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Quantitative traceability study on the water quality driving forces across cities in the Xiang River Basin

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ABSTRACT

Based on the monthly monitoring data of water quality monitoring stations in the Xiang River Basin from 1990 to 2020, the Mann–Kendall test was used to analyze dissolved DO, BOD_5, COD_{Mn}, TP, NH_3-N,Cd, As, and Cr^{6+}. The changing trend of nine indicators, including the stepwise regression method, was used to determine the cross city driving force of each water quality index, and the contribution rate (weight) of each driving force was obtained by principal component analysis. The research results show that (1) agriculture in Yongzhou is the main driving force, and its contribution rate is 67.2%; (2) urbanization has a greater impact on the driving process of the water environment in the Xiang River Basin, and its contribution rate is as follows: Changsha (83%) > Hengyang (80.7%) > Pingxiang (63.7%) > Chenzhou (60.9%) > Xiangtan (57.4%) > Zhuzhou (50%) > Loudi (48.5%); (3) the urbanization of Zhuzhou City and Loudi City's urban sewage discharge not only has an impact on the city's water environment, but also drives the water environment in the downstream Xiangtan area. The research results can provide a basis and reference for the study of water environmental governance in the basin.

Key words: contribution rate, cross city driving force, water quality factor, Xiang River Basin

HIGHLIGHT

- Understanding the trend of water environment changes in the Xiang River Basin and comprehensively analyzing the driving factors of water environment changes can provide ideas and solutions for future pollution prevention and control in the river basin, which is of great significance to ecological environmental protection and regional economic development.

1. INTRODUCTION

The water environment of the river basin is the result of the combined effect of natural factors and human activities (Shao *et al.* 2022), and the global population surge and frequent human activities have put enormous pressure on the water environment (Giri & Qiu 2016). The watershed covers a wide range and the water environment problems are complex. An analysis of the driving force of the water environment is a difficult point in watershed research. Some scholars have used the RSPARROW model to explore the driving forces of total nitrogen and total phosphorus in the Yellow River and Yangtze River Basins and concluded that rainfall and point source emissions are the main driving factors for the temporal changes in nitrogen and phosphorus fluxes in the basin (Zheng 2022). Some scholars have studied the population distribution and change in the driving force of phytoplankton in Dongting Lake and concluded that the driving force of environmental factors is greater than the spatial driving force (Yan *et al.* 2023). Among the many human activities, the process of urbanization has developed rapidly in recent years, which effectively promotes social progress and economic development, and also causes serious water pollution (Luo *et al.* 2022). The level of urbanization affects the type and contribution rate of water pollution sources (Ma *et al.* 2021; Zhou *et al.* 2022).

The Xiang River Basin brings together more than 60% of the population and 70% of the total economic output of Hunan Province, covering the urban agglomeration around Changsha, Zhuzhou, and Xiangtan. The degree of urbanization and economic growth in the basin ranks first in Hunan Province (Wang *et al.* 2023). The basin is rich in water resources, which provides abundant natural resource support for the urbanization process and social development of the basin. However,

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with the rapid development of regional society and economy, coupled with many factors such as urban, industrial, and agricultural pollution, as well as problems such as pollution left over from history, the water environment in the Xiang River Basin has gradually become more complicated (Chen *et al.* 2019). Many scholars have carried out research on the water environment of the Xiang River Basin from various perspectives, including water environment assessment methods (Liu *et al.* 2018; Wang *et al.* 2021), temporal and spatial evolution characteristics of water quality, and analysis of driving factors (Cao *et al.* 2019; Liu *et al.* 2019; Shi 2020). Xie (2016) analyzed that water pollution in the Xiang River was mainly because of large-scale emission of industrial wastewater, extensive pesticide use, and urban sewage pollution. However, Xie's analysis does not have quantitative and accurate identification. Zeng *et al.* (2023) described the calculation of the ingegrated water quality index (IWQI). The authors conclude that the tributaries of Xiao River, Lei River, and Chongling River always had better water quality than the mainstream. But Qiu & Chen (2022) researched that the total potential ecological hazard index of heavy metals is the Chongling River > Lei River > Xiang River mainstream. Chen *et al.* (2019) believed that after 2008, economic factors, such as urban development, were no longer the main factors affecting the pollution of the Xiang River Basin. The authors researched Cao *et al.* (2019), and based on the water environment data of the Xiang River Basin and the basin panel data in 2020, it was concluded that urbanization indicators such as urban sewage discharge and regional GDP are still the main driving forces of pollution in the basin; however, the cross city driving factors are often overlooked by scholars. Further research is needed to quantitatively trace the water quality indicators of the Xiangjiang River Basin, namely the driving factors across cities.

