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EDITED BY
Natasa Maria Vaidianu,
Ovidius University, Romania

REVIEWED BY
Yixiong He,
Zhejiang Ocean University, China
Songhua Huan,
Chinese Academy of Sciences (CAS),
China

*CORRESPONDENCE
Xianjun Liang
nbuandrew@163.com

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From salt to silicon: industrial evolution and freshwater dependence on China's Daishan Island

Liangliang Li[1,2], Shanshan Zheng[1,2], Renfeng Ma[1,2], Xianjun Liang[1,2]* and Jialin Li[1,2]

[1]Donghai Institute, Ningbo University, Ningbo, Zhejiang, China, [2]School of Geography and Remote Sensing, Ningbo University, Ningbo, Zhejiang, China

Introduction: Rapid economic intensification poses a significant threat to freshwater security on small islands. This study examines how industrial structural change impacts freshwater use and pollution in Daishan Island, Zhoushan City, China, and explores the co-evolution of freshwater systems with socioeconomic–ecological dimensions to inform sustainable development strategies for small islands.

Methods: Using standardized socioeconomic, environmental, and freshwater datasets from 2010 to 2019, we applied information entropy analysis and principal component regression to quantify the effects of industrial evolution on freshwater resources.

Results: The results indicate an overall upward trend in the coordination between freshwater use efficiency and socioeconomic development. However, industrial structural evolution significantly influences water pollution levels.

Discussion: These findings provide a theoretical basis for optimizing freshwater allocation and utilization, and clarify the mechanisms through which industrial evolution impacts freshwater resources on small islands, offering valuable insights for sustainable development policy in similar small island contexts.

KEYWORDS

industrial structure evolution, island freshwater security, principal component regression, sustainable island development, water pollution, water use efficiency

1 Introduction

Islands are highly sensitive socioeconomic–ecological systems whose freshwater stocks simultaneously sustain livelihoods and maintain ecological balance. On small islands, limited freshwater directly underpins three pillars of the local economy–agriculture, fisheries (processing and aquaculture), and tourism while also regulating wetland functioning, groundwater seawater equilibrium, and nearshore ecosystem stability. Limited availability of freshwater directly constrains island agriculture, fisheries processing, tourism services, and daily domestic activities while also regulating critical ecological processes such as wetland functioning, groundwater–seawater balance, and nearshore ecosystem health (Qu et al., 2023; van der Velde et al., 2007). Under climate variability and intensifying human activities, many small islands face the coupled challenges of freshwater scarcity and pollution, threatening livelihood sustainability and ecological resilience and undermining progress toward the Sustainable Development Goals (Borger et al., 2014; Koutsoyiannis, 2011; Di and Gu, 2019; Hariram et al., 2023). In view of the increasing climate change and frequent human activities, the imbalance between water supply and demand and the water quality and safety issues in the river basins are becoming more and more serious (Kundzewicz et al., 2008), posing a significant and urgent challenge to the realization of sustainable water resource utilization at the regional level. Therefore, ensuring the sustainable management and utilization of water resources is of inestimable value for maintaining ecological balance and promoting sustainable and healthy socioeconomic development (Men et al., 2023).

Securing sustainable freshwater governance is pivotal for ecological stability and long-term socioeconomic vitality in Daishan (Jiang, 2021; Li et al., 2021). Although the mean annual precipitation exceeds 1,280 mm and is concentrated during the monsoon/typhoon season, topographically controlled runoff efficiency leaves exploitable flows chronically low. With 65% of the technically usable water already withdrawn, further reservoir expansion offers limited relief. Rapid urban industrial growth has concentrated on energy- and water-intensive industries, intensifying both the pollutant load and the ecosystem stress (Wang and Wang, 2012; Feng, 2000). Disentangling how sectoral shifts alter water quantity–quality trade-offs is thus essential for charting an island development path that reconciles economic upgrading with hydrological limits (Sun and Ye, 2022).

Grounded in the theory of anthropogenic externalities, we quantify the environmental repercussions of industrial evolution and its agglomeration footprint in Daishan (Zhang et al., 2021). Compiling county-level data on water withdrawals, sectoral efficiency, and pollution coefficients, we first map the current freshwater stress hotspots (Zhao et al., 2022). Information entropy is then applied to track temporal shifts in the water use structure and to measure the synchrony between freshwater availability and socioeconomic activity (Wang et al., 2020). Finally, principal component regression isolates the marginal contribution of each industry to both water use and contaminant release, delivering targeted benchmarks for restructuring the economy toward higher value-added yet lower water-impact pathways.

The paper integrates socioeconomic–ecological records from 2010 to 2019 with information entropy and principal component regression analyses to quantify how industrial evolution alters both the water use efficiency and the contamination risk in Daishan Island. The aims are threefold: 1) to map the spatiotemporal evolution of freshwater withdrawals and emissions across the salt-to-silicon transition; 2) to identify the marginal contributions of individual sectors to water quantity and quality stress; and 3) to deliver a decision support framework that aligns industrial upgrading with freshwater security for small islands at large.

2 Materials and methods

2.1 Research framework

As an important tool for exploring the multidimensional relationship between freshwater resource use, socioeconomic–

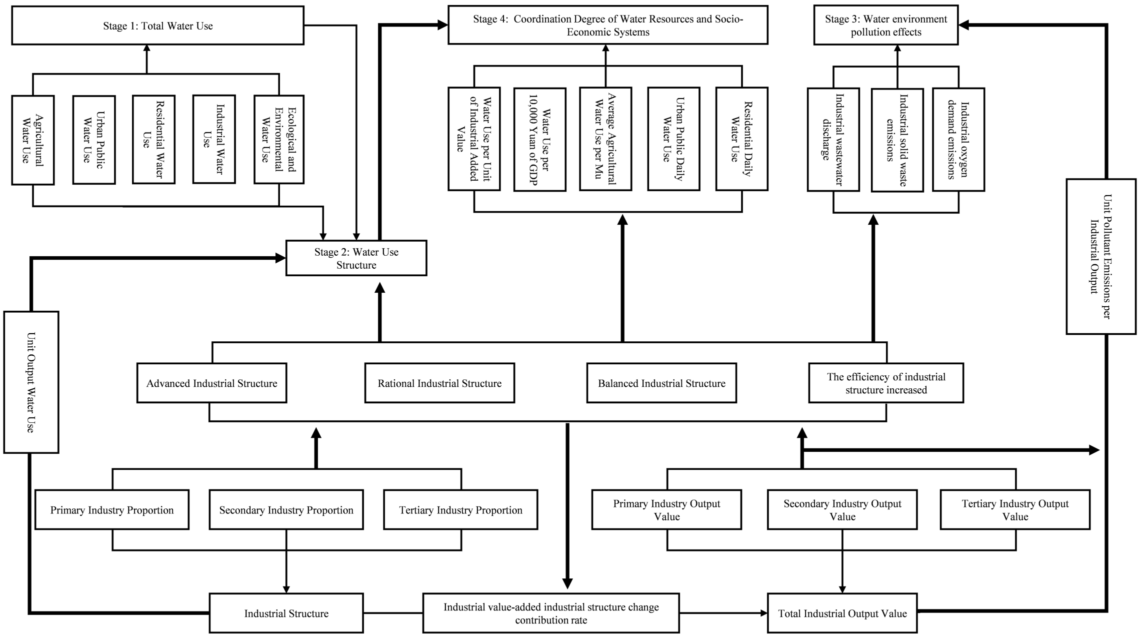

FIGURE 1
Logical framework.

