	18.425	15.311	0.322	[0.293,0.459]
	Double threshold	16.108	0.312	200	32.059	21.283	19.753	0.744	[0.685,0.753]
	Triple threshold	0	0.3	200	0	0	0		

industries in the Pearl River Delta Economic Zone are relatively developed, both of which need a lot of human resources as support. Therefore, the influence of human capital in this region is higher than that in other regions.

Compared with other regions, the Yangtze River Delta Economic Zone has a technical input that plays a more prominent role in the high-quality development of the marine economy, because it covers economically developed regions such as Shanghai and Zhejiang, and has a more active technology trading market, which can provide richer technical support for the development of the marine industry. Considering that the coefficient of marine scientific and technological innovation is lower than the regional technical input, it is believed that the science and technology that promotes the high-quality development of marine economy in the region mainly comes from the regional technology exchange market, rather than the regional marine scientific and technological innovation itself.

Equation 18 shows that the government investment and the contribution of marine scientific and technological innovation in the Circum-Bohai Sea Economic Zone are far greater than those in other regions. As mentioned above, the development of China's marine economy relies heavily on the government, which, while investing in policies, regulations and funds, tends to promote the development of the industrial economy by enhancing the industry's own scientific and technological innovation capabilities. This region not only contains the political center of our country, but also has a large number of marine scientific research institutions and marine economic research institutes, so the government investment and marine scientific and technological innovation in this region contribute more to the high-quality development of marine economy than other regions.

Factor analysis

Test of threshold effect

Threshold effect of marine scientific and technological innovation on marine economic growth is tested with opening to the outside world as the threshold variable. The threshold self-sampling tests are carried out under the assumptions of single threshold, double threshold and triple threshold respectively. In order to judge the threshold model to be selected, the F statistical value and the p-value obtained by Bootstrap method are used.

Table 6 shows the obtained results. The above-mentioned influencing factors are classified on this basis: factors with a significant threshold including two influencing factors of marine human capital and opening to the outside world, and factors with a double threshold including government investment and financial development. However, the above results are not available for the impact of technical input, and the threshold effect has not been detected. Whether the effect of productive force driven by development in science and technology will change due to this has not been determined yet, which needs further analysis.

Estimation and analysis of threshold model

It is necessary to carry out regression test on samples with different threshold intervals. On the basis of the results obtained above, various factors are investigated to determine their impact on marine scientific and technological innovation, whether the latter can drive the development of marine economy, and the role played therein and the subsequent degree of impact are interfered by various factors. Through analysis, different impacts generated by these factors are determined, so as to grasp their importance in

TABLE 7 Regression results of threshold model for each threshold variable.

	OPEN single	GI single	FD double	HC double
lgOPEN		0.0256* (1.84)	0.0185* (1.76)	0.0175* (1.66)
lgGI	0.0758** (2.24)		0.0386** (2.46)	0.0524** (2.14)
lgFD	0.0628* (1.87)	0.0424** (1.75)		0.0485* (1.66)
lgTI	0.0463* (1.82)	0.0498* (1.69)	0.0236* (1.77)	0.0442* (1.75)
lgHC	0.0370** (2.04)	0.0246** (2.27)	0.0329* (1.87)	
lgMST1	0.6433** (2.25)	0.6577** (2.37)	0.6121** (2.28)	0.6322** (2.45)
lgMST2	1.2332*** (3.12)	1.0423*** (2.66)	0.4892** (2.35)	1.0794*** (3.14)
LgMST3			0.5624** (2.30)	1.0974*** (3.34)
Constant	0.4748*** (4.88)	0.3451** (2.17)	\0.4537** (2.24)	0.3228** (2.15)
R^2	0.602	0.426	0.413	0.431

different threshold intervals and grasp their function characteristics. The test results are shown in Table 7.

Table 7 shows the results of threshold regression, indicating the changes of different threshold intervals. The action force of science and technology input presents different change characteristics here, which can be used to formulate accurate marine strategies and implement better policies for marine scientific and technological innovation to drive green development of marine economy. Specifically, there is a single threshold value of 0.54 for opening to the outside world (OPEN). When OPEN<0.54, the effect of marine scientific and technological innovation on the green development of marine economy is 0.6433, indicating that in this threshold interval, the green development of marine economy will be raised by 0.6433 for every 1% increase in marine scientific and technological innovation, and when opening to the outside world exceeds the threshold value, i.e., OPEN>0.54, the coefficient value is 1.2332, indicating that the improvement of opening to the outside world is beneficial to the exertion of marine science and technology. Thus, both of them change positively and play a positive role in promoting.

There is a single threshold value for the government investment (OPEN). When GI < 0.562, the effect of marine scientific and technological innovation on the green development of marine economy is 0.6577, indicating that in this threshold interval, the green development of marine economy will be raised by 0.6577 for every 1% increase in marine scientific and technological innovation. However, when the government investment exceeds the threshold value and GI > 0.562, the above coefficient value is 1.0423, which is obviously improved and changed compared with the original situation, indicating that the improvement of government investment is beneficial to the exertion of marine science and technology, and the two change positively and play a positive role in promoting.

Judging from two factors with double thresholds, there are two obvious thresholds for financial development (FD), which are 0.574 and 0.812 respectively. When the financial development is less than 0.574, the force coefficient of marine scientific and technological innovation driving the green development of marine economy is 0.6121, while when the financial development is 0.574 ≤ FD < 0.812, it decreases to 0.4892, when FD > 0.812, it rises greatly to 0.5624. Therefore, from the overall trend, the role of marine scientific and technological innovation in driving the green development of the marine economy is also on the rise with the increase in financial development, i.e., financial development is an important force for marine scientific and technological innovation to drive the green development of the marine economy, and plays a key role therein with positive effects. From the intermediate stage, the role of marine marine scientific and technological innovation in driving the green development of marine economy is slightly reduced, possibly because financial development and marine marine scientific and technological innovation are synchronized to a certain extent, and can grow together in some stages. The analysis of some samples from coastal provinces and cities shows that financial development can play a positive role in marine marine scientific and technological innovation and produce crowding-out effect.

The threshold value of human capital (HC) is 0.534 and 0.743, which constitute three intervals. The contribution coefficients of marine marine scientific and technological innovation to the green development of marine economy are 0.6322, 1.0794 and 1.0974, respectively, which clearly shows that human capital has played a positive role in this period and effectively promoted the effect of marine marine scientific and technological innovation. The capital invested by HC is positively related to the final force, which can effectively promote the marine marine scientific and technological innovation elements to play a role. This result suggests that there is a shortage of marine scientific and technological talents from the current domestic situation, which seriously restricts the application and popularization of marine science and technology, and marine scientific and technological talents are an important prerequisite for the green development of marine economy.

Conclusion

In this study, the panel data of eleven coastal provinces and cities in China from 2008 to 2017 are tested empirically, and the following conclusions are drawn:

With reference to previous literature (Chen and Ma, 2020; Cu, 2020; Wang et al., 2020; Wang et al., 2021; Zhao et al., 2022), according to the constructed neoclassical growth model that marine scientific and technological innovation driving the green development of marine economy, marine scientific and technological development and green development of marine economy are positively correlated on the whole, and all input variables promote economic development but with certain differences. Among them, government investment and marine scientific and technological innovation play the most prominent role in promoting the green development of marine economy, while the sharing degree of human capital is the weakest, reflecting that China's marine economy is now in the stage where science and technology gradually replace labor, which conforms to the development law of marine science and technology and marine economy in China. Based on the analysis of the growth models of "Circum-Bohai Sea Economic Zone," "Yangtze River Delta

Economic Zone" and "Pearl River Delta Economic Zone," at present, the promotion of science and technology to economic development in each marine economic zone is obvious, and the promotion of green development of regional marine economy varies by various input variables, which reflects that each economic zone fully considers its own regional characteristics and effectively allocates resources for different marine industry types in the process of enhancing marine scientific and technological innovation capability and promoting green development of marine economy (Ning and Song, 2020; Qin and Shen, 2020).

With reference to previous literature (Wang and Han, 2017), by building a panel threshold model, the five factors, namely opening to the outside world, government investment, financial development, human capital and technical input are examined, which contribute to the green development of marine economy driven by marine scientific and technological innovation. According to the empirical results, it is concluded that all kinds of external influencing factors will interfere with the role of marine scientific and technological innovation by means of promotion or restriction. The test results can be classified according to the threshold characteristics, including three factors: first, factors with significant thresholds, including opening to the outside world and government investment; second, factors with double thresholds, including financial development and human capital; third, technical input without thresholds. Thus it is proved that this result is closely related to many factors and is the result of their joint action. The role of marine scientific and technological innovation is affected by external factors under certain conditions with different forces for the green development of the marine economy, which hence should be fully taken into account when formulating the marine scientific and technological strategy and in the implementation of the policies (Aigner et al., 1977; Lai et al., 1995; Leamer, 1995; Wang, 2018).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

FW and FC are responsible for outlining and writing, TL is responsible for data processing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Waterfront ecotourism quality evaluation under the water ecological challenge in West Strait, China

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The relationship between tourism activities and water ecological degradation has become a challenge that cannot be ignored. However, only few studies have evaluated the sustainability of waterfront tourism. This paper takes the West Strait of China, which is rich in ecological resources, as the research object, constructs the evaluation framework of waterfront ecotourism through two rounds of expert consultation, and determines the weights of the following indicators based on Fuzzy Comprehensive Evaluation (FCE): Waterfront Tourism Design (0.112), Ecotourism Experience (0.034), Aquatic Ecological Knowledge Sharing (0.147), Pro-Water Culture (0.238), Pro-Water Identity (0.134), Aesthetic Value of Water Landscape (0.128), Pro-Water City Brand (0.036), Infrastructure Construction (0.061), Regional Economic Development (0.046), Folkway Support (0.028), Government Policy Support (0.036). Data collection in the 5 core cities in West Strait shows that Pro-Water Culture (U4) had the most significant impact, followed by Aquatic Ecological Knowledge Sharing (U3). Pro-Water City Brand (U7) and Folkway Support (U10) have negligible effects on waterfront ecotourism. The weight range distribution is relatively average except for the four above mentioned indicators.

KEYWORDS

waterfront ecology, quality evaluation, FCE, west strait, China

1 Introduction

With the continuous improvement of people's living standard, the traditional way of tourism has been unable to meet the needs of tourism industry. People have begun to pursue more diversified tourism experiences. Waterfront tourism is an economic behavior that satisfies residents' demand for leisure, entertainment and sightseeing by utilizing waterfront resources. Waterfront tourism has become one of the fundamental driving forces of coastal economic development (Holden, 2018; Lu et al., 2019; Arabadzhyan et al., 2021). However, it is also one of the main factors causing the degradation of water ecology. In recent years, the relationship between tourism activities and water environment has been deeply studied. These studies mainly focus on the report of the *status quo* of water environment in different tourist destinations, the impact of tourism activities on water quality and flow, and the investigation of water environment management in tourist destinations. For example, Sun and Liu (2020) studied the interference factors of tourism activities on the water quality of reservoirs, Moreira and Santos (2010) analyzed the impact of different types of tourism on the water environment, and Gedik and Mugan-

Ertugral (2019) evaluated the maximum carrying capacity of the water environment of public tourist attractions. Among previous literature, the significant correlations between tourism activities and water quality in China has been well demonstrated. Chen et al. (2021) studied the causes and consequences of water quality deterioration caused by tourism development by taking traditional villages in Huizhou, which is rich in freshwater resources, as the research object. He listed the construction of man-made facilities during tourism development such as: sewage treatment stations, artificial wetlands, coastal resorts and hotels as the main causes of water pollution, which would cause the bay ecology of coastal tourist cities to receive serious damage. Furthermore, tourism water usage is also widely focused. Shen et al. (2020) followed Sánchez-Martín et al. (2020) and studied the tourism water use in China's Tingxi reservoir and demonstrated the significant influence of tourism on local water waste.