Based on the monthly monitoring data of the water environment in the Xiang River Basin from 1990 to 2020, this paper uses the Mann–Kendall rank correlation test to analyze the long-term trend of water quality factors. The stepwise regressive equation (Wang *et al.* 2019) was used to determine the main driving force of watershed pollution; three indicators of population urbanization, spatial urbanization, and economic urbanization were added in the driving force analysis (Dong *et al.* 2022), to consider the driving force impact of upstream cities on monitoring stations, and to determine the contribution rate of the urbanization process to the changing trend of the water environment in the Xiang River Basin. Understanding the trend of water environment changes in the Xiang River Basin and comprehensively analyzing the driving factors of water environment changes can provide ideas and solutions for future pollution prevention and control in the river basin, which is of great significance to ecological environmental protection and regional economic development.

2. MATERIALS AND METHODS

2.1. Study area

The Xiangjiang River flows through Yongzhou, Hengyang, Xiangtan, Zhuzhou, and Changsha from south to north in Hunan Province, and then flows into Dongting Lake and the Yangtze River in Xiangyin County, Yueyang City, as shown in Figure 1.

The Xiang River Basin covers an area of 96,000 km^2, and the basin area within Hunan Province is 85,300 km^2. The average annual rainfall in the basin reaches 1,460 mm, and the average annual runoff is over 60 billion m^3. The Xiang River is the mother river of the Hunan people and the river of life that nurtures the Hunan civilization. There are seven prefecture-level cities along the coast, including Changsha, Zhuzhou, Xiangtan, Hengyang, Yongzhou, Chenzhou, and Loudi. The total population of the basin is 32.765 million, accounting for about 48% of the provincial population. Its total economic output accounts for two-thirds of the province, making it the most densely populated and economically developed basin in Hunan.

The basin has a developed river system and many tributaries. Among them, the tributaries with a basin area of more than 10,000 km^2 are Xiao River, Lei River, and Mi River; the first-class tributaries with a drainage area of 3,000–10,000 km^2 are Chungling River, Zhen River, Lu River, Lian River, and Liuyang River. The first-level tributaries with a drainage area of 1,000–3,000 km^2 include Guan River, Zixi River, Luhong River, Bai River, Yi River, Qi River, Juan River, Laodao River, and Wei River. The tributaries of the watershed involve Chenzhou and Loudi, as well as Quanzhou County, Xing'an County, and Guanyang County in Guilin City, Guangxi Province, Shangli County, Lianhua County, Luxi County, Anyuan District, Xiangdong District in Pingxiang City, and Yuanzhou District in Yichun City, Jiangxi Province.

2.2. Data sources

The data used in this paper are the monthly monitoring data of surface water quality from January to December of 16 monitoring sites in the Xiang River Basin from 1990 to 2020. The monitoring site information is shown in Figure 2. Monitoring