ecological impact, system coordination, and water pollution effect, the complexity of the freshwater resource and the socioeconomic–ecological system coordination measure is visualized (Figure 1). Taking the "total freshwater use" as the center of the circle, the four core dimensions are radiated outward to construct a brief analytical framework, which provides a visual path for an in-depth understanding of freshwater resource management, socioeconomic–ecological impact, and water pollution prevention and control, as well as emphasizes the complexity of the interaction of the multidimensional dimensions. In this context, the impact of the industrial evolution process on the freshwater resource is particularly prominent, and the levels of influence include dynamic changes in the demand structure, the evolution of the pollution conditions, the improvement of use efficiency, and the readjustment of spatial distribution. Therefore, the impact of industrial evolution on freshwater resource needs to be considered comprehensively when formulating industrial policies and freshwater resource management strategies aimed at promoting the harmonious coexistence of the economy, society, and the environment.

Through the comprehensive use of various scientific methods, the use of the freshwater resource, the change in the water use structure, and water pollution and its intrinsic connection with industrial structure were systematically analyzed, aiming at exploring the theoretical support and practical path for the sustainable development of the island economy.

2.2 Analytical method

2.2.1 Freshwater use accounting method

Firstly, data standardization (Equation 1) ensures comparability across heterogeneous datasets. Structural information entropy (Equation 2) then quantifies the spatial–temporal evolution of the water use structure in Daishan Island and measures its balance degree. The information entropy, *J*, formula (Equation 3) provides precise quantification of this equilibrium condition, while an integrated assessment model (Equation 4) evaluates the coordination between freshwater resource utilization and socioeconomic–ecological development, including the specific impacts of anthropogenic activities on the freshwater environment. Finally, principal component regression analysis elucidates the causal relationships between industrial evolution and the water system, thereby informing evidence-based strategies for integrated water resource management and sustainable industrial development (Table 1).

Freshwater resource management in Daishan Island is critical to ecological integrity, residents' quality of life, and long-term sustainable development. Developing evidence-based strategies through integrated scientific approaches addresses challenges while fulfilling intergenerational environmental responsibilities (Liu et al., 2003).

2.2.2 Impact analysis of the industrial structure on freshwater resources

Principal component regression was adopted to address potential multicollinearity among the industrial structure indicators, which are often highly correlated due to overlapping information on output shares, employment structure, and productivity. Prior to principal component extraction, a correlation matrix analysis confirmed strong interdependence among the original variables. After transformation, the extracted principal components were mutually orthogonal, thereby eliminating multicollinearity in the regression stage. To further verify robustness, variance inflation factors (VIFs) were calculated

TABLE 1 **Analysis of the freshwater resource use in Daishan Island.**

Research method	Formula	Relevant parameters and definitions	Remarks
Data standardization processing	$X_{ij} = \frac{x_{ij} - x_{ij\min}}{x_{ij\max} - x_{ij\min}}$ (Equation 1)	X_{ij}Represents the standardized value of *j* index in region *i*, x_{ij} Represents the observed value of *j* index in region *i*, $x_{ij\min}$, $x_{ij\max}$ Represents the minimum observation value and the maximum observation value of *j* index in region *i*, respectively	
Spatial–temporal analysis of the water use structure–water use structure information entropy	$H_W = -\sum_{j}^{n} P_{ij} \ln P_{ij}$ (Equation 2)	*n* indicates the number of freshwater types; P_{ij}Is the proportion of freshwater use of type *j* in the total freshwater use of city *i*	Higher entropy indicates a more balanced and stable system, used to assess the proportional balance and the spatial–temporal variation of the water use in Daishan
Water use structure information entropy balance degree *J*	$J_i = H_{wi}/H_{wi\max}$ (Equation 3)		When $H_{w\max} = \ln n$This means that the proportions of the various types of freshwater use are consistent. At this time, the water use structure has no advantage categories, the system node information entropy is the largest, and the system reaches the most balanced and stable state.
Coordination degree of freshwater resource and socioeconomic–ecological composite system (U_i) and freshwater environmental effect (T_i) evaluation	The proportion of *j* index in region *i* in *j* index during the study period $P_{ij} = X_{ij}/\sum_{i=1}^{n} X_{ij}$ (Equation 4)	P_{ij}Represents the proportion of the *j* item index value in region *i* after standardization to the synthesis of the *j* item index value after standardization during the study period	

for the reconstructed independent variables, with all VIF values remaining below the conventional threshold, indicating that multicollinearity does not distort the regression results. The core idea was to convert the factor coefficients according to the regression coefficients and the principal component coefficients and determine the correlation between the factors and the dependent variables (Equation 5).

$$FAC_i = \alpha_1 \cdot X_1 + \alpha_2 \cdot X_2 + \alpha_3 \cdot X_3 + \alpha_4 \cdot H + \alpha_5 \cdot S_{ij} + \alpha_6 \cdot \varphi_1 + \alpha_7 \cdot \varphi_2 + \alpha_8 \cdot V + \alpha_9 \cdot \vartheta_i + \alpha_{10} \cdot B + \alpha_{11} \cdot S + \alpha_{12} \cdot LnMX + \alpha_{13} \cdot LnDIF \tag{5}$$

After the principal component extraction and score calculation, the principal components were used as independent variables for multiple linear regression (Equation 6):

$$H_w(U_i/T_i) = A_0 + \lambda_1 \cdot FAC_1 + \lambda_2 \cdot FAC_2 + \lambda_3 \cdot FAC_3 + \ldots \ldots \lambda_i \cdot FAC_i + \varepsilon \tag{6}$$

In the formula, H_w, U_i, T_i represents the information entropy of the water use structure, the degree of coordination of the freshwater resource and the socioeconomic–ecological complex system, and the level of the freshwater environment effect of the three dependent variables. λ_1, … λ_i are the regression coefficients of each principal component. A_0 and ε represent the constant and the residual, respectively.