Although the correlation between the water environment and tourism has been well studied from many aspects, the ecological development of waterfront tourism has received much resistance in practice. Liu et al. (2017) pointed out that the overall development of China's waterfront tourism is poor due to the large differences in ecological environment and economic composition among different regions and the lack of environmental regulations and governance. The main problems of China's waterfront tourism are the poor performance of ecological service innovation and regional ecological protection (Yang, 2022). More and more Chinese scholars have begun to call for the concept of 'waterfront ecotourism' since the over-exploitation of water resources in tourism areas has harmed regional sustainable development (Shan, 2020). However, there is still no relevant evaluation framework and data collection on the construction of waterfront ecotourism, which constitutes the research objective of the present study.

In order to explore the evaluation of waterfront ecotourism, the West Taiwan Strait City Belt (also called: West Strait) in the southern China is selected as the research area. Affected by the climate, southern China has a lower latitude and a pleasant climate. In particular, the West Strait is rich in water resources, which is the area where tourists like to carry out waterfront and water activities (Zan and Xijun, 2014). In December 2009, China issued the Plan for the Coordinated Development of Urban Agglomeration on the West Strait. In this plan, ecological and environmental protection has been strongly promoted, especially in the five core cities of the West Strait: Fuzhou, Quanzhou, Xiamen, Wenzhou, and Shantou. However, the effectiveness of the ecological governance has not been evaluated so far. Therefore, the five core cities of the West Coast urban agglomeration are selected as the target of the study, and eleven evaluation indexes are constructed for their waterfront ecotourism based on previous research theories on tourism system through fuzzy comprehensive evaluation (FCE) method, and their current situation is measured.

2 Evaluation framework construction

2.1 Framework construction

2.1.1 Fuzzy comprehensive evaluation (FCE)

The fuzzy comprehensive evaluation (FCE) is a method based on membership theory that can transform qualitative evaluation into quantitative evaluation. It is highly systematic with accurate results and can deal with problems that are difficult to be quantified. In 1965, Professor Zadeh developed the theory of fuzzy mathematics by combining mathematics with fuzzy fields. In recent decades, fuzzy mathematics has been widely applied and achieved outstanding outcomes across various disciplines. FCE has been widely used in ecological environment evaluation and sustainability index construction for its superiority in measuring sophisticated influencing factors. FCE has been seen as an ideal way to realize ecotourism evaluation (Zabihi et al., 2020; Wen et al., 2021; Ma and Tang, 2022; Zhu and Jiang, 2022). As with other ecotourism evaluations in the past, the factors drive the high-quality development of waterfront ecotourism are multi-faceted. It is a fuzzy decision to determine which factor has a greater impact on the tourism quality evaluation system, because each tourist and expert's evaluation is different. Therefore, it is appropriate to use FCE method for the intended evaluation. Table 1.

2.1.2 Evaluation indicators

Wu (1998) first introduced the tourism system theory that the tourism system mainly includes four aspects: the market system (also called: tourist source system), the travel system, the destination system, and the support system. This theory has guided the evaluation of tourism quality in the past, and has been used to establish the evaluation frameworks of coastal, marine and ecological tourisms (Ruan et al., 2019; Peihai et al., 2020; Ota et al., 2022). The study most similar to the waterfront ecotourism evaluation is Zheng and Hu's (2022) exploration of marine tourism based on FCE. Thus, the *Marine Tourism High-Quality Development Evaluation Framework*established by Zheng and Hu (2022) is referred in the present study and revised the proposed three evaluation dimensions.

In order to identify and construct the evaluation indicators, first of all, the factors affecting the quality of waterfront ecotourism were qualitatively understood. During the identification process, a total of 16 experts, 6 waterfront tourism researchers, 6 scenic spot managers and 4 staff of the Wenzhou Culture and Tourism Bureau were consulted, and the weight of waterfront ecotourism evaluation index was then obtained. They were also invited to give an unbiased assessment of the identified waterfront ecotourism indicators. The specific process of indicator selection and data collection is as follows. Two rounds of consultation were conducted:

The first round was to screen the evaluation indicators of waterfront ecotourism to confirm the impact factors included in the calculation model. Through evaluation and screening, 11 key evaluation indicators were selected: Waterfront Tourism Design (U1), Ecotourism Experience (U2), Aquatic Ecological Knowledge Sharing (U3), Pro-Water Culture (U4), Pro-Water Identity (U5), Aesthetic Value of Water Landscape (U6), Pro-Water City Brand (U7), Infrastructure Construction (U8), Regional Economic Development (U9), Folkway Support (U10), Government Policy Support (U11). Then, the definition of the indicators is revised to ensure the rigor of the content and prevent ambiguity (The meaning of "pro-water" mainly refers to the fact that tourists' choice of tourist destinations will prefer cities with water resources, such as lakes, rivers, and oceans, as

TABLE 1 Evaluation framework of waterfront ecotourism.

Primary index	Secondary index	Definitions
Waterfront Protection	Waterfront Tourism Design (U1)	The consideration of ecological protection in the design of waterfront tourism routes and tourism products
	Ecotourism Experience (U2)	The ability to strike a balance between tourism experience and waterfront ecological conservation
	Aquatic Ecological Knowledge Sharing (U3)	The ability to communicate and share waterfront ecotourism knowledge with tourists through multiple media channels, methods and means
Ecological Value	Pro-Water Culture (U4)	The ability of tourists to understand the cultural connotation of water protection after traveling
	Pro-Water Identity (U5)	Tourists' identification of 'pro-water' identity after travelling
	Aesthetic Value of Water Landscape (U6)	Tourists' recognition of the aesthetic value of water landscape
	Pro-Water City Brand (U7)	Tourists' recognition of the city's brand value brought by waterfront ecology and water environment protection
Social-Economic Support	Infrastructure Construction (U8)	The construction of basic infrastructures for appealing tourists
	Regional Economic Development (U9)	The perceived regional economic support for waterfront ecotourism
	Folkway Support (U10)	Tourists' cognition and recognition of local water-related folk customs
	Government Policy Support (U11)	The perceived governmental policy support for waterfront ecotourism

the main tourist resources). The pro-water concept here was derived from the studies of pro-environmental psychology (Liu et al., 2020; Chen and Zhang, 2021; Zhang et al., 2022).

In the second round, were asked to rate the importance of each of the 11 indicators on a 5-Point Likert Scale. Specifically, each indicator was measured with five points [5,4,3,2,1]. A range from five to one indicates a difference in importance, with the importance decreasing in turn. The collected data are normalized to obtain the weight set of evaluation indicators A, where:

A = [0.112.0.034.0.147.0.238.0.134.0.128.0.036.0.061.0.046. 0.028.0.036].

2.2 Mathematics expression

Indicator weights can be determined by subjective or objective assignment methods. The entropy method is one of the objective assignment methods and has been widely used in studies related to indicator systems. The entropy method is one of the objective assignment methods and has been widely used in studies related to indicator systems (Tang and Liu, 2014).

If we let Z represents the quality of waterfront ecotourism, the fuzzy function for Z is:

$$Z = W^{*}C \tag{1}$$

Where: W is the weight set of waterfront tourism evaluation indicators, C is the comment sets of consulted experts to the indicators.

The weight set W is determined as following equations:

$$W = \left(\frac{m_1}{\sum_{i=1}^{n_1} m_i}, \frac{m_2}{\sum_{i=1}^{n_1} m_i} \cdots\cdots \frac{m_n}{\sum_{i=1}^{n_1} m_i} \right) \tag{2}$$

$$m_i = \frac{1}{w} \sum_{j=1}^{n_2} m_{ij} \tag{3}$$

Where: n_1 is the number of waterfront ecotourism evaluation indicators, m_{ij} is the comment of the ith evaluation indicator from the jth expert, n_2 is the number of experts.

The comment sets are determined as follows:

$$C = \begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1q} \\ c_{21} & c_{22} & \cdots & c_{2q} \\ \cdots & \cdots & \cdots & \cdots \\ c_{n1} & c_{n2} & \cdots & c_{nq} \end{pmatrix} \tag{4}$$

Where: n is the number of waterfronts tourism evaluation indicators, q is the evaluation score from the expert to waterfront ecotourism, c_{ij} is the degree of membership of ith index to jth evaluation score, and $\sum_{j=1}^{q} c_{ij} = 1, i = 1, 2, \cdots, n; j = 1, 2, \cdots, q$.

3 Result and discussion

Based on the above methods, we take Fuzhou, Quanzhou, Xiamen, Wenzhou, Shantou as the object of study. Among the selected cities, Fuzhou has the highest GDP, which can reflect the impact of economic aggregate on waterfront ecotourism. The waterfront economy of Wenzhou has been developing for the longest time, but the local waterfront ecotourism started late. Although Xiamen has a relatively small economic aggregate, its *per capita* GDP is the highest among the five cities and it is well known as a tourist city. Although Shantou is also a tourist city, its tourism is not famous for seaside tourism, but for its unique food resources. According to 11 indicators, we designed a questionnaire for tourists and invited them to evaluate five waterfront tourist destinations (the respondents answered the questions according to their last travel experience in a certain place, if none of the five places are available, they did not fill in the questionnaire). A 5-Point Likert Scale questionnaire was designed to ask tourists to make a single choice. In this

TABLE 2 Comment sets.

Object	Rank	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11
Weight		0.112	0.034	0.147	0.238	0.134	0.128	0.036	0.061	0.046	0.028	0.036
Fuzhou	5	38	19	20	4	40	53	43	31	24	20	46
	4	61	51	61	55	69	60	73	53	57	49	57
	3	52	70	62	71	35	40	35	56	55	76	52
	2	7	9	4	21	7	9	7	9	13	13	5
	1	7	16	18	14	14	3	7	16	16	7	5
Quanzhou	5	41	28	33	35	32	43	41	32	26	31	44
	4	66	61	63	57	71	75	77	58	56	52	61
	3	52	68	63	71	60	45	51	67	71	68	58
	2	18	18	22	16	14	12	8	18	18	20	16
	1	8	10	4	6	8	10	8	10	14	14	6
Xiamen	5	34	19	16	27	27	22	26	28	25	28	33
	4	42	39	46	36	49	54	57	50	36	35	44
	3	35	52	53	53	40	43	38	37	49	46	45
	2	13	13	11	9	8	4	3	8	10	11	2
	1	4	5	2	3	4	5	4	5	8	8	4
Wenzhou	5	38	19	18	27	31	24	27	32	9	27	40
	4	47	41	52	41	46	51	61	47	42	40	46
	3	39	52	50	52	45	45	38	38	55	52	42
	2	6	16	14	12	8	8	6	11	18	5	4
	1	8	10	4	6	8	10	6	10	14	14	6
Shantou	5	46	31	24	39	28	50	46	37	29	15	50
	4	70	75	70	63	79	77	84	68	58	67	68
	3	58	58	70	68	58	49	18	56	79	76	65
	2	9	19	24	16	18	11	35	20	19	22	6
	1	9	9	4	6	9	5	9	11	7	12	3

survey, members of the research team pushed the electronic questionnaire link to the we-media in their hometown, and invited respondents to fill in the questionnaire. A total of 808 valid questionnaires were collected, among which 165 were evaluated in Fuzhou, 185 in Quanzhou, 128 in Xiamen, 138 in Wenzhou and 192 in Shantou. The comments set of five regions were collected, as shown in Table 2. The comment sets in Table 2 were then normalized respectively to obtain the membership degree and the normalized membership degree (weight), as shown in Table 3.