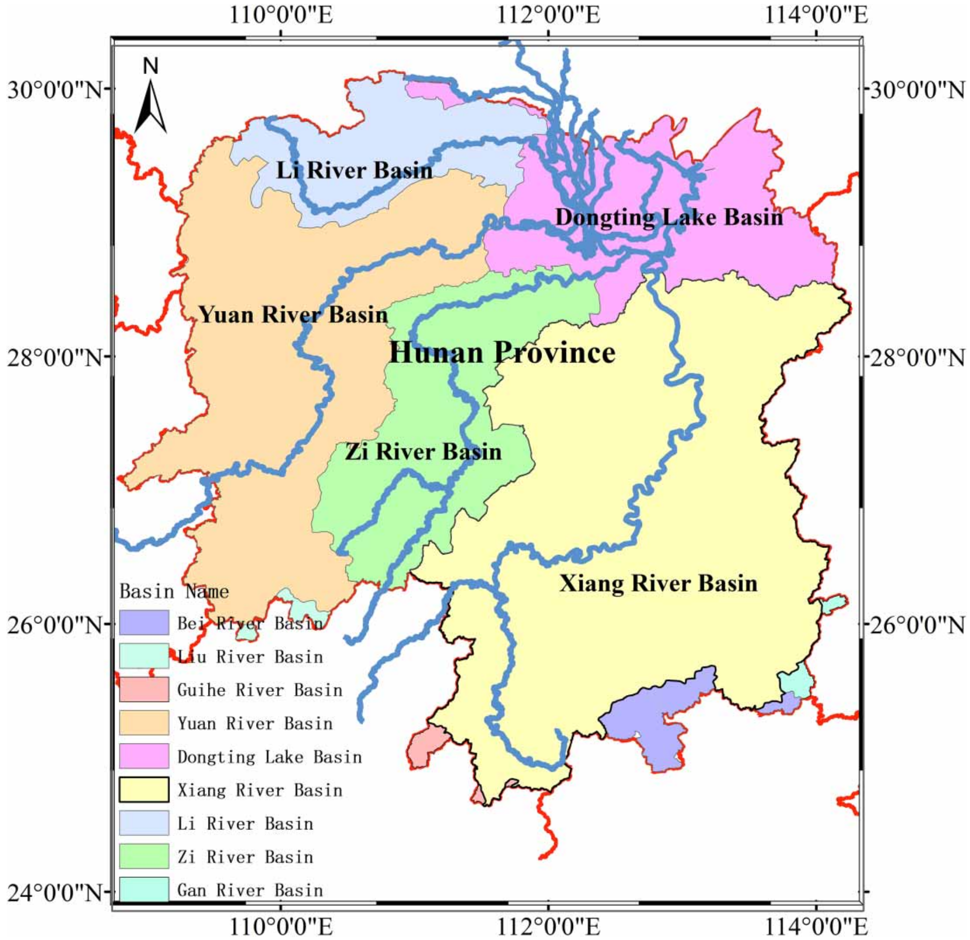

Figure 1 | Location map of the Xiang River Basin.

indicators included water temperature (T), pH, dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD_5), permanganate index (COD_{Mn}), total phosphorus (TP), ammonia nitrogen (NH_3-N), cadmium (Cd), arsenic (As), hexavalent chromium (Cr^{6+}), electrical conductivity, total hardness, total alkalinity, petroleum, fecal coliform, fluoride, chloride, and other indicators. Since water quality reflects the state of the water environment in a region, nine water quality parameters were selected as candidate indicators according to the water quality characteristics in the past 30 years, including DO, BOD_5, COD_{Mn}, TP, and so on.

2.3. Research methods

2.3.1. Mann–Kendall rank correlation test

The Mann–Kendall rank correlation test (M–K test) is a nonparametric statistical test method. In the M–K test, the size of the statistical variable Z represents the changing trend of the data, $Z > 0$ indicates an increasing trend, and $Z < 0$ indicates a decreasing trend. At α significance levels of 0.05 and 0.01, the corresponding $Z_{1-\alpha/2}$ values were 1.96 and 2.32, respectively.

2.3.2. Stepwise regression equation

A regression equation is a data prediction model that can be used for parameter prediction (Wang *et al.* 2019). Regression analysis is a calculation method and theory that studies the specific dependence of one variable (explained variable) on other variables (explaining variables). Regression analysis is further divided into the forward method, the backward method, and the stepwise regression method. The stepwise regression method introduces factors with significant variance