The freshwater resource and the socioeconomic–ecological composite system are conceptualized as a coupled human–water system, in which freshwater pressure emerges from the interaction between resource endowment, production efficiency, use structure, and management capacity. Accordingly, the indicators in Table 2 were selected to reflect four core dimensions: the freshwater use intensity (per capita freshwater use and freshwater use per unit GDP), the sectoral production efficiency (industrial and agricultural freshwater use per unit output), the residential demand characteristics (urban and rural domestic freshwater use), and the resource utilization efficiency (freshwater development and utilization rate). These indicators are commonly adopted in studies on island and water-scarce regions to capture both the scale effects and the efficiency effects of the socioeconomic activities on freshwater systems. To reduce subjectivity in multi-indicator evaluation, the indicator weights were determined using the entropy weight method, which assigns higher weights to indicators with greater temporal variability and information contribution, thereby enhancing the objectivity and robustness of the composite evaluation framework (Table 2).

TABLE 2 Evaluation index and weight of the freshwater resource–social economic complex system in Daishan Island.

Index	Weight
Per capita annual comprehensive freshwater use (m^3)	0.0972
Freshwater use for 10,000 yuan of GDP (m^3)	0.1049
Freshwater use for 10,000 yuan of industrial added value (m^3)	0.0452
Daily freshwater use of urban residents (L)	0.0875
Urban public daily use of freshwater (L)	0.0809
Daily freshwater use of rural residents (L)	0.1008
Freshwater use per mu of paddy field (m^3)	0.1083
Freshwater use per mu in dry land (m^3)	0.0907
Freshwater use per mu of vegetable field (m^3)	0.0774
Average freshwater use per mu for forest fruit irrigation (m^3)	0.0491
Freshwater per mu for replenishing fish pond (m^3)	0.0968
Usage rate of freshwater resource (%)	0.0613

2.2.3 Environmental pollution effect assessment of the industrial structure

To evaluate the effect of industrial structure evolution based on water pollution factors within this comprehensive assessment index (Lu and Ma, 2010; Li, 2007). The index system is reflected in the natural attributes of the freshwater body and the various aspects of socioeconomic development, in which the significant factors include land use, agricultural pollution, industrial wastewater, and industrial solid waste and domestic sewage discharge, among others. The indicators related to industrial structure were selected to construct a composite water pollution indicator system, and the weight of each indicator was determined according to the entropy weight method (Table 3).

2.3 Data sources

The water use structure data were obtained from the Daishan County Water Resource Bureau, primarily derived from the *Zhoushan City Water Resource Bulletin* and the *Daishan County Waterworks Supply Report*, while the freshwater use efficiency data were sourced exclusively from the *Zhoushan City Water Resource Bulletin*. Socioeconomic indicators, including the proportions of the primary, secondary, and tertiary industrial output values, the population density, the per capita GDP, and the fertilizer application rate per unit area were extracted from the *Daishan*

TABLE 3 Evaluation index and weight of the water pollution effect in Daishan Island.

Index	Weight
Proportion of primary industry	0.1112
Proportion of secondary industry	0.1266
Proportion of tertiary industry	0.0000
Density of population (per/km^2)	0.1012
Per capita GDP	0.1196
Fertilizer per unit area (t/km^2)	0.0710
Industrial wastewater per unit area (t/km^2)	0.0893
Industrial solid waste discharge per unit area (t/km^2)	0.0576
Industrial oxygen demand emissions per unit area (kg/km^2)	0.0467
Industrial ammonia nitrogen per unit area (kg/km^2)	0.0448
Total industrial nitrogen per unit area (kg/km^2)	0.0768
Industrial petroleum emissions per unit area (kg/km^2)	0.0770
Total chromium discharge per unit area of industrial wastewater (kg/km^2)	0.0781

County Statistical Yearbook (2015–2019). The industrial pollution metrics (i.e., wastewater discharge, solid waste, chemical oxygen demand, total nitrogen, petroleum pollutants, and total chromium per unit area) were obtained from the *Daishan County Pollution Source Census Data (2010, 2020)* and the *Industrial Pollution Discharge and Treatment Utilization reports (2015–2019)* provided by the Zhoushan City Ecological and Environmental Protection Bureau, Daishan Sub-bureau.

The study period from 2010 to 2019 was selected for three main reasons. Firstly, consistent and systematically recorded data on freshwater use, industrial structure, and pollution emissions at the county level became available after 2010, ensuring data comparability and continuity. Secondly, this period captures a critical phase of industrial evolution in Daishan Island, including the decline of the traditional salt and fisheries industries and the rise of the port-related manufacturing and service sectors. Thirdly, data after 2019 were excluded to avoid distortions associated with the coronavirus disease 2019 (COVID-19) pandemic, which caused atypical disruptions to industrial activity, water use structure, and environmental monitoring. Together, the 2010–2019 period provides a stable and representative baseline for the analysis of long-term industrial–freshwater interactions. The global outbreak of the epidemic in 2019 not only caused a huge impact on human health and socioeconomics but also significantly affected the normal work of data collection and statistics. The special economic environment and social conditions during the outbreak, the temporary stagnation or adjustment of industrial production activities, and the changes in the lifestyle of the population had atypical impacts on the freshwater use structure and the pollution status, thus increasing the complexity and uncertainty of data interpretation. In order to ensure the consistency and validity of the data, as well as to avoid abnormal fluctuations brought about by the epidemic from being misleading for long-term trend analysis, the data after 2019 will not be updated for the time being until data quality has been sufficiently verified and normal monitoring conditions have been restored.

Although the empirical analysis focuses on the 2010–2019 period, the COVID-19 pandemic may have altered the industrial operation modes and the freshwater demand structure in Daishan Island. Temporary contraction of the manufacturing activities and logistics disruptions may have reduced the industrial freshwater withdrawals and pollution loads, while increased residential water use and sanitation demand could have partially offset these reductions.

More importantly, post-pandemic industrial upgrading strategies emphasizing port-related services and high-tech manufacturing may have further reshaped freshwater dependence through indirect water use and supporting infrastructure demand. Therefore, the results of this study provide a pre-pandemic baseline for understanding the structural freshwater–industry relationships and offer policy-relevant insights for adaptive freshwater governance under future uncertainties.

3 Water use characteristics and system coordination

3.1 Structural analysis of water use

3.1.1 Evolution of the tap water use structure

The tap water supply in Daishan exhibited a fluctuating decline until 2014, after which it rose sharply. Industrial water use (the largest use type) mirrored this trajectory, underscoring its dominant influence on the total water demand. Residential water use, the second largest component, remained relatively stable with a gradual upward trend. Urban public water use was negligible, each consistently below 1 million tons annually (Figure 2). Production water refers to water specifically used for product manufacturing.