By analysing the result vector, it can be found that when the index is summed up with the total evaluation membership degree of 3 and above, the scores of each city are 0.61, 0.665, 0.687, 0.672 and 0.706 respectively. After summing the total evaluation membership degree of 4 and above, the scores of each city are 0.372, 0.427, 0.449, 0.434 and 0.441 respectively. It can be seen that Shantou and Xiamen have the highest overall evaluation and Fuzhou has the lowest score. In general, from the perspective of tourist cognition, it can be observed that the positive evaluation of tourism in the five cities is mostly, with scores above 0.6 for each city and 0.4 for scores above 4, and the highest value is 0.449, which is less than half, indicating that the performance of waterfront ecotourism in service quality is not satisfactory. According to the observation of the membership degree of 2 and below, it can be found that Xiamen and Quanzhou have the lowest proportion of poor evaluation, followed by Shantou. The overall evaluation of Fuzhou is poor, which indicates that the economic aggregate has no obvious help to waterfront ecotourism. The overall evaluation of tourism in Fuzhou city is poor, indicating that the economic

TABLE 3 Degree of membership.

City	Membership indexes	5	4	3	2	1
Fuzhou	Membership degree	0.134	0.238	0.238	0.127	0.109
	Weight	0.158	0.281	0.281	0.15	0.129
Quanzhou	Membership degree	0.189	0.238	0.238	0.119	0.054
	Weight	0.226	0.284	0.284	0.142	0.064
Xiamen	Membership degree	0.211	0.238	0.238	0.102	0.046
	Weight	0.253	0.285	0.285	0.122	0.055
Wenzhou	Membership degree	0.196	0.238	0.238	0.101	0.072
	Weight	0.231	0.281	0.281	0.12	0.086
Shantou	Membership degree	0.203	0.238	0.238	0.125	0.057
	Weight	0.236	0.276	0.276	0.145	0.067

aggregate does not guarantee satisfactory waterfront tourism. The membership degree distribution of the five cities has the characteristics of the normal distribution with a mean of 3. Meanwhile, through the analysis of the weight set of indicators, it can be known that among the 11 indicators, Pro-Water Culture (U4) has the most significant impact on the overall tourism industry, followed by Aquatic Ecological Knowledge Sharing (U3). Pro-Water City Brand (U7) and Folkway Support (U10) have the most negligible impact on eco-tourism.

4 Conclusion

Ecotourism is one of the development directions of tourism in the future. Developing ecotourism in waterfront cities plays an important role in promoting the coordinated and sustainable development of economy, society and environment. At present, waterfront ecotourism is developing rapidly in China, but many tourism project planning is still in the initial stage, especially in the process of development, how to strengthen the publicity of the existing water culture of waterfront cities, while preventing blind development caused by waste and destruction of resources and other problems. The study on the development impact of the five core waterfront tourism cities on the west coast of the Taiwan Straits shows that, in the ecotourism development planning and environmental assessment in coastal areas, it is necessary to consider the dissemination factors of hydrophilic culture as comprehensively as possible, analyze and predict the impact degree and scope of infrastructure and policy support under different circumstances, and take timely environmental protection measures. Make waterfront tourism really sustainable development.

In order to systematically evaluate the factors affecting the development of waterfront ecotourism, this paper establishes the evaluation framework of waterfront ecotourism by fuzzy comprehensive evaluation method. The weight set of the identified indicators was obtained by consulting experts. Based on the weight set of indicators, questionnaire was designed with 5-Point Likert Scale to collect tourists' evaluation of the waterfront ecotourism in Fuzhou, Quanzhou, Xiamen, Wenzhou and Shantou on the West Strait. The main findings are as follows:

1) The evaluation indicators of waterfront ecotourism is constructed by "Waterfront Tourism Design (U1), Ecotourism Experience (U2), Aquatic Ecological Knowledge Sharing (U3), Pro-Water Culture (U4), Pro-Water Identity (U5), Aesthetic Value of Water Landscape (U6), Pro-Water City Brand (U7), Infrastructure Construction (U8), Regional Economic Development (U9), Folkway Support (U10), Government Policy Support (U11)", the corresponding weight set is 0.112, 0.034, 0.147, 0.238, 0.134, 0.128, 0.036, 0.061, 0.046, 0.028, 0.036].
2) Among the five studied cities, Shantou and Xiamen have the highest overall evaluation, while Fuzhou has the lowest. It shows that there is no direct correlation between the development of waterfront ecotourism and the economic aggregate. Cities that take tourism as the main development direction tend to get higher tourist evaluations regardless of whether waterfront tourism is the main publicity direction.
3) Pro-Water Culture (U4) had the most significant impact, followed by Aquatic Ecological Knowledge Sharing (U3). Pro-Water City Brand (U7) and Folkway Support (U10) have negligible impact on waterfront ecotourism. The overall weight range distribution is relatively average except for the four indicators mentioned above.

As an exploratory study, limitations need to be clarified. In this paper, only fuzzy comprehensive evaluation method is used to analyse the influencing factors, which may lead to sample bias. At the same time, a relatively simple method is adopted in the aspect of data standardization, and the weight calculation method has room for further research in the future. In addition, in order to expand the sample size, this paper did not ask the demographic data of tourists in the process of questionnaire survey. And the influence factors of stakeholders were not added to the evaluation system as important reference indicators (Wondirad et al., 2020). Therefore, in future studies, more extensive data will be collected for quantitative analysis and contribute to the waterfront ecotourism evaluation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by CW and XH. The first draft of the manuscript was written by CW and ZL, and all authors commented on previous versions of the manuscript. CS and XH performed the data collection and final draft editing. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The network analysis of organizations in watershed management toward sustainability in Northern Iran

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Introduction: The integrated water resource management is considered for development planning and water and soil resources management with an emphasis on the socio-economic features of the region for sustainability. The main purpose of study was to identify the organizations involved in the watershed management of Chehelchay of Golestan province in Iran, as well as analyzing the types of communications and interactions between organizations in terms of intensity and type.

Methods: Three networks of information exchange, coordination and participation were studied due to network analysis. Thus, the related organizations involved in participatory and comprehensive management of Chehelchay watershed (30 organizations) were introduced during the trips of the research team to the site and using special questionnaire. Then, the other specialized questionnaires were collected from the informed panels of each organization to provide the required data in the network analysis. A total of 84 specialists were interviewed. About half of the respondents (42 individuals) had graduate education and their average work experience was about 15 years. One third of the respondents (28 individuals) were women. The data analysis process was performed with UCINET6.631 and NetDraw.

Results and Discussion: The results indicated that the density index in information exchange (31.5%), coordination (27.5%) and participation (10%) networks were less than average. In the participation network, the values of the density index are very low and coherence is the same among the networks (information exchange, coordination, and participation). The results of reciprocity index among the organizational actors in the networks of information exchange (31.10%), coordination (33.52%) and participation (10.13%) were also less than average. Therefore, identifying the key actors with high social power in the network of local natural resources is a requirement of watershed participatory management plan. The runtime and cost of implementing natural resource projects can be significantly decreased by understanding and deploying these organizations and individuals. Social power and comprehensive participatory management is generally the key tools for building trust between local natural resource users. A systematic shift is also required from governmental management toward governance in order to achieve sustainable natural resource and watershed management.

KEYWORDS

network analysis, watershed management, information exchange, coordination, participation, Iran

1 Introduction

Natural resources are considered an inseparable component of human life. The scope of activity of ecosystems are separated based on the boundaries that humans have established due to political and social considerations. Thus, the scope of natural resource management has been defined due to the political divisions of countries, states, and provinces. This has led to the formation of numerous organizations and stakeholders with different interests competing with each other for the exploitation of natural resources services. Several strategies have been raised on the appropriate and sustainable use of global natural resources. In this regard, watershed management has been regarded as a comprehensive and appropriate method for the sustainable management of natural and human resources in watersheds. In recent studies, experts emphasized the model of "governance" of natural resources instead of the model of "governmental management" (Duit and Galaz, 2008; Salajegheh et al., 2020). The governmental management model largely relies on specialized knowledge and lacks the conditions to integrate social issues with biophysical conditions through cooperation, coordination, real participation, negotiation, and conflict resolution between different stakeholders. While governance as a wide system includes formal and informal organizations, each of them has its own structure, strategy, and resources, and they also play a significant role in the process of resources management as well as common-goals achievement (Armitage et al., 2007). Therefore, in the governance model of natural resources, social issues are facilitated through flexible and compatible mechanisms and cooperation between organizations (Carlsson and Berkes, 2005). In this regard, the participatory management approach based on compatibility emphasizes the social aspects of the management process (Armitage et al., 2007).

In governance model, institutions that are responsible for the management of socio-ecological systems change behaviors to consider all stakeholders based on a systematic process due to the pattern of participation and learning (Armitage et al., 2008). This model emphasizes a fundamental concept involving the need for coordination, participation, and learning among researchers, organizations, and resource managers (Dougill et al., 2006; Reed et al., 2009). The main point is the identification of organizations and stakeholders that each have their own management area, and that they are also related to each other in the resource governance process. The process of selecting and organizing the stakeholders is considered as one of the main pillars of Adaptive Co-Management (ACM) (Armitage et al., 2007). Replacing the classical managerial system with the governance model instead has drawn the attention of many scholars toward the study and analysis of natural resources governance (Ostrom, 2005; Salajegheh et al., 2020). Studies in this regard have led to the emergence and growth of some principles and applied models for the development and improvement of common-pool resource governance methods, many of which, especially the coordination, participation, and learning resulting from them, are basically related to social interactions (Plummer et al., 2012).

The contradictory view on watershed resource management is one of the biggest reasons for failure in watershed management in Iran. The multiplicity of organizational stakeholders with changing policies, approaches, priorities, capacities, and interests, and the lack of a comprehensive system to identify their role and structural relationships in the watershed management network are the most significant challenges faced by integrated watershed management in Iran. In participatory resource management, identifying key stakeholders is significant in terms of which stakeholders are more influential on the participatory management of natural resources based on their relationships with other people in the network (Fatemi et al., 2021). In this regard, social network analysis would be an appropriate method to use.

1.1 Social network analysis and watershed management

The concept and theory of social networks was first introduced by Alfred Radcliffe-Brown in 1940 and was used by Barnes in the 1950s (Korom, 2015). The main approaches of network analysis are divided into three main groups: the metaphorical approach, descriptive approach, and structural explicit approach (Folke et al., 2005; Hahn et al., 2006). In the metaphorical approach, social networks are often considered as a metaphor. The general idea of this approach is that each of the actors in the social area that form the network are either related to each other and benefit from this relationship to achieve different goals, or they are not related to some people and are more self-reliant. Overall, this approach includes a series of applied studies in which social networks have been considered as a research tool in the governance of natural resources. But it provides little information about the real structure and patterns of social networks. Thus, this approach lacks the analytical and explanatory capabilities of the social network, and it is difficult for the researcher to investigate the effect of a specific factor in social networks through analytical processes such as participation and coordination (Fabricius et al., 2007).