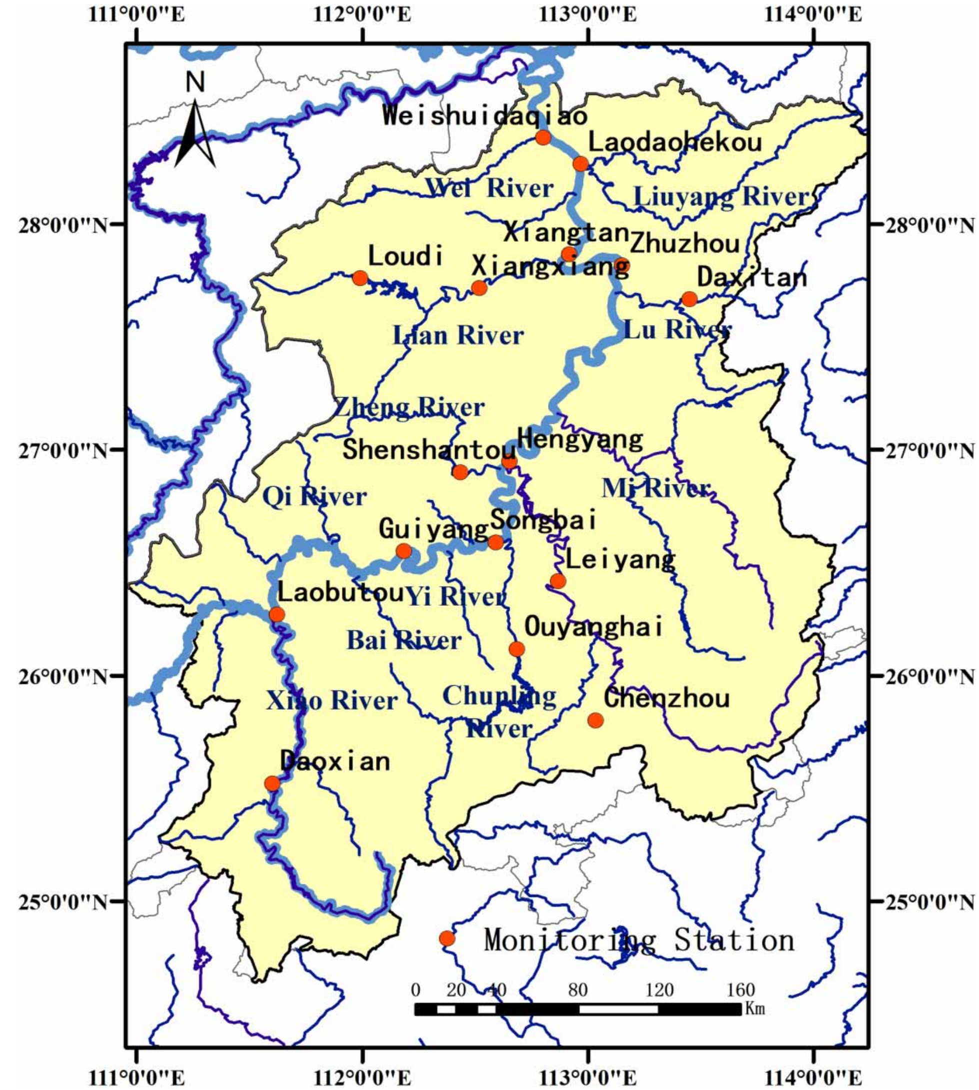

Figure 2 | Location map of the Xiang River water quality monitoring station.

contribution into the regression equation one by one, tests the old factors one by one, and eliminates the factors whose variance contribution becomes insignificant. The optimal regression variance consists of independent variables that have a significant influence. This paper adopts the stepwise regression method, takes the pollution factor as the dependent variable and the corresponding regional socioeconomic factor as the independent variable, and uses SPSS 24.0 software to establish a stepwise regression equation to find the socioeconomic factor that has a significant impact on the pollution factor.

2.3.3. Principal component analysis

Principal component analysis (PCA) is a dimensionality reduction processing technique (Dong *et al.* 2022). Starting from the structural characteristics of the data itself, the data results are relatively objective. Using this method, we can form multidimensional data that are independent of each other and calculate the contribution rate weight of the factor indicators, so that the results can retain the original main information while solving the correlation between indicators. Due to the strong sexuality, the weighting of low-weight indicators is repeated, and the weight of high-weight indicators is too low, which makes the weighting more reasonable. The score of the principal component is the corresponding factor score multiplied by the corresponding arithmetic square root of the variance (Wang *et al.* 2017). The principal component model takes the principal component according to the cumulative contribution rate, and the selection standard requires that the characteristic root is greater than 1. There are k principal components that are mentioned as follows:

$$\begin{aligned}&F_1 = a_{11}Z_1 + a_{21}Z_2 + \ldots + a_{p1}Z_p \quad (\text{first} - \text{principal component})\\&F_2 = a_{12}Z_1 + a_{22}Z_2 + \ldots + a_{p2}Z_p \quad (\text{second} - \text{principal component})\\&\ldots\\&F_k = a_{1k}Z_1 + a_{2k}Z_2 + \ldots + a_{pk}Z_p\end{aligned}$$

where a_{ij} describes the factor score coefficient of factor i in the principal component of factor j, that is, the contribution rate of factor i to the principal component of factor j. It is combined with the corresponding variance contribution rate E_j of the principal component to determine the weight value of the i factor, see formula (1). Since the sum of ownership weight is 1, it needs to be normalized on the basis, see formula (2).

$$W_\mathrm{i} = \sum_{j=1}^{k} |a_{ij}| \times E_j \tag{1}$$

$$W_i^0 = \frac{W_i}{\sum_{i=1}^{p} W_i} \tag{2}$$

The PCA module in SPSS 24.0 is used to analyze the water quality driving factors that have been sought to obtain the contribution rate of each driving factor to the water environment.

2.3.4. Range standardization method

In view of the differences in the dimension and order of magnitude in the original data and the significant differences in measurement units between indicators, this paper uses range standardization methods to standardize the monitoring data, which are positive indicator normalization (see formula (3)) and negative index normalization (see formula (4)).

$$X'_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

$$X'_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \tag{4}$$

where X_{ij} and X'_{ij} are the original data and the standardized data, respectively, and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the corresponding indicator data, respectively.

3. RESULTS

3.1. Spatial variation in water quality factors

The M–K test method was used to analyze the trend of nine indicators from 1990 to 2020, including DO, BOD_5, COD_{Mn}, TP, NH_3-N, Cd, Hg, Cr^{6+} and As, as shown in Figure 3.