According to the *Zhoushan City Water Resources Bulletin*, the total water use in Daishan is categorized into five sectors: agriculture use, industry use, urban public services use, residential use, and ecological and environmental use. Between 2010 and 2018, the total water use and all subcategories exhibited an upward trend. Industrial water use dominated, averaging approximately 14 million

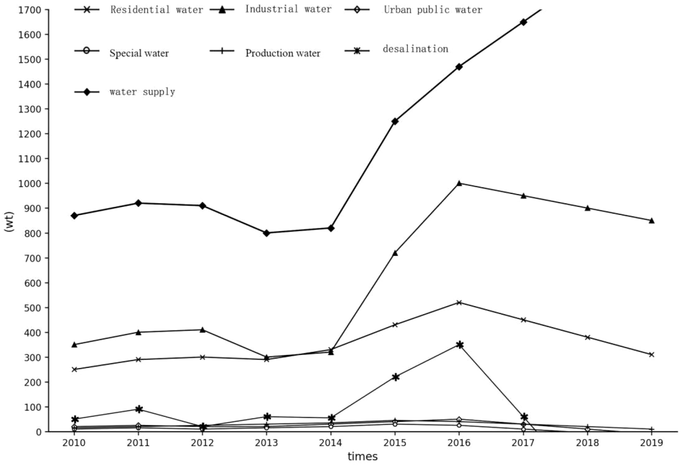

FIGURE 2
Structure and evolution of the tap water use in Daishan Island.

m^3 annually, followed by residential use at approximately 8 million m^3. Agricultural water use declined markedly over time, dropping below 4 million m^3/year, with paddy field irrigation accounting for the largest share compared with forestry, livestock, and aquaculture. Urban public water use ranked fourth, increasing gradually during 2014–2018 and averaging approximately 2.5 million m^3/year. This category aggregates construction and service sector use, with the latter significantly outweighing the former, underscoring the water intensity in the service sector. Ecological and environmental water use, the smallest category at <1 million m^3/year, comprises the urban and rural ecological environment components. While critical for ecosystem preservation, allocation heavily favors urban environmental needs (Figure 3).

3.1.2 Information entropy analysis of the freshwater use structure

As Table 4 and Figure 4 jointly reveal, it can be analyzed that the information entropy of the tap water structure in Daishan over the past 10 years has generally shown a smooth and slight increase and then tended to decline, with an average of 0.989 information entropy and an average annual change of 0.1%–0.2%. From the perspective of the whole trend of change, in 2010–2016, the degree of balance showed a slight upward trend and the tap water use structure changed in the direction conducive to economic development. The 2016–2019 tap water information structure entropy gradually decreased, indicating that the degree of orderliness of the tap water system decreased, and the industrial use of freshwater rose sharply after 2014. The 2010–2019 tap water use structure balance degree showed the same trend. The balance degree of the tap water use structure showed the same trend change from 2010 to 2019, with the balance degree rising steadily from 2010 to 2016 and decreasing significantly from 2016 to 2019. The change amplitude of industrial water use and domestic water use increased significantly. The information entropy and balance degree of the total water use structure remained basically stable in 2014–2018, and the change amplitude of the total water use in each type was small.

3.2 Coordination assessment of the freshwater resource–socioeconomic system

The results of the comprehensive evaluation from the perspective of the freshwater resource–socioeconomic composite system in Daishan Island are shown in Table 5. From the table, it can be seen that the comprehensive evaluation value of the freshwater resource system from 2014 to 2018 showed a general trend of first rising and then slightly declining, with an average value of 0.5396 and an average annual growth of 11.93%, indicating that the freshwater resource efficiency, the freshwater resource use, and the economic and social development coordination generally showed an upward trend, with the freshwater resource use efficiency and the freshwater resource use structure moving in a direction conducive to socioeconomic development. The overall trend of coordination between freshwater resource use efficiency, freshwater resource system use, and economic and social development was on the rise, and the freshwater resource use efficiency and freshwater resource use structure were developing in the direction favorable to social and economic development.

4 Industrial structure impact on freshwater resource

4.1 Industrial structure impact on the freshwater use structure

4.1.1 Correlation between the industrial and water use structures

SPSS 23.0 was used to analyze the relationship between industrial development and various types of freshwater use in Daishan. Table 6 shows that the primary industry proportion was positively correlated with the agricultural, urban public, residential,

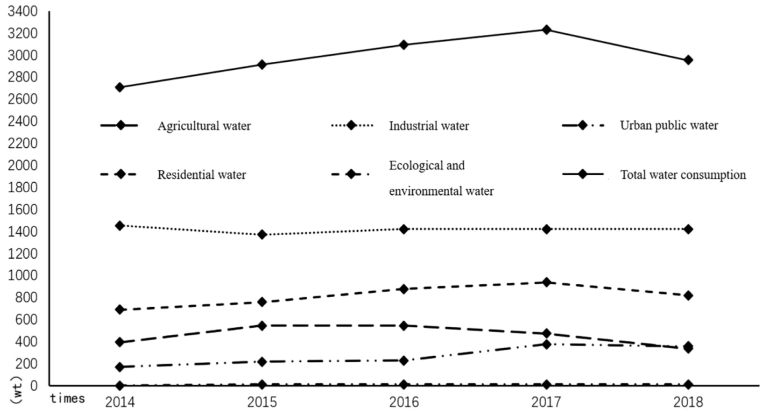

FIGURE 3
Structure and evolution of the total water use in Daishan Island.

TABLE 4 **Information entropy and balance degree of the tap water structure in Daishan Island from 2010 to 2019.**

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Information entropy of the tap water structure	0.99	1.01	1.01	1.02	1.04	1.05	1.04	0.97	0.89	0.87
Information entropy of the total water structure					1.14	1.24	1.24	1.28	1.24	
Balance degree of the tap water structure	0.94	0.96	0.96	0.97	0.99	1.00	0.99	0.92	0.85	0.83
Freshwater balance of the total water structure					0.89	0.97	0.97	1.00	0.97	

and ecological and environmental water use, with the strongest correlation observed for ecological and environmental water use. However, it was negatively correlated with industrial water use. The proportion of secondary industry was only positively proportional to the industrial water use and inversely proportional to the other five types of water use. The larger the proportion of secondary industry output value, the lower the agricultural, urban public, residential, and ecological and environmental freshwater use, and even the total water use. Therefore, it can be seen that the development of the secondary industry can greatly improve the efficiency of water resource use. The proportion of output value of the tertiary industry was only inversely proportional to the industrial use, with the other five types of freshwater use being positively proportional. Therefore, it can be seen that the tertiary industry consumed a large amount of freshwater and that the development of water-saving technology is important.

4.1.2 Alignment of industrial output and tap water use proportions

Analysis of the relationship between industrial output and industrial tap water use (Figure 5) revealed that, from 2010 to 2014, the proportions of both industrial output and tap water use in Daishan exhibited similar declining trends. However, from 2014 to 2019, their trajectories diverged: the proportion of industrial output slightly decreased, while the industrial tap water use increased significantly, suggesting a marked rise in industrial water use. This increase may be attributed to industrial expansion and the introduction of water-intensive industries such as petrochemicals in Daishan.

4.2 Dynamic impact of industrial evolution on the freshwater use structure

4.2.1 Impact on tap water use

Based on the 2010–2019 Daishan industrial structure evolution characteristic data and the tap water structure information entropy data, using SPSS23.0, we carried out principal component regression of the industrial factors, calculated the score of each principal component, performed multiple regression analysis, and, finally, through conversion calculations, obtained the coefficients of each industrial factor (Table 7).