The descriptive approach goes beyond the metaphorical approach; specific features of social networks such as horizontal and vertical networks, links, communication bridges, and network density are studied in this approach (Pretty and Ward, 2001). But this approach lacks a methodological strategy for identifying and differentiating aspects of social network structures and provides little ability to increase our understanding of various issues of social networks in relation to natural resources. The structural approach has transformed the researcher's perception towards the concept of network structures and their function by introducing computational and quantitative aspects in the process of network analysis (Hahn et al., 2006). This approach includes a set of studies that examines social networks through applying systematic methods of data collection related to network relationships, methodology, and calculation-based modeling. The final goal of this approach is to explain the relationship between official definitions through quantitative and calculable features of the structure of social networks, and to present the results obtained from the analysis of this relationship in the governance of natural resources (Folke et al., 2005). The structural approach was used in this current study.

Social networks consist of a set of relationships and nodes, that is, the various types of stakeholders and the relationships between these stakeholders (nodes). In general, a social network can be considered as a graph of nodes and lines. Nodes in the network represent the actors and lines between nodes indicate the relationships between actors. Network analysis provides an empirical basis or an understanding of the flow of information and influence in governance networks to identify key organizations (Vignola et al., 2013). The main research on social networks seeks to understand how individual patterns of social relationships affect behavior (Ford et al., 2011). Social network analysis allows research into relationships beyond purely physical relationships and very significant relationships, and can provide very useful results which help improve social processes (Molano and Polo, 2015). Network analysis focuses on the relationship between actors, not on the actors themselves and their characteristics. Network analysis criteria can indicate the relationships between organizations, including which ones have the most active members of a network or those whose connections are interrupted by network members (Pedroza et al., 2016).

From a theoretical point of view, social network analysis is based on network theory and graph theory. Network theory is a very general term for evaluating relationships (Celik and Corbacioglu, 2016). Using social network analysis techniques, researchers evaluate social networks with a focus on relationships between individuals and organizations, and social network analysis has been widely used to help improve the efficiency and effectiveness of decision-making processes. In addition, it may identify the groups of people that have a central role, or separate groups or individuals. Further, it can identify opportunities to improve the flow of information and knowledge, improve the efficiency of formal communication channels, and increase the importance of informal networks (Bae et al., 2015). In social network analysis, more emphasis is placed on the type, quantity, and quality of communications and interactions instead of on the underlying variables. Indeed, matrices include the actors involved in interaction as well as the direction and frequency of interaction between them (Celik and Corbacioglu, 2016). An important point about the analysis of organizational networks is that the components of different organizations are not in direct contact with each other and their connections are *via* complex, extensive, and multiple relationships. Here, the concept of a network becomes necessary for the analysis of organizational relationships.

In many cases, Social Network Analysis (SNA) is used as a tool to determine influential actors in a collaborative process (Narayan et al., 2020). SNA makes it possible to study the interactions between activists, organizations, and other individuals who are involved in the process of natural resource management and governance. It is seen as a valuable method in management and governance studies. Focusing on the system's relationships and not its elements is the main emphasis of this method. In other words, it examines all the system's connections and provides a comprehensive understanding of its social structures and actions through discovering the relationships. This strategy is the main basis of the social communication hypotheses (Emirbayer and Goodwin, 1994; Freeman, 2004). This method can identify different social factors in the process of common-pool resource governance and can be used to determine these factors in the success or failure of resource management as well (Bodin et al., 2006; Bodin and Crona, 2009). For instance, SNA will determine what is the pattern of relations between activists and organizations in order to avoid the tragedy of common resources and to establish their self-imposed systems to use these resources in a regulated and sustainable manner (Prell et al., 2009). Obtaining such information is very valuable for external institutions that have the mission of facilitating the process of developing communication patterns between actors (Schneider et al., 2003; Ernstson et al., 2010). Therefore, SNA can be used as an efficient tool to analyze the process of information flow and knowledge exchange in the network of stakeholders and organizations; it can be used to create a successful system for the development and distribution of natural resources knowledge (Dempwolf and Lyles, 2012). In fact, mutual relationships between organizations in social networks play a much more important role than the development of official organizations to define and observe the rules of natural resource exploitation (Scholz and Wang, 2006).

There are several publications that have used SNA to study different aspects of environmental, natural resources, and watershed management and governance. For instance, Raum (2018) argued that appropriate models for ecosystem services need to identify different actors. The study showed that ecosystem governance and management would be effective and sustainable if various stakeholders and ecosystem services and their abilities are analyzed using the SNA method. In a similar study by Giurca and Metz (2018), SNA was used to identify some of the main organizations involved in Germany's wood-based bio-economy innovation system and their relationship to each other. The figures indicated high density but this was only due to the information exchange of the actors. Based on the results, although the connection between organizations was weak, the level of trust was high due to their cooperation. Application of SNA was also used in the study by Ghorbani and Azadi (2021) to analyze trust and collaboration networks in rangeland co-management. It found low levels of trust and collaboration between different stakeholders including rangeland users and the experts and managers of governmental and non-governmental institutions. This caused severe challenges in the governance of natural resources.

Narayan et al. (2020) studied the governance of decentralized watershed treatment in four cities of India. According to the complexity of the different groups of stakeholders involved in the governance of Water, Sanitation and Hygiene (WASH) and the diversity of their interests, SNA method was used. The results revealed the key differences between mega- and secondary cities in terms of institutions, community engagement, and overall sanitation, including aspects of decentralized wastewater treatment plants, based on the city types. Another study by Nabiafjadi et al. (2021) analyzed the knowledge and information exchange networks among governmental organizations and NGOs that contributed to water governance in the Zayandeh-rud basin of Iran. The study showed that the collaboration of the institutions was necessary to implement better strategies in water management. It also indicated that high participation of the mentioned organizations as well as identifying power relations and densities in different processes of water governance could be used in other countries of the Middle East. The role of various actors and their social capital in groundwater management was analyzed using SNA in the study by Rahimi-Feyzabad et al. (2022). It revealed that the social capital of these organizations was low. In fact, the heterogeneous nature and contrasting strategies of these organizations led to the poor collaboration.

Reviewing the most recent year of SNA study publications, this method was used in different research areas as well: Joyez and Laffineur (2022) studied the occupation space, network structure, centrality, and the potential of labor mobility in the French labor market; Flemming et al. (2022) used the SNA method to identify networks of physicians responsible for the care of specific patient populations; Blanken et al. (2023) studied intersectoral collaboration at a decentralized level, and information flows in child welfare and healthcare networks; and Arnold et al. (2022) studied information exchange networks regarding chronic diseases in primary care practices in Germany.

The network analysis method is used for identifying the main stakeholders and actors in the community (Bodin and Prell, 2012). The appropriate understanding of the position and capacity of the main actors and stakeholders can lead to their appropriate organization in collaborative management programs (Ghorbani and Azadi, 2021). The current study aims to identify the organizations involved in the watershed management of Chehelchay in Golestan province, Iran, and analyze the communications and interactions between the organizations in terms of intensity and type. The research objectives are as follows:

- Identifying the various organizations active in Gorganrood watershed management
- Undertaking network analysis at the organizational level and studying the various relationships of relevant organizations in the studied area
- Providing applied suggestions to improve and enhance the interactions of various organizational stakeholders to implement the comprehensive and participatory management of the watershed.

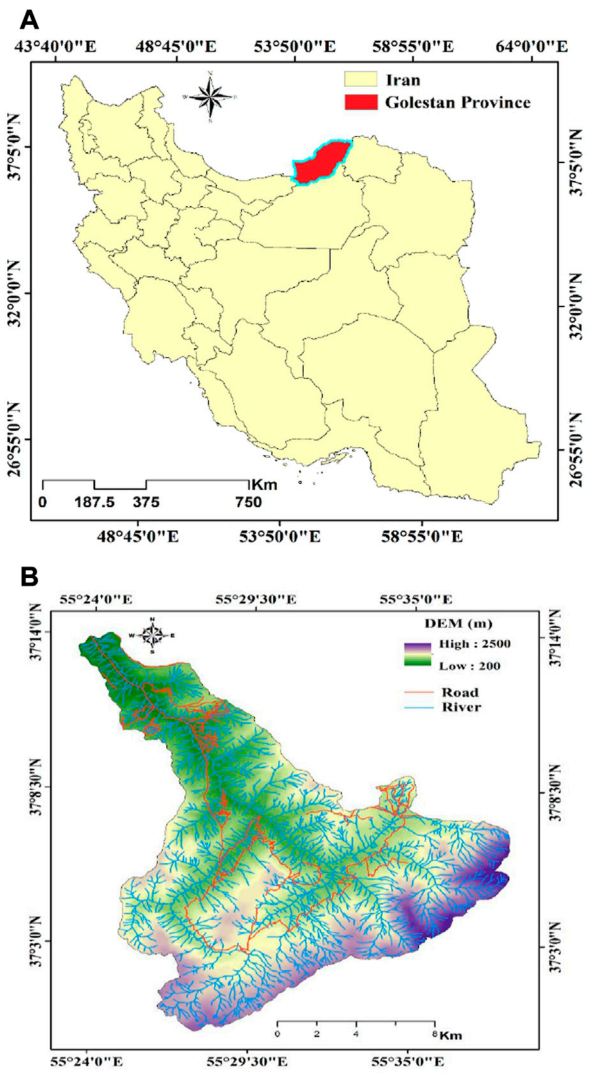

FIGURE 1
Geographical location of the study area **(A)** Golestan province on map of Iran **(B)** Chehelchay watershed of Golestan province.

2 Research method

2.1 Research area

Golestan province (Figure 1A) has six sub-watersheds including the Voshmgir watershed dam with 8,100,000,000 square meters (m^2), Western Gorganrood watershed with 3,500,000,000 m^2, Atrak watershed with 8,000,000,000 m^2, Qareh Sou watershed with 1,650,000,000 m^2, Gorgan bay watershed with 400,000,000 m^2, and Nekarood watershed with 1,000,000,000 m^2. The highest level of altitude of the province and consequently the maximum water available in the province comes from the Gorganrood watershed which is considered one of the most important rivers in Golestan province, flowing through all plains of Gorgan and dividing it into two parts. The main bed direction is from northeast to southwest, is 350,000 m long, and originates from the heights of Golestan forest. Chehelchay watershed is one of the mountainous regions of Iran with an area of about 61,777 acres located between 55° 23 and 55° 38 east longitudes and 36° 59 and 37° 13 north latitudes (Figure 1B). This watershed is located in Minoudasht in terms of political divisions and is one of the largest sub-watersheds of Gorganrood.

2.2 Sampling and data analysis

Network analysis is based on the common social science method of using different techniques, such as interviews and questionnaires, to collect the required data (Butts, 2008; Bodin and Prell, 2012). In this study, the social network of related organizations was analyzed. Thus, the related organizations involved in the participatory and comprehensive management of the Chehelchay watershed (30 organizations) were introduced during the trips by the research team to the site and using specialized questionnaires. Based on purposeful sampling, key informants were selected

TABLE 1 Introduction of social network analysis indices.