There was no obvious change in the trend of DO in Yongzhou, Chenzhou, Guiyang, Chunling, and Lei Rivers; there was a clear upward trend from Hengyang Songbai to the downstream Xiangtan, Zhuzhou, and Loudi. The Changsha Laodao River showed a clear downward trend. BOD_5 in the mainstream of the Xiang River, Yongzhou area (Laoquan), and Chenshui (Chenzhou) showed an obvious downward trend; Hengyang, Zhuzhou, the lower reaches of Lianshui (Xiangxiang), and the Changsha Laodao River all showed an obvious upward trend.

TP in Hengyang and its tributaries, such as Lei River and Chunling River, showed an upward trend, and the mainstream of the Xiang River in Changsha showed an upward trend; the mainstream of the Xiang River in Zhuzhou and Xiangtan showed a downward trend, and in the Lian River and Loudi, it showed a downward trend. COD_{Mn} in the mainstream of the Xiang River in Yongzhou (Laoputou), Hengyang, Zhuzhou, and Xiangtan areas and its tributaries such as Xiao River, Chunling River, Chen River, Zheng River, and the upper reaches of Lianshui showed a significant downward trend; the Lianshui Xiangtan area and the Changsha Laodao River mouth showed a significant upward trend. NH_3-N showed a significant upward

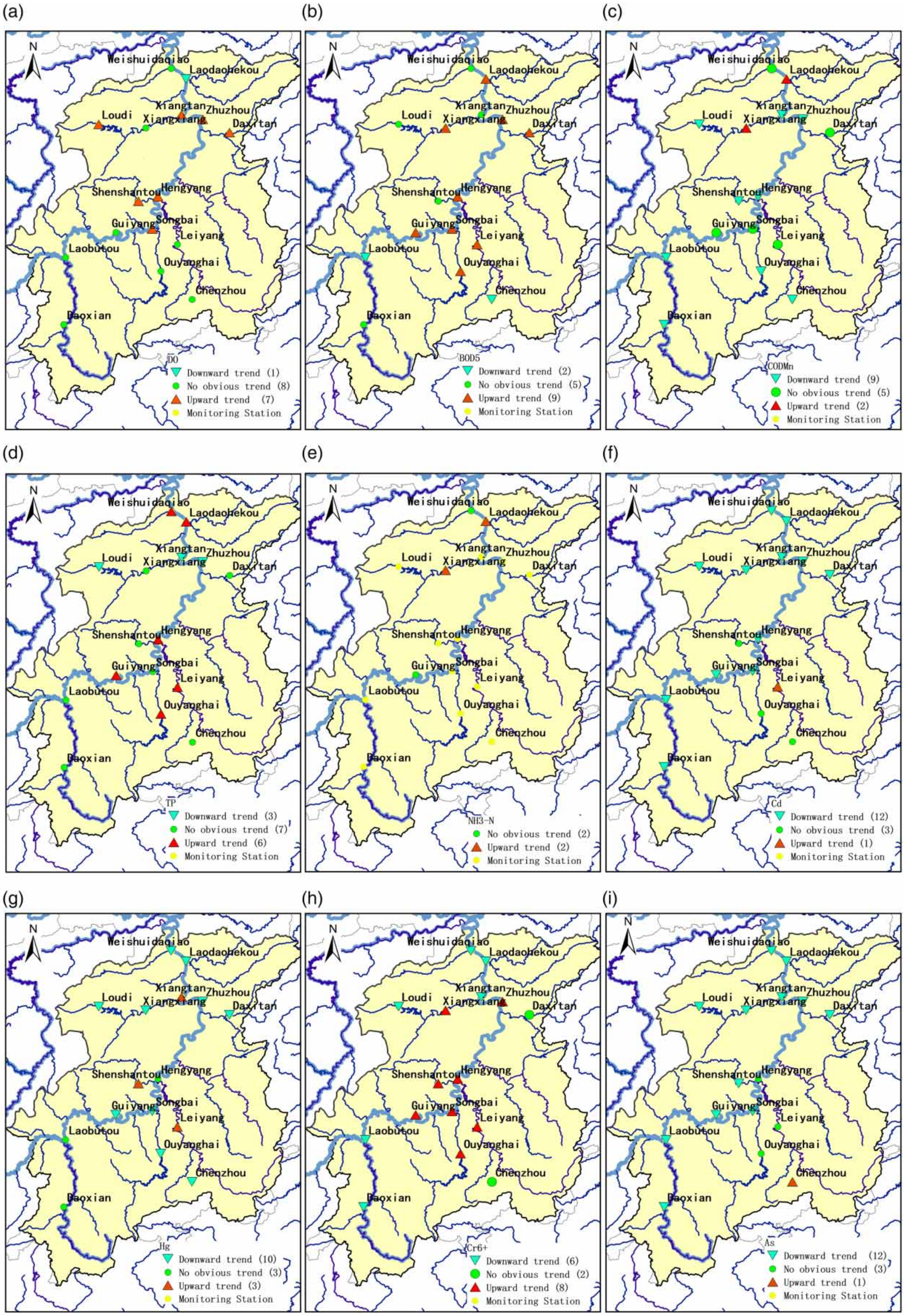

Figure 3 | Spatial distribution of changes in water quality factors. (a) BOD_5, (b) DO, (c) COD_{Mn}, (d) TP, (e) NH_3-N, (f) Cd, (g) Hg, (h) Cr^{6+}, and (i) As.