Table 7 displays the three principal components of the industrial structure factors affecting the freshwater resource use in Daishan.

1. Component 1 was dominated by the employment–industrial structure deviation coefficient, followed by the secondary industry's comparative labor productivity and employment–industrial structure deviation, indicating that industrial structure efficiency was the primary influence.

2. Component 2 showed strong loadings for the primary industry's output value share, industrial structure entropy, and employment–industrial structure deviation degree, reflecting the impact of the primary industry scale and structural efficiency.

3. Component 3 exhibited notable loadings for the tertiary industry's comparative labor productivity coefficient and industrial structure transformation speed, suggesting that it captured the tertiary industry benefits and institutional stability effects.

The conversion coefficient analysis revealed that four factors significantly influenced the freshwater use structure: the primary

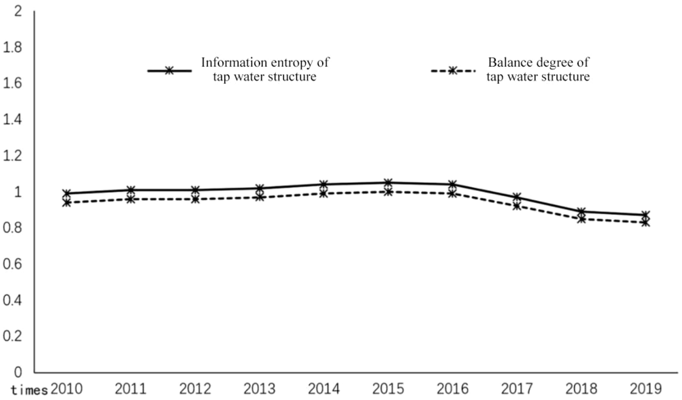

FIGURE 4
Information entropy and balance degree curve of the tap water structure in Daishan Island.

TABLE 5 Results of the evaluation of the freshwater resource–social economy complex system in Daishan Island.

	2014	2015	2016	2017	2018
Ui	0.2799	0.5737	0.5807	0.6935	0.5704

industry employment–industrial structure deviation, the primary industry comparative labor productivity coefficient, the primary industry output value proportion, and the industrial structure entropy. Notably, the industrial structure entropy and the primary industry comparative labor productivity coefficient showed negative correlations with the freshwater use structure entropy.

The employment–industrial structure deviation of the primary industry exerted the strongest positive influence (conversion coefficient = 0.297). From 2010 to 2019, Daishan's primary industry consistently exhibited a negative deviation where the employment share exceeded the output share, indicating an initially low productivity. However, the shrinking absolute values demonstrated a gradually converging output and employment proportions, signaling effective productivity improvements. The freshwater use structure entropy remained near 0.989, reflecting relative stability that increases as the gap between the primary industry employment and the output shares narrows.

Conversely, the primary industry comparative labor productivity coefficient demonstrated the most substantial negative influence (conversion coefficient = −0.297). During 2010–2019, this coefficient stayed above 1, substantially exceeding those of the secondary and tertiary industries, although the gap narrowed over time. This suggests that Daishan's primary industry maintained a clear productivity advantage that diminished gradually. The relationship followed an inverted U-shape: as the primary industry productivity approaches a critical threshold, the freshwater use structure entropy peaks, indicating an optimal industrial structure ratio that maximizes the freshwater use stability.

The proportion of the primary industry output value mirrored the effect of the comparative labor productivity coefficient. The industrial structure entropy inversely affected the freshwater use structure entropy, with its 2010–2019 trend showing a decline. This suggests that more balanced three-industry ratios correlated with greater freshwater use instability and uneven industrial distribution of water resources.

4.2.2 Impact on the total freshwater use structure

The principal component regression analysis of the results of Daishan's industrial structure evolution characteristics and the entropy data of the total water use structure from 2014–2018 is shown in Table 8. From the table, it can be seen that there are four principal components of the industrial structure factors in Daishan.

1. In the first principal component, the employment–industrial structure deviation degree of the primary industry, the employment–industrial structure deviation degree, the comparative labor productivity in the primary industry, and the deviation coefficient of the comparative labor productivity in the industry. The load value of the first principal component was relatively large, indicating that it mainly reflected the influence of the primary industry structural efficiency and the balance of industrial development on the total water use structure.
2. The load value of the second principal component of the secondary industry conversion direction coefficient and the tertiary industry conversion direction coefficient was large, indicating that the second principal component mainly reflected the influence of the degree of the advantages of the secondary and tertiary industries on the total water use structure.
3. The load value of the third principal component of the industrial structure competition effect and the industrial structure entropy had larger loading values (>0.5), showing that the third principal component mainly reflected the influence of the degree of balance of the industrial structure and its specialized production capacity on the total water use structure.
4. The factor with the largest influence in the fourth principal component was consistent with the second principal component: the direction coefficient of conversion of the secondary and tertiary industries had the largest loading value, and the loading value of the efficiency of the composition of the industrial structure was also larger, showing that the fourth principal component reflected the influence of rationalization and advanced industrial structure on the total water structure.

According to the regression results of the converted independent variable coefficients:

1. The coefficient of comparative labor productivity of the secondary industry, the employment–industrial structure deviation of the secondary industry, the proportion of output value of the tertiary industry, the index of difference in comparative labor productivity of the industry, the coefficient of deviation of the employment–industrial structure, and the employment–industrial structure deviation of the primary industry had a relatively significant impact on the total water

TABLE 6 Relationship between the proportion of industries and water use in Daishan Island.

Proportion	Agricultural water use	Industrial water use	Urban public water use	Residential water use	Ecological and environmental water use	Total water content
Primary production	0.794	−0.573	0.117	0.635	0.79	0.689
Secondary production	−0.52	0.295	−0.087	−0.56	−0.68	−0.545
Tertiary production	0.367	−0.163	0.088	0.507	0.604	0.465

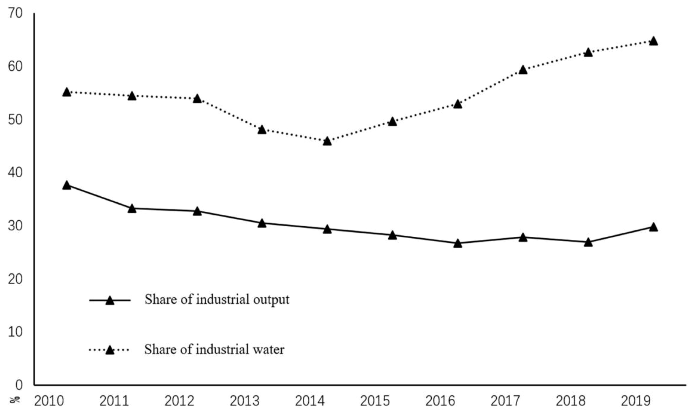

FIGURE 5
Trends of the industrial output value and industrial water use in Daishan Island from 2010 to 2019.

use structure, in which the proportion of output value of the tertiary industry was negatively correlated with the total water use industry structure entropy.