Index	Definition
Power	The concept of power is reduced or increased based on the status, position, and communication of each individual or organization within the network and due to the constraints or opportunities created for them Brandes and Erlebach (2005). The fewer limitations of an individual or organization, the more their opportunities will be, and as a result they will achieve a more favorable position Bae et al. (2015). Thus, they will make more exchanges with others, and will have more impact.
Grouping	Grouping the actors of a network allows understanding of how an agent or organization behaves within a group, as well as the overall behavior of the network Leahy and Anderson (2008). Also, the identification of weak and strong sections within a network is provided by examining the number and severity of communications between and within the groups Fatemi et al. (2021).
Centrality	Centrality is a broad concept used to identify the most important actors in the network. It indicates the degree to which an actor is embedded in the network Freeman (1979), Narayan et al. (2020), Joyez and Laffineur (2022)
Degree centrality	The value of degree centrality of any point or organization is obtained only by counting the number of neighbors or adjacent organizations Herzog et al. (2014). In its analysis, the greater the degree centrality of a person or organization, the more communications and networks it has, and it is more powerful and influential Zhang and Lou (2017). In-degree centrality measures the number of nodes that an actor receives, and the out-degree centrality measures the number of nodes leaving an actor Saqr and Alamro (2019)
Closeness centrality	It represents how fast an actor can access others in the network. In fact, it is considered as the mean of all geodesic distances between mentioned actor and other actors in the network Zhang and Lou (2017). Proximity centrality is an index for measuring the ease of access at the node to the rest of the nodes in the network Gandasari et al. (2022).
Between centrality	In this type of centrality, the organization's position in the network, as well as its path to other organizations, is considered. What matters is finding the shortest path between organizations. The actors with high between centrality can influence the flow of resources among other actors Zhang and Lou (2017). These organizations are the intermediary points that the communication paths pass through. The importance of identifying and analyzing such points is their strength in limiting or increasing communication Saqr and Alamro (2019)
Eigenvector centrality	This focuses on finding central actors that are least distant from others Gan et al. (2018)
Network density	Density in the information network means the ratio of all available links or information nodes in the network to all possible links or the most nodes; high network densities represent a high degree of consistency among individuals Narayan et al. (2020), Rezaei et al. (2015).
Reciprocity of links in the network	In order to determine the stability of the network of relationships and the degree of reciprocity of the links of trust and participation, the reciprocity of links in the network is used Karimi Gougheri et al. (2018b). The higher the level of this index in the network of relationships is, the higher the level of constructive interaction between the people in the network, and the stability of the network of relationships is ensured Fatemi et al. (2021).
Transitivity of links in the network	This index is derived from the sharing of links between three individuals, one of which is the bridge between two other people Borgatti et al. (2013)
The shortest distance between two actors **(mean Geodesic distance)**	This index shows the shortest path between two pairs of actors based on trust and participation links. The higher the rate of this index, the more the speed of circulation, distribution of trust, and the links of participation among individuals and unity in society Bae et al. (2015).
E-I[1] Index	This index displays the links outside the group to the links inside the group. Individuals with EI-positive have more links outside the group; EI-negative individuals have more links inside the group, and those with zero EI have equal inter-group and intra-group links Fatemi et al. (2021).
Network size	This indicates the total number of links in the network; the larger the network size, the greater the density of the network Mohammadi Kangarani et al. (2011).
Isolates	The actors who have nothing to do with other actors in the network Herzog et al. (2014), Fatemi et al. (2021).
Core/periphery	This index demonstrates which actors are located in the center and which ones are located around the network. Using this indicator, all members are divided into two groups of centers and surroundings Herzog et al. (2014); Gan et al. (2018). The central cluster has a lot of connections and therefore the network density is low Narayan et al. (2020).

among the experts, managers, and authorities of these organizations in order to collect the required data in the network analysis. In these panels, a total of 84 specialists (three individuals from each organization) were interviewed. Then, the data were entered into Excel and UCINET6.631 software in the form of a matrix, and data processing and analysis were performed. This data processing was conducted using the concepts which are the basis of all of the mathematical algorithms (Klenk et al., 2009; Herzog et al., 2014). The most important of these concepts is centrality, power, and grouping (Narayan et al., 2020; Fatemi et al., 2021). Graph theory and NetDraw software were used to plot the data (Scott, 2012). In this research, a number of social network analysis measures were analyzed to assess the different network criteria between individuals, between organizations, and between individuals and organizations (Table 1).

2.3 Research steps

In order to conduct the present study, eight steps were performed to examine the existing interaction and communication patterns among the actors using the social network analysis technique (Brandes and Erlebach, 2005; Vignola et al., 2013; Bae et al., 2015; Fatemi et al., 2021).

Step 1. Determining the type of analysis
Step 2. Determining the relationships within the network using the theoretical measurement tools
Step 3. Collecting the data related to the network
Step 4. Measuring the relationships
Step 5. Entering the characteristics of actors in the analysis
Step 6. Analyzing the data related to the network
Step 7. Creating descriptive indices for social structures
Step 8. Providing data for each network

In the present study, various social networks were studied and analyzed at organizational and social levels:

2.3.1 Information Exchange

Organizations communicate with other organizations when information is required regarding other organizations' programs or *vice versa*. In other words, the organizations collaborate with each other only for information sharing, and they work together only when the opportunity arises (Giurca and Metz, 2018; Rocker et al., 2022). For example, the Regional Water Company provides some information about unauthorized wells for the Organization of Agriculture Jihad or Meteorological Organizations provide information regarding weather forecast for Department of Environment.

2.3.2 Coordination

In order to prevent duplication, organizations coordinate with other organizations. Indeed, the organizations inform each other of their plans and schedules to prevent attending repeated programs (Mohammadfam et al., 2015; Karimi Gougheri et al., 2018a). For example, the Agriculture and Natural Resources Engineering Organization and Golestan University share their educational schedules of the current year so that parallel educational classes and workshops are not held for different groups of agricultural clients.

2.3.3 Participation

As a specialized team to achieve a common goal, the organizations participate with other organizations. This means that different organizations have mutual collaboration with each other from the process of decision-makings to the implementation phase (Ghorbani and Azadi, 2021; Flemming et al., 2022). Participation is considered as a specialized concept in social science, indicating the highest level of communication between individuals, organizations, and societies. For instance, the national/regional strategic plan is defined to be completed by Golestan University, the Organization of Agriculture Jihad, Department of Natural Resources and Watershed Management, and the Department of Environment in a participatory manner.

3 Results

The results of first questionnaire, which determine and introduce the active organizations in the watershed management of the Chehelchay region, have been provided in Table 2. Based on field studies and observations, 30 organizations which have been active in the watershed network were identified. Their full names as well as their abbreviations are presented in Table 2.

3.1 Description of the sample

All of the respondents had an academic education, except for two individuals finishing their high school. Nearly half (54%) of the samples had a master's degree, and bachelor's degree and Ph.D. were the subsequent most frequent education levels achieved, respectively. Based on the findings, 50% of respondents were in their second decade of working. After that, the individuals with more working experience with more than 20 years of work experience constituted 28% of the sample, and the remaining 21% included young workers with less than 10 years of experience (Table 3). One third of respondents (28 individuals) were female experts and two thirds were male experts.

The age range of the respondents was 28 years, with a minimum and maximum age of between 26 and 54 years old. The average age of respondents was about 41 years and the highest recurrence age among the sample was 40 years. In terms of the degree of education, the minimum and maximum number of years of study was between 12 and 23 years to give a range of 11 years. The average study years of the studied sample was 18 years (to master's degree). The results included a diverse range of occupational backgrounds, meaning that both people with 30 years of work experience and on the edge of retiring and freshly recruited staff with 1-years' experience could be observed. The average years of employment was 15 years and a large number of people in the sample had an occupational history of 20 years.

3.2 SNA of organizations

3.2.1 Information exchange network

The size of the information exchange network is 274 links from the expected 870 total links. The calculated density index in the information exchange network is 31.5%, which is lower than the average, indicating the low level of institutional coherence based on this link (network) in the organizations affiliated with watershed management (Table 4). In other words, achieving and sharing information on watershed management in organizations is not easy and has many problems. The network centralization index based on the input and output links in the information exchange network is 35.2% and 45.9%, respectively. In addition, the percentages of 31.1% for link reciprocity and 46.2% for link

TABLE 2 Full names and abbreviations of the organizations involved in the Chehelchay basin.

Abbreviation	Organization's full name
OAJ	Organization of Agriculture Jihad
DENV	Department of Environment
NRWM	Department of Natural Resources and Watershed Management
RWC	Regional Water Company
ANRREC	Agriculture and Natural Resources Research and Education Center
GH	Government House
ANREO	Agriculture and Natural Resources Engineering Organization
MO	Meteorological Organization
DEDU	Department of Education
PVO	Provincial Veterinary Office
RWWC	Rural Water and Wastewater Company
CLSW	Department of Cooperative, Labor, and Social Welfare
NAO	Nomadic Affairs Organization
SFDA	Support Fund Development in Agriculture
UPCC	Union Production Cooperative Companies
UNAC	Union of Nomadic Agriculture Cooperative
ASSC	Agriculture Support Services Company
AIF	Agriculture Insurance Fund
SIFVN	Social Insurance Fund for Farmers, Villagers, and Nomads
CCIMA	Chamber of Commerce, Industries, Mines, and Agriculture
AEA	Agricultural Experts' Association
AGS	Agricultural Guild System
ORC	Organization of Rural Cooperative
WO	Welfare Organization
CHHTA	Cultural Heritage, Handicrafts, and Tourism Administration
GU	Golestan University
ANRBO	Agricultural and Natural Resources Engineering Basij Organization
BO	Broadcasting
IKRF	Imam Khomeini Relief Foundation
HA	Hilal Ahmar

transitivity indicate low and average stability of the information exchange network among the organizations involved in watershed management, respectively.

In order to investigate the role of different organizations in the studied networks, the values of in-degree and out-degree centralities were compared. Based on these indices, the amount of information received or provided in the information exchange network was determined. As shown in Figure 2A, the findings indicated that Iran Broadcasting, the Department of Natural Resources and Watershed Management (NRWM), the Government House, the Regional Water Company (RWC), the Department of Environment (DENV), and the Organization of Agriculture Jihad (OAJ)—with out-degree centrality levels of 75.9%, 72.4%, 58.6%, 58.6%, 55.2%, and 51.7%, respectively—had a higher social permeability in the information exchange network for watershed management based on

TABLE 3 Demographic characteristics of respondents in the studied organizations.

Variable	Mean	SD	Min	Max	Mode	Range
Age	41.12	5.920	26	54	40	28
Educational level	18.07	2.592	12	23	18	11
Background	14.76	6.726	1	30	20	29

TABLE 4 Indicators measured of the studied networks.

Network	Density (%)	Centrality (%)	Network centrality based on input links (%)	Network centrality based on output links (%)	Network size	Reciprocity (%)	Transitivity (%)
Information Exchange	31.5	47.5	35.2	45.9	274	31.10	46.2
Coordination	27.5	37.1	53.6	35.8	239	33.52	45.3
Participation	10	18.8	28.9	18.2	87	10.13	25.9

870 total expected links of 30 organizations.