trend in Yongzhou, Hengyang, Zhuzhou, and Changsha; the mainstream of the Xiang River and the tributaries such as Chen River, Lei River, and Chunling River, all showed an upward trend. The trend of water changes is not obvious.

Hg showed a significant downward trend in Hengyang, Zhuzhou, and Changsha; the mainstream of the Xiang River and its tributaries such as Chen River, Chunling River, Lian River, and Lu River also showed a significant downward trend. The tributaries of the Zheng River also showed an obvious downward trend in the Xiangtan area of the mainstream of the Xiang River. The Lei River showed a clear upward trend. Cd in the mainstream of the Xiang River and some tributaries, including the Xiao River, Lu River, and Lian River, all showed a downward trend; the tributary Lei River showed an upward trend. Cr^{6+} is mainly in the area from Hengyang to Zhuzhou, the mainstream of the Xiang River, and the Chunling River, Lei River, and Zheng River, and the Lian River and Xiangtan areas are on the rise; the mainstream of the Xiang River is Yongzhou, Xiangtan, and Changsha, and the Xiao River and Lian River and Loudi areas show a significant downward trend. As the Chenzhou area of the Chen River showed an upward trend, the mainstream of the Xiang River and some tributaries of the Xiao River, Zheng River, Lian River, and Lu River showed a significant downward trend.

The water environment of the mainstream of the Xiang River in Yongzhou and its tributary, the Xiao River, is better than that in other areas, and the main pollution indicators show a downward trend as a whole. The Changsha area (the mouth of the Laodao River) and Lianshui, a tributary, are seriously polluted by NH_3-N.

3.2. Quantitative traceability of water quality factors across cities

3.2.1. Regression analysis of water quality

Referring to the existing research results (Cao *et al.* 2019), industrial wastewater discharge, fertilizer consumption, large livestock inventory, urbanization rate, and the proportion of GDP of each industry in the mainstreams of the Xiang River are the main driving forces for the water environment of the mainstream. This paper analyzes economic urbanization, population urbanization, and spatial urbanization combined with industrial wastewater discharge, fertilizer consumption, and large livestock herds as driving forces. Among them, economic urbanization, population urbanization, and spatial urbanization draw lessons from Deng *et al.* (2016). The level of economic urbanization is equal to the ratio of non-agricultural GDP to regional GDP, the level of population urbanization is equal to the ratio of the non-agricultural population to the regional population, and the level of spatial urbanization is the ratio of the urban construction land area to the total regional area. The social and economic data of each city are based on the 1990–2020 Hunan Statistical Yearbook, Hunan Agricultural Statistical Yearbook, Jiangxi Statistical Yearbook, Guangxi Statistical Yearbook, and China Urban Statistical Yearbook.

This study analyzes the cross city driving forces of monitoring stations, taking into account both the city where the monitoring point is located and the upstream city. The location of the water quality monitoring station and various upstream indicators are used as the driving forces for the water quality of the monitoring station. The traceability process is shown in Table 1.

Principles of the stepwise regression analysis of water quality indicators and driving forces (1) standardize the range of water quality indicators and driving forces and (2) trace the driving factors of upstream and tributaries, analyze Pingxiang, Chenzhou, Loudi, and Yongzhou Cities, and obtain the key driving forces entering the downstream tracing process. (3)

Table 1 | Corresponding drivers of water quality monitoring sites

Monitoring site	River system	Belongs to	Corresponding driver of city
Chenzhou, Ouyang Hai	Chunling River, Chen River	Chenzhou	Chenzhou
Loudi	Lian River	Loudi	Loudi
Daxitan	Lu River	Zhuzhou	Pingxiang
Laoputou	Xiang mainstream	Yongzhou	Yongzhou
Hengyang	Xiang mainstream	Hengyang	Yongzhou, Chenzhou, Hengyang
Zhuzhou	Xiang mainstream	Zhuzhou	Zhuzhou, Pingxiang, Hengyang
Xiangtan	Xiang mainstream	Xiangtan	Loudi, Zhuzhou, Xiangtan
Laodao River	Xiang mainstream	Changsha	Xiangtan, Changsha

The larger the adjustment R^2 is, the better the fitting equation is, so the fitting factor adjusted $R^2 < 0.5$ does not enter the downstream tracing process. (4) The driving force of Chenzhou, Yongzhou, and Hengyang is considered for the water quality index of Hengyang City. The water quality index of Zhuzhou City considers the driving forces of Hengyang, Pingxiang, and Zhuzhou Cities. The water quality index of Xiangtan City considers the driving forces of Loudi, Zhuzhou, and Xiangtan Cities. The water quality index of Changsha City considers the driving forces of Xiangtan and Changsha Cities. The stepwise regression analysis results are shown in Table 2.