2. The coefficient of comparative labor productivity of the secondary industry in Daishan in 2014–2019 showed a fluctuating downward trend, but its value remained above 1, indicating the high efficiency of the industrial structure; however, its degree of dominance weakened. The information entropy value of the total water use structure was high, and the proportion of water use in each industry was basically stable. Therefore, it can be seen that the weakening of the structural benefits of the second industry can instead consolidate the stability of the total water use system.
3. The degree of deviation of the employment–industrial structure of the secondary industry from 2014 to 2018 was greater than 0 and showed a decreasing trend in general, showing that the structures of both the industry and employment tend to be balanced and the degree of coordination of the inter-industry transfer of the labor force is enhanced. This shows that the more balanced the development of the structure of the secondary industry and the structure of employment and the more coordinated the inter-industry transfer of labor, the more balanced the structure of the total water use and the more stable the system.
4. The proportion of output value of the tertiary industry in Daishan in 2014–2018 showed obvious fluctuations, first rising and then falling. Its negative effect on the information entropy of the total water use structure indicates that the higher its proportion of output value, the smaller the information entropy of the water use structure, the more unbalanced the proportion of the total water use structure, and the more unstable the total water use structure.
5. The industry ratio labor productivity difference index of Daishan decreased year by year from 2014 to 2018, showing that the development of the various industries in Daishan was equalized and that the industrial structure benefit increased. This indicates that the industrial structure benefit is inversely proportional to the stability and balance of the total water use structure, and the bigger the industrial structure benefit, the more uneven the total water use structure is instead. The employment–industrial structure deviation coefficient and the primary industry employment–industrial structure deviation were positively

TABLE 7 Results of the principal component regression of the industrial structure and the tap water structure in Daishan Island.

Component	*a*	*a*	*a*	*λ*
x_1	0.0125	0.4104	0.2196	0.2255
x_2	0.2664	−0.1546	−0.2575	0.1694
x_3	−0.2992	−0.1263	0.1193	−0.0230
H	−0.0223	0.3885	0.2552	−0.2215
ϑ_1	0.2024	−0.3447	0.0765	0.2967
ϑ_2	0.3084	0.0141	−0.1911	0.0882
ϑ_3	0.3041	0.0109	0.1531	0.1240
Φ	0.3153	−0.1140	−0.0314	0.1862
V	0.2306	0.1591	0.3056	0.0206
θ_1	0.1631	0.3401	−0.2243	−0.1710
θ_2	−0.2326	−0.1646	−0.2647	−0.0138
θ_3	0.1696	0.0160	0.4783	0.1035
B_1	−0.2024	0.3447	−0.0765	−0.2967
B_2	0.3094	0.0096	−0.1934	0.0911
B_3	−0.1959	−0.2645	0.3074	0.1205
S	0.3041	−0.1614	0.0012	0.2145
MIX	0.1312	0.3529	−0.2611	−0.1947
DIF	−0.2526	0.0401	−0.3003	−0.1511
T	0.3780	−0.6160	0.1030	0.5329
R	0.4160			
R^2	0.1730			
After adjusted R^2	0.4470			
Sig.	0.0350	0.0175	0.2390	
E	0.0170			

MIX refers to the mixture index calculated, measuring the degree of integration based on the weighted sum of principal component scores. DIF refers to the difference index calculated, representing the absolute or relative divergence across the identified components.

TABLE 8 **Principal component regression of the industrial structure and the total water structure in Daishan Island.**

Component	a	a	a	a	λ
x_1	−0.2244	0.2897	0.2253	0.0036	−0.2647
x_2	0.2355	−0.2814	0.1190	−0.1423	0.7755
x_3	−0.2296	0.2545	−0.2524	0.1885	−0.9482
H	−0.1910	0.2110	0.4713	−0.2205	0.2066
ϑ_1	0.2941	0.1407	0.0048	−0.0124	0.8410
ϑ_2	0.2864	0.1125	0.2269	0.0107	1.0686
ϑ_3	0.2667	0.1796	0.0200	0.2845	0.6546
Φ	0.2907	0.1462	0.0527	0.0854	0.8445
V	−0.2395	0.2758	−0.0831	0.1592	−0.7525
θ_1	−0.2451	0.2152	0.1662	0.2952	−0.5478
θ_2	0.0160	−0.3887	0.1070	0.4650	−0.1449
θ_3	−0.0145	0.3823	0.0016	−0.4988	0.2937
B_1	−0.2941	−0.1407	−0.0048	0.0124	−0.8410
B_2	0.2793	−0.0764	0.2317	−0.2356	1.1243
B_3	0.2512	0.2346	−0.1710	0.1654	0.4538
S	0.2932	0.1430	0.0328	0.0293	0.8529
MIX	−0.1608	−0.2953	−0.3012	−0.3761	−0.6919
DIF	−0.1543	−0.1837	0.6119	0.0640	0.2415
T	2.7000	0.2500	1.2000	−0.4720	9.0153
R	0.7900				
R^2	0.4500				
After adjusted R^2	0.5200				
Sig.	0.0174	0.0025	0.0089	0.1570	
E	2.8823				

MIX refers to the mixture index calculated, measuring the degree of integration based on the weighted sum of principal component scores. DIF refers to the difference index calculated, representing the absolute or relative divergence across the identified components.

correlated with the industry structure entropy, reflecting that the development balance of the industry structure and the employment structure and the coordination of inter-industry labor force transfer had a strong positive influence on the total water structure.

4.3 Industrial structure evolution and freshwater resource stress

SPSS 23.0 was used to conduct principal component analysis of the industrial structure factors, followed by regression analysis to obtain the independent variable coefficients through conversion calculations. The results are presented in Table 9.

Daishan's industrial structure factor showed three principal components.

1. In the first principal component, the factor loadings of the industry–employment structure deviation coefficient, the secondary industry comparative labor productivity coefficient, and the secondary and tertiary industry employment–structure deviation degrees were all markedly high. This indicates that the first principal component primarily captured the balance between the secondary and tertiary industrial structures and the employment structure, as well as the influence of industrial–structural efficiency on the coordination of water resource utilization.
2. In the second principal component, the proportion of output value of the primary industry, the industrial structure entropy and industrial structure composition effect, the primary industry comparative labor productivity, and the primary industry employment–industrial structure deviation degree loading values were relatively large. The principal component mainly reflected the industrial structure and the primary industry structure benefit and the development balance on the coordination of water resource.
3. In the third principal component, the tertiary industry conversion direction coefficient and the tertiary industry employment–industrial structure deviation degree loading values were obviously larger. In the third principal component of the conversion direction coefficient of the

TABLE 9 **Results of the principal component regression of the industrial structure and the water resource–socioeconomic complex system in Daishan Island.**