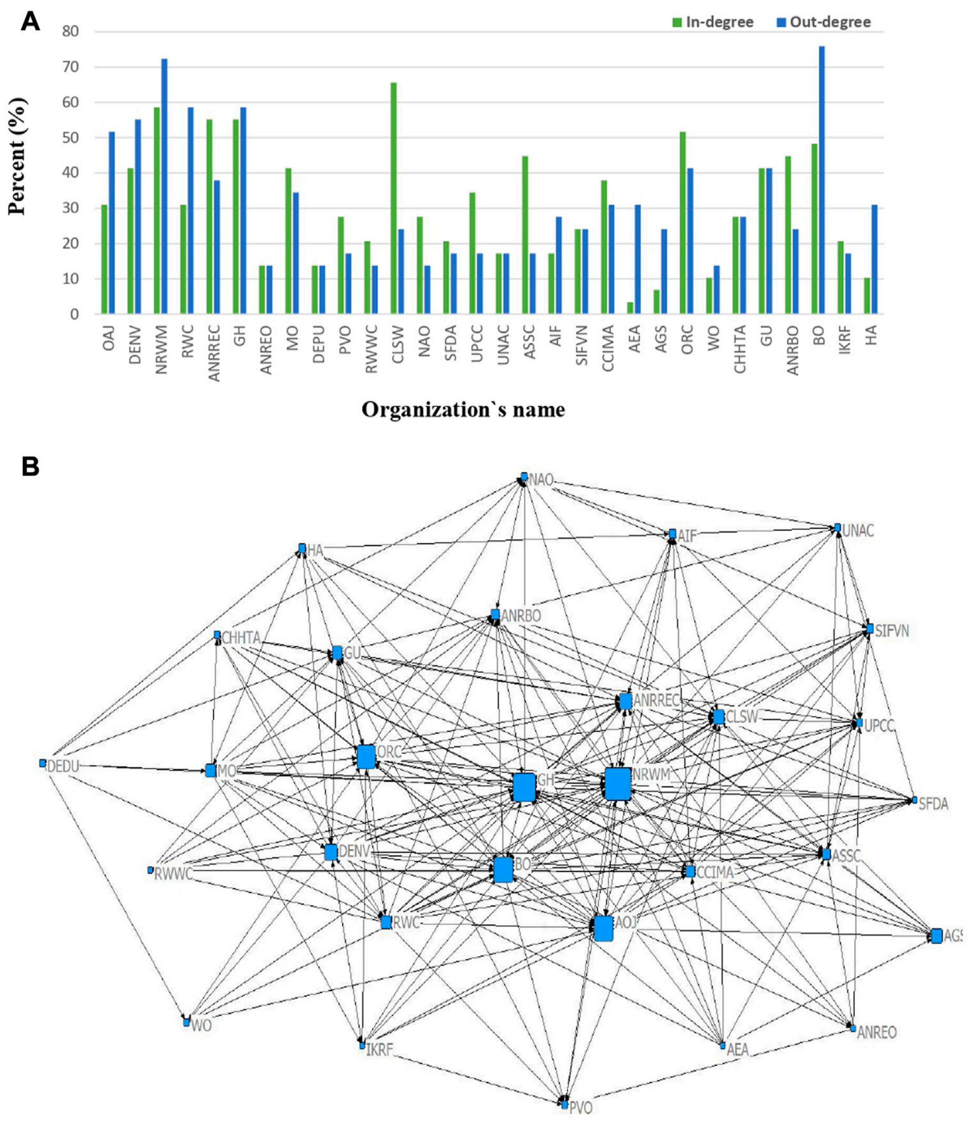

FIGURE 2
SNA results of Information Exchange network **(A)** In-degree and out-degree centrality **(B)** Between centrality (*Larger size indicates higher between centrality*).

the links of information exchange. In addition, the General Department of Cooperatives, Labor, and Social Welfare (CLSW), the Department of Natural Resources and Watershed Management (NRWM), the Government House (GH), the Agriculture and Natural Resources Research and Education Center (ANRREC), and the Organization of Rural Cooperative (ORC)—with in-

TABLE 5 Primary and secondary organizations in terms of information exchange of watershed management.

Primary organizations	Secondary organizations
Organization of Agriculture Jihad	Agriculture and Natural Resources Engineering Organization
Department of Environment	Department of Education
Department of Natural Resources and Watershed Management	Provincial Veterinary Office
Regional Water Company	Rural Water and Wastewater Company
Agriculture and Natural Resources Research and Education Center	Nomadic Affairs Organization
Government House	Support Fund Development in Agriculture
Meteorological Organization	Union Production Cooperative Companies
Department of Cooperative, Labor, and Social Welfare	Union of Nomadic Agriculture Cooperative
Organization of Rural Cooperative	Agriculture Support Services Company
Golestan University	Agriculture Insurance Fund
Agricultural and Natural Resources Engineering Basij Organization	Social Insurance Fund for Farmers, Villagers, and Nomads
Broadcasting	Chamber of Commerce, Industries, Mines, and Agriculture
	Agricultural Experts' Association
	Agricultural Guild System
	Welfare Organization
	Cultural Heritage, Handicrafts, and Tourism Administration
	Imam Khomeini Relief Foundation

degree centrality levels of 65.5%, 55.2%, 55.2%, and 51.7%, respectively—had a higher score than the other actors in the network and had high authority in the network. Therefore, these actors have higher social capital and are considered key actors in the information exchange network for watershed management, so that many actors in the network refer to these actors to receive information.

The introduction of relevant organizations in terms of primary and secondary organizations is regarded as one of the most important findings of each network analysis. In this regard, the main organizations have a more important role and function in watershed management, and secondary organizations are at a lower level of information exchange to the primary organizations. The list of organizations in different groups of primary and secondary organizations is presented in Table 5.

The Organization of Agriculture Jihad (OAJ), the Department of Environment (DENY), and the Department of Natural Resources and Watershed Management (NRWM) of the province have been ranked first to third, respectively, as the primary organizations involved in watershed management of the study area. Conversely, the Agriculture and Natural Resources Engineering Organization (ANREO), the Department of Education (DEDU), and Provincial Veterinary Office (PVO) were specified as the first to third secondary organizations involved in the watershed management of this province, respectively (Table 5).

Graphs can be used to better understand the geometry of actors and their social power in the network. As shown in Figure 2B, some organizations were displayed with larger points and others had very small points. The difference in the size of points is determined by the level of intermediate centrality of organizations, so that organizations which can interact more with other organizations are represented with larger points. Based on these interpretations, the Department of Natural Resources and Watershed Management (NRWM), the Government House (GH), the Organization of Agriculture Jihad (OAJ), Iran Broadcasting (BO), and the Organization of Rural Cooperative (ORC) have a strong place in the network and can influence the flow of information exchange among the other actors (Figure 2B). Thus, they control the flow of information in the network based on the shortest paths among other organizations. Such organizations are referred to as the information hubs in the network and play a significant role as brokers controlling and transmitting information in the network.

The research results aimed at analyzing the information exchange network among organizations active in sustainable management of natural resources in the Alborz Dam in Mazandaran province, Iran, based on the social network analysis approach indicate that the access and information sharing among the studied organizations is not easy and there is a moderate level of communication between organizations. In the information network of these organizations, the Organization of Agricultural Jihad is as a moderate power in the network. Gorgan University, the Organization of Agricultural Jihad, and the Agriculture and Natural Resources Research and Education Center play a vital role in facilitating and sharing information with other organizations, while at the same time they are not dynamic in

TABLE 6 Primary and secondary organizations in terms of coordination of watershed management.

Primary organizations	Secondary organizations
Organization of Agriculture Jihad	Department of Environment
Department of Natural Resources and Watershed Management	Agriculture and Natural Resources Engineering Organization
Regional Water Company	Meteorological Organization
Agriculture and Natural Resources Research and Education Center	Department of Education
Government House	Provincial Veterinary Office
Social Insurance Fund for Farmers, Villagers, and Nomads	Rural Water and Wastewater Company
Organization of Rural Cooperative	Department of Cooperative, Labor, and Social Welfare
Cultural Heritage, Handicrafts, and Tourism Administration	Nomadic Affairs Organization
Golestan University	Support Fund Development in Agriculture
Agricultural and Natural Resources Engineering Basij Organization	Union Production Cooperative Companies
Broadcasting	Union of Nomadic Agriculture Cooperative
	Agriculture Support Services Company
	Agriculture Insurance Fund
	Chamber of Commerce, Industries, Mines, and Agriculture
	Agricultural Experts' Association
	Agricultural Guild System
	Welfare Organization
	Imam Khomeini Relief Foundation

the process of information exchange with other organizations. In analyzing the legislative processes and their relationship with the information exchange network of organizations, it became clear that the Department of Natural Resources and Watershed Management has more power than other organizations in this field (Rezaei et al., 2015). Based on the study, there are few organizations with a large amount of power in the information network of organizations involved in the sustainable management of natural resources. In other words, this network requires an organization which can take responsibility for providing information and knowledge to other organizations in the network. Also, the findings of our study are in line with the study by Nabiafjadi et al. (2021) in terms of the power analysis that demonstrated how the dominant role of governmental bodies and the weak contribution of private organizations and civil society result in up-down decision-making.

3.2.2 Coordination network

The density of the coordination network among organizational stakeholders was 27.5%, indicating breakdown between actors and weak organizational cohesion based on this link. From all 870 possible and potential links, only 239 links were activated for the coordination network. Regarding the direct relationship between the network size index and the institutional network cohesion, it can be stated that by strengthening the organizational coherence among the above-mentioned institutions, coordination between these institutions can be facilitated, possible parallel work can be prevented, and watershed management activities can be made feasible at a lower cost and in quicker time. The network centralization index based on input and output links in the matrix of coordination was 53.6% and 35.8%, respectively, for both links. The reciprocity of links is another index being studied among organizational agents. The value of 33.52% represents a weak link between organizations in the coordination network. Thus, the stability of organizational stakeholders associated with the studied network was low. The transitivity of links indicates the sustainability of the network and was 45.3% for the coordination network. Such an index confirmed an average stability of the coordination network in watershed management activities (Table 4).

In the coordination network, the Organization of Agriculture Jihad (OAJ), the Department of Natural Resources and Watershed Management (NRWM) of Golestan Province, and the Regional Water Company (RWC) were ranked first to third as the main organizations, respectively. Eleven organizations were considered the main organizations and 19 other organizations were considered secondary organizations in the coordination network of watershed management. The Department of Environment (DENY) of the province, the Agriculture and Natural Resources Engineering Organization (ANREO), and the Department of Cooperatives, Labor, and Social Welfare (CLSW) were included as secondary organizations (Table 6).