The analysis results of various regression models indicate that the adjustment coefficients of BOD_5 in Daxitan, Cr^{6+} in Laobutou, and DO are $R^2 < 0.5$, while the adjustment coefficients of other parameters are $R^2 > 0.5$. The linear regression model fits well and can be used for driving force tracing research.

Table 2 | Analysis results of the driving force of water quality indicators in cities and states

Monitoring site	**City**	**Factor**	**Driver**	**R^2**	**Adjusted R^2**	**β**
Chenzhou, Ouyang Hai	Chenzhou	NH_3-N	Chenzhou large livestock inventory	0.784	0.73	0.886
		TP	Chenzhou large livestock inventory	0.892	0.865	0.944
		DO	Chenzhou population urbanization	0.736	0.670	0.858
		BOD_5	Chenzhou urban sewage discharge	0.689	0.611	0.830
Loudi	Loudi	NH_3-N	Loudi space urbanization	0.815	0.769	0.903
		COD_{Mn}	Loudi economic urbanization	0.727	0.658	0.852
		Cr^{6+}	Loudi fertilizer application rate	0.724	0.655	0.851
		DO	Loudi large livestock inventory	0.996	0.993	−1.103
			Loudi urbanization sewage discharge			0.367
		As	Loudi urban sewage discharge	0.749	0.686	0.865
		TP	Loudi industrial wastewater discharge	1	1	1
Daxitan	Zhuzhou	NH_3-N	Pingxiang spatial urbanization	0.610	0.571	0.781
		Cr^{6+}	Pingxiang fertilizer consumption	0.379	0.316	0.615
		DO	Pingxiang spatial urbanization	0.610	0.571	0.781
		BOD_5	Pingxiang large livestock inventory	0.448	0.393	−0.669
		TP	Pingxiang population urbanization	0.645	0.574	0.803
Laoputou	Yongzhou	COD_{Mn}	Yongzhou industrial wastewater discharge	0.87	0.852	−0.933
		Cd	Yongzhou fertilizer consumption	0.897	0.877	−0.947
		Cr^{6+}	Yongzhou industrial wastewater discharge	0.436	0.374	0.661
		DO	Yongzhou economic urbanization	0.406	0.340	−2.48
		AS	Yongzhou large livestock inventory	0.700	0.667	−0.837
Hengyang	Hengyang	Cd	Hengyang population urbanization	0.630	0.578	−0.794
		Cr^{6+}	Hengyang economic urbanization	0.697	0.663	−0.855
		DO	Hengyang space urbanization	0.897	0.871	0.784
			Hengyang fertilizer dosage			−0.416
		As	Hengyang economic urbanization	0.755	0.694	−0.749
			Hengyang fertilizer dosage			−0.520
		TP	Hengyang space urbanization	0.912	0.899	−0.955
Zhuzhou	Zhuzhou	Hg	Zhuzhou economic urbanization	0.744	0.702	−0.863
		Cd	Zhuzhou chemical fertilizer application rate	0.719	0.649	0.848
Xiangtan	Xiangtan	COD_{Mn}	Xiangtan population urbanization	0.782	0.709	0.884
		Cd	Xiangtan industrial wastewater discharge	0.766	0.707	0.875
		Hg	Zhuzhou economic urbanization	0.781	0.745	−0.884
		Cr^{6+}	Xiangtan large livestock inventory	0.59	0.522	−0.768
		As	Xiangtan fertilizer application rate	0.973	0.953	0.982
			Xiangtan urban sewage discharge			−0.358
			Loudi urban sewage discharge			−1.329
		BOD_5	Xiangtan fertilizer application rate	0.634	0.573	0.796
Laodao River	Changsha	Hg	changsha large livestock inventory	0.609	0.544	−0.780
		DO	Changsha urban sewage discharge	0.584	0.515	−0.764
		BOD_5	Changsha's population urbanization	0.836	0.809	−0.915
		TP	Changsha urban sewage discharge	0.991	0.986	0.995