Component	a	a	a	λ
x_1	0.0125	0.4104	0.2211	0.8908
x_2	0.2664	−0.1546	−0.2594	0.7443
x_3	−0.2992	−0.1263	0.1201	−1.4412
H	−0.0223	0.3885	0.2570	0.6410
ϑ_1	0.2024	−0.3447	0.0771	−0.9460
ϑ_2	0.3084	0.0141	−0.1924	1.2575
ϑ_3	0.3041	0.0109	0.1542	0.3329
Φ	0.3153	−0.1140	−0.0317	0.4049
V	0.2306	0.1591	0.3078	0.2837
θ_1	0.1631	0.3401	−0.2259	2.1549
θ_2	−0.2326	−0.1646	−0.2665	−0.4149
θ_3	0.1696	0.0160	0.4817	−0.8113
B_1	−0.2024	0.3447	−0.0771	0.9460
B_2	0.3094	0.0096	−0.1948	1.2500
B_3	−0.1959	−0.2645	0.3096	−2.1828
S	0.3041	−0.1614	0.0012	0.1275
MIX	0.1312	0.3529	−0.2630	2.2234
DIF	−0.2526	0.0401	−0.3024	0.3505
T	2.2900	3.5060	−2.6070	
R	0.9840			
R^2	0.9690			
After adjusted R^2	0.8760			
Sig	0.0262	0.0177	0.0233	
E	2.7300			

MIX refers to the mixture index calculated, measuring the degree of integration based on the weighted sum of principal component scores. DIF refers to the difference index calculated, representing the absolute or relative divergence across the identified components.

tertiary industry, the comparative labor productivity of the tertiary industry and the speed of conversion of the industrial structure load values were significantly larger, with the principal component mainly reflecting the degree of development advantage of the tertiary industry and the industrial structure benefits on the degree of coordination of water resource use.

The results of the analysis of the conversion coefficients of the independent variables of the tertiary industry's comparative labor productivity and the proportion of its output value were less than −1, i.e., the two indicators were strongly negatively correlated with the coordination of the water resource–socioeconomic composite system. The coefficients of the conversion direction of the primary industry, the employment of the secondary industrial structure deviation, and the independent variable coefficients of the secondary industry comparative labor productivity were all >1; that is, the three indicators were negatively correlated with the. The coefficients of the primary industry conversion direction, the secondary industry employment–industrial structure deviation, and the secondary industry comparative labor productivity were >1; that is, the three indicators were strongly positively correlated with the coordination of the water resource–socioeconomic complex system. The regression coefficients of the coefficient of comparative labor productivity of the tertiary industry and the coordination of the water resource–socioeconomic composite system were −2.1828; that is, for every unit of increase in the industrial structure efficiency of the tertiary industry, the coordination of the water resource–socioeconomic composite system decreases by 2.1828 units, indicating that the tertiary industry was the main influencing factor for the irrational distribution of water resource in the social and economic systems due to the catering and car washing services in the tertiary industry being the main influencing factors. The tertiary industry was the main influencing factor for the irrational allocation of the water resource in the social and economic systems because the catering and car washing services in the tertiary industry are high-water-use industries. The regression coefficient between the comparative labor productivity coefficient of the secondary industry and the coordination of the composite system of water resource and the socioeconomic system was 1.25, showing that the structural efficiency of the secondary industry had a positive influence on it. Comprehensive analysis of the degree of deviation of the secondary industry from the employment–industrial structure revealed that the structural efficiency of the secondary industry increased with the improvement of the balance between the employment structure and the industrial structure, and the more reasonable the distribution of the water resource in the social and economic system, the higher the efficiency of its use.

4.4 Freshwater environmental pollution assessment of the industrial structure

Table 10 displays the results of the comprehensive evaluation of the effect of water environment pollution. Daishan's pollution effect evaluation index showed a trend of first decreasing and then increasing from 2015 to 2019, indicating that the water pollution in Daishan had significant fluctuations, with the 2015–2016 water pollution obviously weakened and, after 2016, worsened again. Analysis of the evaluation index demonstrated that the change was mainly due to the industrial wastewater, the industrial oxygen demand, and the industrial petroleum emissions, among others, which appeared to first decrease and then increase the trend of change. The significant impact of industrial structure changes on water pollution is evident from the observed variations.

TABLE 10 Results of the evaluation of the water pollution effect in Daishan Island.

	2015	2016	2017	2018	2019
Ui	0.6564	0.3882	0.4038	0.4175	0.4248

SPSS 23.0 was used to carry out the principal component analysis of the industrial structure factors, on the basis of which regression analysis was carried out to obtain the coefficients of the independent variables through conversion calculations. The results of the principal component regression are shown in Table 11.

In the principal component analysis, there were four factors in the industrial structure evolution.

TABLE 11 Regression results of the industrial structure evolution and the water pollution impact in Daishan Island.

Component	a	a	a	a	λ
x_1	−0.2244	0.2897	0.2253	0.0036	−0.5765
x_2	0.2355	−0.2814	0.1190	−0.1422	1.3027
x_3	−0.2296	0.2545	−0.2524	0.1884	−1.5165
H	−0.1910	0.2110	0.4713	−0.2204	0.3109
ϑ_1	0.2941	0.1407	0.0048	−0.0124	0.4490
ϑ_2	0.2864	0.1125	0.2269	0.0107	0.7620
ϑ_3	0.2667	0.1796	0.0200	0.2844	−0.0990
Φ	0.2907	0.1462	0.0527	0.0853	0.3537
V	−0.2395	0.2758	−0.0831	0.1591	−1.2766
θ_1	−0.2451	0.2152	0.1662	0.2951	−1.0455
θ_2	0.0160	−0.3887	0.1070	0.4648	0.0426
θ_3	−0.0145	0.3823	0.0008	−0.4986	0.1791
B_1	−0.2941	−0.1407	−0.0048	0.0124	−0.4490
B_2	0.2793	−0.0764	0.2317	−0.2355	1.4056
B_3	0.2512	0.2346	−0.1710	0.1662	−0.3091
S	0.2932	0.1430	0.0328	0.0293	0.4204
MIX	−0.1608	−0.2953	−0.3012	−0.3759	0.2233
DIF	−0.1543	−0.1837	0.6119	0.0631	0.7332
T	2.1330	−1.4530	1.4580	−1.5330	
R	1.0000				
R^2	0.8860				
After adjusted R^2	0.6523				
Sig.	0.0123	0.2420	0.0241	0.0223	
E	0.1112				

MIX refers to the mixture index calculated, measuring the degree of integration based on the weighted sum of principal component scores. DIF refers to the difference index calculated, representing the absolute or relative divergence across the identified components.