Based on Figure 3A, in the coordination network, the institutions involved in watershed management activities including the Department of Natural Resources and Watershed

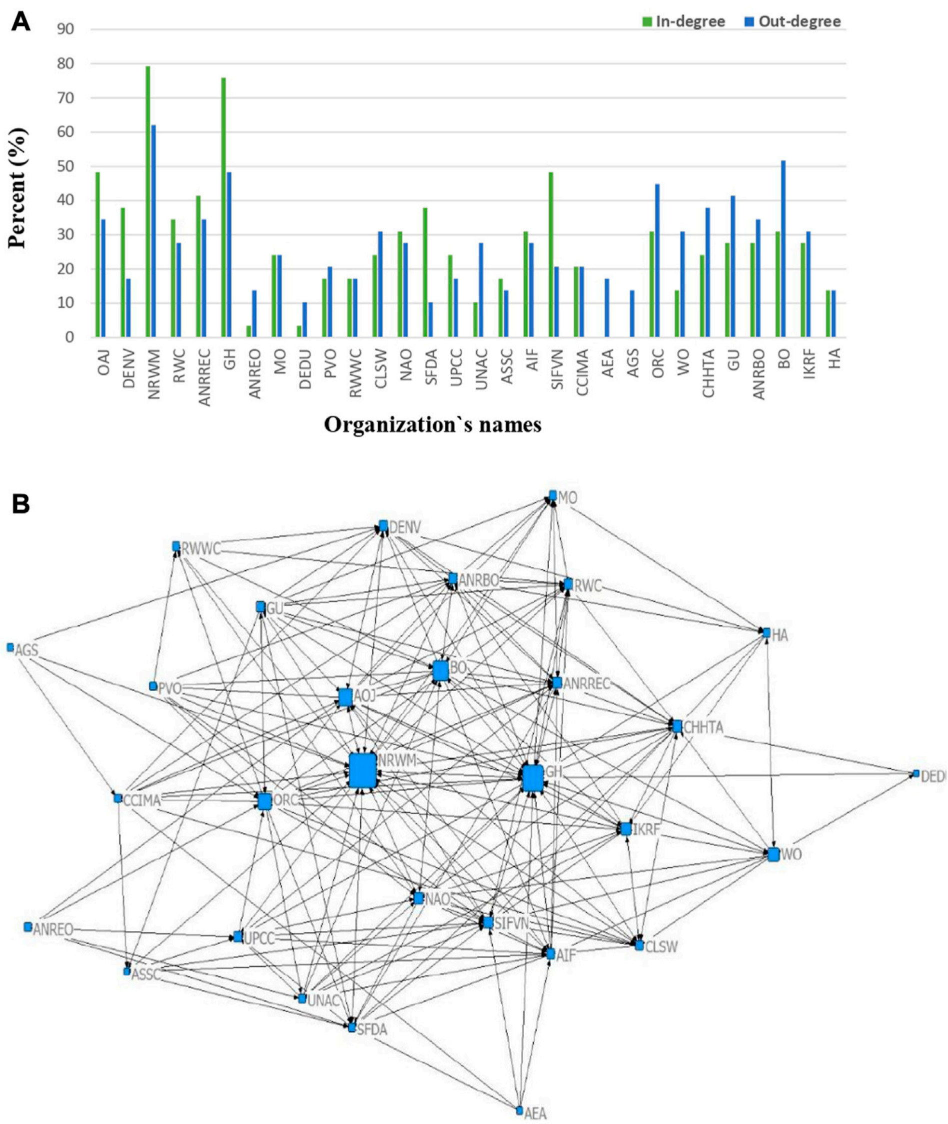

FIGURE 3
SNA results of the coordination network. **(A)** In-degree and out-degree centrality. **(B)** Between centrality (*Larger size indicates higher between centrality*).

Management (NRWM), Iran Broadcasting (BO), the Government House (GH), Organization of Rural Cooperative (ORC), Golestan University (GU), and the Cultural Heritage, Handicrafts, and Tourism Administration (CHHTA) had higher social influence, with out-degree centralities of 62.1%, 51.7%, 48.3%, 44.8%, 41.4%, and 37.9%, respectively. The Department of Natural Resources and Watershed Management (NRWM), the Government House (GH), the Organization of Agriculture Jihad (OAJ), the Social Insurance Fund for Farmers, Villagers, and Nomads (SIFVN) of Golestan Province, and the Agriculture and Natural Resources Research and Education Center (ANRREC) had the maximum reputation and authority, with in-degree centralities of 79.3%, 75.9%, 48.3%, 48.3%, and 41.4%, respectively. Furthermore, based on the intermediate centrality index, the Department of Natural Resources and Watershed Management (NRWM) (17.04), Government House (GH) (12.168), Iran Broadcasting (BO) (7.516), Organization of Rural Cooperative (ORC) (6.258), and the Organization of Agriculture Jihad (OAG) (5.688) were the key effective actors in the coordination network of the organizations involved in watershed management activities (Figure 3B).

In a similar study, the effects of the formal and informal power of organizations on budget allocation in the field of natural resources were analyzed in the fourth development plan of Kohgiluyeh and Boyer-Ahmad province in Iran. The results of this study revealed that having a relationship with the main focus of power is effective in regard to allocating budget, and more informal power can more effectively affect the allocation of funds than formal power (Mohammadi Kangarani et al., 2011). Also, the formal and informal networks of organizations in Kohgiluyeh and Boyer-Ahmad province

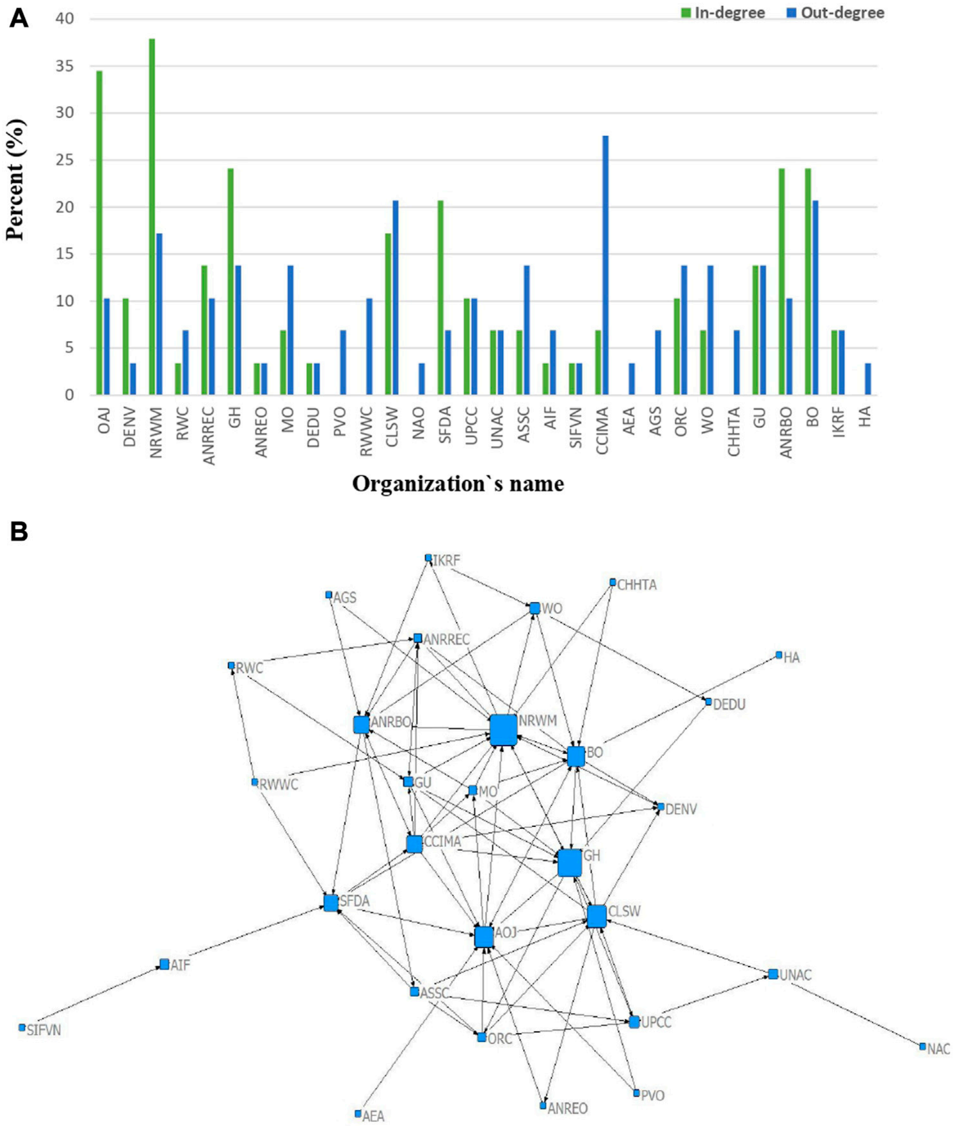

FIGURE 4
SNA results of the participation network. **(A)** In-degree and out-degree centrality. **(B)** Between centrality (*Larger size indicates higher between centrality*).

was investigated using social network analysis. Based on the results, the non-similarity of these organizations in these two networks affects the environmental management decisions of the province. In addition, this research confirmed the efficiency of the network analysis approach in solving managerial problems.

3.2.3 Participation network

The network size for the 30 organizations involved in the comprehensive watershed management activities was obtained as 87 links out of the total 870 links. The low level of the link density index (10.0%) indicated a very low level of organizational coherence based on these links (network). Furthermore, the obtained value for the network centralization indices based on input and output links was 28.9% and 18.2%, respectively. Finally, based on the indices of link reciprocity and transitivity, indicating the balance in the network (which was 10.13% and 25.9%, respectively), the sustainability of participation network was inferred at a low level, suggesting the vulnerability of the desired network (Table 4). Meanwhile, the Department of Natural Resources and Watershed Management (NRWM), the Organization of Agriculture Jihad (OAJ), the Government House (GH), Iran Broadcasting (BO), and the Agricultural and Natural Resources Engineering Basij Organization (ANRBO) had a higher reputation and authority than other actors, so that the actors in the network were more dependent on these actors. The Chamber of Commerce, Industries, Mines, and Agriculture (CCIMA), Iran Broadcasting (BO), the Department of Cooperative, Labor, and Social Welfare (CLSW), the Department of Natural Resources and Watershed Management (NRWM), and Golestan University (GU) were the most participatory organizations in the field of comprehensive

TABLE 7 **Primary and secondary organizations in terms of participation in watershed management.**

Primary organizations	Secondary organizations
Organization of Agriculture Jihad	Department of Environment
Department of Natural Resources and Watershed Management	Regional Water Company
Government House	Agriculture and Natural Resources Engineering Organization
Golestan University	Support Fund Development in Agriculture
Agricultural and Natural Resources Engineering Basij Organization	Department of Education
Meteorological Organization	Provincial Veterinary Office
Department of Cooperative, Labor, and Social Welfare	Rural Water and Wastewater Company
Chamber of Commerce, Industries, Mines, and Agriculture	Union Production Cooperative Companies
Broadcasting	Nomadic Affairs Organization
	Organization of Rural Cooperative
	Agriculture and Natural Resources Research and Education Center
	Union of Nomadic Agriculture Cooperative
	Agriculture Support Services Company
	Agriculture Insurance Fund
	Social Insurance Fund for Farmers, Villagers, and Nomads
	Agricultural Experts' Association
	Agricultural Guild System
	Welfare Organization
	Cultural Heritage, Handicrafts, and Tourism Administration
	Imam Khomeini Relief Foundation

watershed management activities. The above-mentioned organizations had a higher social impact on promoting the participation links with other organizations (Figure 4A).

In the participation network, which was almost the same as the coordination network, the Organization of Agriculture Jihad (ORJ), the Department of Natural Resources and Watershed Management (NRWM) of Golestan Province, and the Government House (GH) were ranked higher as the main organizations (Table 7). The number of main organizations in the participation network (nine organizations) was lower than the other networks of information exchange (12 organizations) and coordination (11 organizations), so that some organizations, such as the Department of Environmental (DENY) and the Agriculture and Natural Resources Research and Education Center (ANRREC) of the province, were included in the participation network as secondary organizations.