1. In the first principal component, the primary industry comparative labor productivity coefficient, the primary industry employment–industrial structure deviation, the industry comparative labor productivity difference index, and the employment–industrial structure deviation loading values were larger. It can be seen that the principal component mainly reflected the primary industry structure benefit that and the comprehensive balance of industrial development with the.
2. In the second principal component, the loading value of the direction coefficient of the conversion of the second and third industries was the largest; therefore, this principal component mainly reflected the influence of the structural status of the second and third industries on the effect of water pollution.
3. In the third principal component, the loading value of the entropy of the industrial structure only was a little bit larger; therefore, this principal component mainly reflected the influence of the comprehensive industrial structure on the effect of water pollution.
4. In the fourth principal component, the loading value of the conversion direction of the second and third industrial structures and the effect of the composition of the industrial structure were larger; therefore, it can be seen that this principal component mainly reflected the influence of the status of the second and third industrial structures and the rationalization and advancement of the industry on the effect of water pollution.

Further analysis found that the proportion of output value of the tertiary industry, the speed of industrial structure transformation, and the coefficient of the direction of primary industry structure transformation were negatively correlated with the effect of water pollution, and the coefficients of the independent variables were all less than−1. The coefficient of the comparative labor productivity of the secondary industry and the proportion of the output value of the secondary industry were positively correlated with the effect of water pollution, and the coefficients of the independent variables were all >1. The regression coefficient of the proportion of the output value of the tertiary industry and the effect of water pollution was −1.5165. The regression coefficient was −1.5165 when the proportion of the output value of the tertiary industry increased by 1 unit and the effect of water pollution decreased by 1.5 units, indicating that the development of the tertiary industry can effectively reduce the water pollution, with the tertiary industry being a low-pollution industry. The conversion speed of the industrial structure was related to the proportion of industrial structure: the bigger the difference, the faster the conversion speed. Its regression coefficient with the effect of water pollution was −1.2766, indicating that the faster the conversion speed of the industrial structure, the lower the effect of water pollution; that is, the bigger the difference of the regional industrial structure, the lower the effect of water pollution. The regression coefficient of the primary industry structure conversion direction coefficient and the water pollution effect was −1.0455; that is, the faster the primary industry structure conversion speed, the lower the water pollution effect. It can be seen that the primary industry of Daishan in the past few decades of the development of the water environment had a greater impact. The regression coefficient of the comparative labor productivity of the secondary industry and the freshwater environment effect was 1.4056. This shows that there is a significant positive correlation between the structural benefit of the secondary industry and water pollution; that is, the greater the structural benefit of the secondary industry, the weaker the water pollution effect. The regression coefficient between the proportion of output value of the secondary industry and water pollution was 1.3027, reflecting a positive correlation between the proportion of output value of the secondary industry and the water pollution in the region: the larger the proportion of industrial output value, the higher the effect of water pollution. Considering the impact of the comparative labor productivity of the secondary industry, it can be seen that improving the structural effect of the secondary industry is an important approach to alleviating the industrial development and water pollution.

5 Discussion and conclusions

Focusing on Daishan Island, Zhoushan City, this study empirically dissects how industrial restructuring reshapes freshwater use efficiency and modulates the coupled socioeconomic–ecological system. The research data revealed that dynamic adjustments of the industrial structure in Daishan had a significant impact on the allocation structure of the freshwater resource in the region. Specifically, the enhancement of production efficiency in the primary industry contributed to the entropy reduction of the tap water supply structure in a positive way, reflecting the promotion of the stability of freshwater resource use by the enhancement of agricultural effectiveness. However, along with the flourishing of the secondary and tertiary industries, in particular the industrial and service sectors, the structure of freshwater use showed more significant fluctuations, thus weakening the stability of the tap water supply system. Further analysis showed that the expansion of the secondary and tertiary industries in Daishan had a profound impact on the coordination of the integrated freshwater resource–socioeconomic system. Optimization of the employment structure of the secondary industry and improvement of the balance of the industrial structure significantly contributed to the enhancement of the efficiency of freshwater resource use and the improvement of the coordination of the system. In contrast, the rapid expansion of the tertiary industry, particularly the rise of freshwater-consuming service industries, may lead to the imbalance of freshwater allocation and weaken the overall coordination of the system. The study also reveals the double impact of industrial structure advancement and rationalization on water pollution. The increase in the proportion of the tertiary industry, as a positive signal for environmental protection, effectively reduced the pollution burden of the freshwater environment. However, the rapid expansion of the secondary industry, especially the intensification of industrial activities, may become an important driver of the deterioration of the freshwater environment, emphasizing the urgency of balancing optimization of the industrial structure and environmental protection in regional economic planning.

The demand for freshwater resource and the pressure of pollution in the sea are subtle threats to the sustainable development of islands. Freshwater scarcity not only limits the economic growth of islands but also damages natural ecosystems, which in turn can lead to social stability risks. At the same time, marine pollution leads to the degradation of ecosystems, reduction of fishery resources, and loss of tourism, exacerbating pressures on island economies to develop, consume, and produce in ways that define economic sustainability (Stoddart et al., 2024). To address these challenges, island regions need to adopt multilevel integrated measures, including strengthening freshwater resource management, promoting freshwater conservation techniques, and improving freshwater use efficiency to cope with increasing freshwater demand. Moreover, implementing strict marine environmental protection policies, establishing marine protected areas and total pollutant discharge controls to ensure the restoration and protection of marine ecosystems, promoting economic diversification, and reducing dependence on a single resource or industry, thereby increasing the resilience of island economies, are also beneficial. Island cities are facing the decline of traditional agriculture and fisheries and the restriction of residents' livelihoods in the transformation of their industrial structure, which are turning into port terminals and service industries. Urbanization has led to a decline in natural villages and an increase in concentrated settlements, bringing land use changes and traffic impacts, and the island city faces unique urbanization challenges. While the city has grown in size and diversified its functions, the economy is mostly dependent on the marina, which is highly affected by the volatility of the shipping market. In contrast, traditional marine economic activities such as fishing are more stable. Therefore, the island city needs to develop its economy in a prudent manner, reduce its over-reliance on the port industry, and explore new growth points such as tourism and creative technology in order to ensure sustainable economic development (Fu et al., 2023). This study primarily adopts a temporal and system-level analytical perspective due to limitations in sub-island spatial data availability. However, the freshwater stress and pollution processes in Daishan Island are inherently spatially heterogeneous, influenced by uneven industrial clustering, population distribution, and the water infrastructure layout. Industrial parks, port-adjacent zones, and urban centers are likely to exert disproportionate pressure on local freshwater bodies. Future research incorporating spatially explicit data and GIS-based or spatial econometric methods would enable the identification of intra-island freshwater risk hotspots and improve the precision of freshwater management and industrial layout optimization.

In order to realize the long-term development of the region, policymakers need to incorporate the dual considerations of efficient freshwater resource use and environmental protection in the industrial structure adjustment and promote a deep integration and coordination between water resource management strategies and socioeconomic–ecological systems.

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

LL: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. SZ: Formal analysis, Investigation, Software, Writing – original draft. XL: Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – review & editing. RM: Supervision, Writing – review & editing. JL: Funding acquisition, Project administration, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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