Regarding the management of watershed management activities in the inter-organizational participation network, the Department of Natural Resources and Watershed Management (NRWM), the Government House (GH), the Department of Cooperative, Labor, and Social Welfare (CLSW), the Organization of Agriculture Jihad (OAJ), and Iran Broadcasting (BO), with intermediate centralities of 18.139, 15.094, 11.607, 10.506 and 10.226, respectively, were the most important involved organizations which could play an important role in the network as highly appropriate brokers. Based on these results, the above-mentioned organizations can be very effective in developing their participation in the organizational network (Figure 4B).

The studies by Rezaei et al. (2015) and Karimi Gougheri et al. (2018a) showed that more participatory activities are required in this network for the equal distribution of information among different organizations, so that they can be encouraged in an interactive and dynamic way to better manage natural resources such as development of mutual scientific activities in defining research plans and executive programs with collaboration of different organizations in terms of sustainable natural resources management.

3.3 Discussion

The QAP correlation index was used to investigate the correlation between the studied networks (Table 8). The correlation between the networks of information exchange, coordination, and participation was positive and significant at 1% level. In addition, coordination and participation had the highest correlation, while information exchange and participation had the lowest correlation. Thus, if there is an exchange of information between the two organizational actors, the links of coordination (0.193) and participation (0.107) can established in the network.

The results of the study indicated that the density index in information exchange, coordination, and participation networks is

TABLE 8 Correlation of studied networks in terms of QAP index.

Network	Information exchange	Coordination	Participation
Information Exchange	1	—	—
Coordination	0.193**	1	—
Participation	0.107**	0.250**	1

The coefficients with two stars were significant at 0.01 level.

less than average. In the participation network, the values of the density index are very low and coherence is the same among the networks (information exchange, coordination, and participation). Based on the results of this index, no dense network can be expected in the studied links, especially in the network of participation. Therefore, with regard to the direct relationship of social cohesion with density, the degree of social cohesion based on the matrix of participation is very weak. As a result, integrated water management activities face some challenges and effort should be made to increase density in the above-mentioned networks to form the system. Based on the results of link reciprocity among the organizational actors, the total amount of information exchange links and coordination was below the moderate level, and the level of interaction among organizational actors was very low. Based on these results, as well as that of the link transitivity index, all networks of information exchange, coordination, and participation has showed minimum sustainability. Some mutual links in the decision-making processes for water management activities should be conducted to strengthen organizational integrity.

The total network size indicated that nearly one-tenth of the expected links were found in the participation network. The value of this indicator in the networks of information exchange and coordination was more favorable, although less than half of the expected links were established in the above-mentioned networks. Based on the results of the research into the information exchange, coordination, and participation networks, the ratio of centrality increased on the basis of the input links to the output links. In other words, based on the input links related to coordination, the participation in the investigated organizational network was almost weak and was dependent on limited activists. However, the distribution of coordination and participation in terms of output links had less dependence on the presence of the actors with high centrality in the above-mentioned networks. On the other hand, the centrality of the entire network of information exchange, based on output and input links, had a more dispersed structure and were similar to each other, indicating the moderate influence of the actors with a central position in terms of reputation and influence. In other words, nearly half of the input and output links of the information exchange are available for central organizations and the rest of the links are shared with other organizations in the network of information exchange.

4 Conclusion

Relationship between humans and nature is an inevitable phenomenon that has a long history since the beginning of human life. However, human intervention has expanded overtime in terms of the various exploitations of natural resources and the environment through scientific and technological developments. Human societies have taken advantage of natural resources by performing individual or collective activities through formal and informal organizations in order to meet their needs and desires. The multiplicity of organizations and the different missions and goals that are defined by each has led to the increased exploitation of nature. The classic management system of organizations has typically been that their managers and members have planned and performed independently in their working areas to achieve institutional goals. Sometimes, organizations have made independent decisions due to a lack of proper communication and information about the programs of other organizations, which have often been parallel to and repeated by other organizations. In this regard, better governance of natural resources has been suggested in recent decades in order to realize the sustainable use of natural resources. Governance refers to a wide system that includes formal and informal institutions in that while each of them has its own structure, strategy, and resources, they also play an important role in the process of resources management and common goal achievement. Thus, the identification of different groups of inter-organizational actors, mutual interactions, and communication networks between them is proposed. In the study of natural resource governance, it is necessary to use the methods and techniques that are appropriate to the nature of the subject. SNA is the most common method used in these studies to identify actors related to different areas of natural resources and the communication between its stakeholders. The purpose of this article was to identify the organizations involved in the management of the Chehelchay watershed in Golestan province, Iran, and to analyze the communications and interactions between the organizations in terms of intensity and type. Using the SNA method, 30 organizations related to the studied watershed were identified and information was collected through a questionnaire from specialist panels (84 people) in the aforementioned organizations. The indicators of centrality, density, in-degree, out-degree, between centralities, network size, reciprocity, and transitivity were measured in three networks: information exchange, coordination, and participation. Data were analyzed by UCINET and network maps were drawn with NetDraw.

The main findings showed that the index of centrality in the networks of information exchange, coordination, and participation was 31.5%, 27.5%, and 10%, respectively. The density index for the information exchange network was 47.5%, for the coordination network it was 37.1%, and for the participation network it was

18.8%. The network size of the information exchange, coordination, and participation networks were calculated at 274, 239 and 87, respectively. Moreover, the reciprocity and transitivity indices were measured as follows, respectively: information exchange network (31.10% and 46.2%), coordination network (33.52% and 45.3%), and participation network (10.13% and 25.9%). By reviewing the trends of the numbers related to the indicators calculated in the studied networks, it is clear that the participation network of organizations involved in the watershed is weaker than the other two networks in terms of all dimensions. However, the amount of these indicators for the two networks of information exchange and coordination were also at an average level. Therefore, it can be concluded that the interactions between the organizations involved in the considered watershed have been moderately weak. It seems that these interactions are only for the exchange of necessary information or coordination in the implementation of some separate programs. According to the findings, these collaborations are very limited and scattered, and no significant participation is observed between the mentioned organizations. To improve the sustainable governance and management of the watershed area, it is suggested that the beneficiary organizations hold periodic and monthly meetings in the form of small and large organizational groups in order to be informed and updated with the information and programs of other organizations; their communications should not be limited only to the information exchange and coordination of their separate programs. Moving toward active, mutual, and comprehensive participation is required, in which different stakeholders, including government institutions, private organizations, and NGOs, are considered.

The network graphs and maps related to the in-degree, out-degree, and between centrality indicators also showed that the government institutions were the main organizations in all three studied networks and were considered as brokers with other organizations. Indeed, based on the results, the public organizations in all of studied networks (information exchange, coordination, and participation) had a greater impact than non-governmental organizations (private, for-profit, and non-profit). The results indicated that non-governmental organizations should be considered as key actors in integrated watershed management by considering the functions of comprehensive watershed management, as well as the deep links with the target communities of agricultural and rural areas. However, these organizations are marginalized in practice and have the least degree of authority, influence, and ability to control the network in the studied networks. Such organizations also had lower social capital and received less support and were less emphasized in the policy-making and decision-making of watershed management. This finding revealed a kind of weakness in the networks under consideration, because the involvement of all stakeholders, especially private, for-profit, and non-profit organizations, is necessary to achieve the goals of comprehensive watershed management. In this regard, it is recommended that appropriate policies be made by the main organizations responsible for the comprehensive watershed management (including the Department of Natural Resources and Watershed Management, Organization of Agriculture Jihad, Government House, and Agriculture and Natural Resources Research and Education Center) to change the positions of these actors in the organizational networks, as neglecting these organizations challenges the implementation of comprehensive watershed management in the Chehelchay watershed and less success is achieved at greater time and cost. In addition, developing incentive mechanisms for the greater participation of NGOs in the decision-making processes and implementation of comprehensive watershed management activities in the Chehelchay watershed is suggested, so that these organizations can enter the network center in the long run and play a more significant role. As a result, the changes in organizational arrangements in the network and the distribution of power among public organizations and NGOs would be optimal and balanced. Public organizations can reduce their incumbency by adopting appropriate policies and taking the task of monitoring and evaluating. The development of strategies, activities, and services for the integrated watershed management based on stakeholders' participation and coordination of responsible organizations in natural resources is proposed as a fundamental step for realizing the effective participation of stakeholders. The Department of Environment of the province is responsible for protecting the environment and can play a significant role in the development of natural resources as the active organization. Therefore, the coordination of the activities of this institution with other organizations is essential. Overall, a systematic shift is required from governmental management toward governance in order to achieve sustainable natural resource and watershed management. In this regard, organizations should go beyond information exchange and the mere coordination of their programs and move towards a participatory network.

Scheduling an interview with a panel of experts that were mainly the top managers of their institutions from a large number of organizations (30 organizations for this study) was a time-consuming process. Asking the respondents the questions of the questionnaires one by one in order to avoid missing data was another limitation and challenge of the study. In other words, the research team could not give the questionnaire to the experts to fill out individually and needed to gather all of the panel members of each organization in a special meeting in order to interview them and collect the data. As for the research implications, the human-nature relationship as the base of environmental sociology should be considered a topic of interest for not only academia but other groups of people worldwide. Human beings affect natural resources and the environment in different ways, especially through the organizations and decisions that they make for different purposes. In this regard, SNA is an applicable tool which simply visualizes the communication and interactions of individuals, organizations, or societies (rural or urban). Researchers, authorities, and politicians should be able to provide applicable decisions/solutions based on research findings such as the current study in order to achieve sustainable resource management and governance. It is suggested for future studies to repeat this study in other watersheds of Iran or other developing countries. It is also helpful to analyze the social network analysis of individuals or rural/urban working groups as well as the organizational level.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

This study was approved in the committee related to National macro plan for comprehensive management of watersheds of Iran.

Author contributions

KR-M: Develop research design, data collection, data analysis and interpretation, write and finalized the manuscript. MF: Data collection, data analysis and interpretation, write and finalize the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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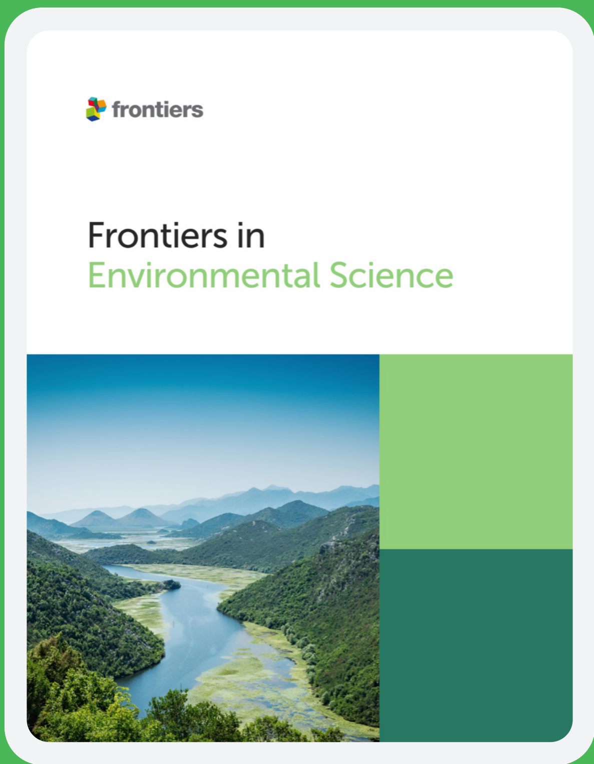

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