3.2.2. Analysis of driving factor weights

The specific driving forces of the water environment in each city were determined by the step-by-step regression analysis model, and the driving forces were formed into a new index system. The weight of each driving force, namely the contribution rate, was mined by the PCA method. The process is shown in Tables 3–10, a_1 and a_2 are factor score coefficients, W_1 and W_2

Table 3 | Weights of driving factors in Chenzhou

Driver	a_1	W_1	W_i^0
Chenzhou large livestock Inventory	0.487	0.305	0.391
Chenzhou population urbanization	0.442	0.277	0.355
Chenzhou urban sewage discharge	0.316	0.198	0.254
Characteristic root F	1.878		
Variance contribution rate E	62.614		
Cumulative variance contribution rate $\triangle E$	62.614		
KMO	0.516		
Bartlett Sig.	0.005		

Table 4 | Weights of various driving factors in Loudi

Driver	a_1	a_2	W_1	W_2	$W_1 + W_2$	W_i^0
Loudi space urbanization	0.235	0.244	0.152	0.041	0.193	0.162
loudi economic urbanization	0.217	0.393	0.140	0.066	0.207	0.173
Loudi fertilizer application rate	−0.178	0.578	0.115	0.098	0.213	0.178
Loudi large livestock inventory	0.226	0.407	0.146	0.069	0.215	0.180
Loudi industrial wastewater discharge	0.172	−0.449	0.111	0.076	0.187	0.157
Loudi urban sewage discharge	−0.207	0.266	0.134	0.045	0.179	0.150
Characteristic root F	3.885	1.014				
Variance contribution rate E	64.743	16.892				
Cumulative variance contribution rate $\triangle E$	64.743	81.635				
KMO	0.703					
Bartlett Sig.	0.000					

Table 5 | Weights of driving factors in Pingxiang

Driver	a_1	W_1	W_i^0
Pingxiang spatial urbanization	0.342	0.248	0.292
Pingxiang fertilizer consumption	0.425	0.308	0.363
Pingxiang population urbanization	0.404	0.292	0.345
Characteristic root F	2.171		
Variance contribution rate E	72.37		
Cumulative variance contribution rate $\triangle E$	72.37		
KMO	0.620		
Bartlett Sig.	0.000		

Table 6 | Weights of driving factors in Yongzhou

Driver	a_1	W_1	W_i^0
Yongzhou fertilizer application rate	0.349	0.327	0.338
Yongzhou large livestock inventory	0.345	0.323	0.334
Yongzhou industrial wastewater discharge	−0.340	0.318	0.329
Characteristic root *F*	2.807		
Variance contribution rate *E*	93.554		
Cumulative variance contribution rate $\triangle E$	93.554		
KMO	0.752		
Bartlett Sig.	0.000		

Table 7 | Weights of driving factors in Hengyang

Driver	a_1	W_1	W_i^0
Hengyang population urbanization	0.310	0.232	0.270
Hengyang space urbanization	0.306	0.229	0.267
Hengyang economic urbanization	0.310	0.232	0.270
Hengyang chemical fertilizer application rate	0.222	0.166	0.193
Characteristic root *F*	2.988		
Variance contribution rate *E*	74.700		
Cumulative variance contribution rate $\triangle E$	74.700		
KMO	0.548		
Bartlett Sig.	0.000		

Table 8 | Weights of driving factors in Zhuzhou

Driver	a_1	W_1	W_i^0
Zhuzhou chemical fertilizer application rate	0.574	0.435	0.5
Zhuzhou economic urbanization	0.574	0.435	0.5
Characteristic root *F*	1.516		
Variance contribution rate *E*	75.822		
Cumulative variance contribution rate $\triangle E$	75.822		
KMO	0.515		
Bartlett Sig.	0.049		

are weights, and W_i^0 is the normalized weight. In each PCA model, the Kaiser-Meyer-Olkin (KMO) value is 0.515–0.779 (>0.5), and the Bartlett sphericity test value is 0.000–0.005 (<0.05), which is suitable for factor analysis.

The results indicate that the stepwise regression equation is more accurate and reasonable compared to regression analysis methods, which can ensure that the identified driving factors are more accurate. In addition, the results of PCA include the eigenvalues of each principal component and their cumulative contribution rate. The eigenvalues reflect the influence of the component on each evaluation indicator, and the cumulative contribution rate reflects the explanatory power of the principal component on each evaluation indicator. The factors obtained by PCA can reflect the majority of information of the original evaluation indicators. The combination of the stepwise regression equation method and PCA ensures accurate and

Table 9 | Weights of driving factors in Xiangtan

Driver	a_1	a_2	W_1	W_2	$W_1 + W_2$	W_i^0
Xiangtan population urbanization	0.215	−0.072	0.137	0.017	0.154	0.135
Xiangtan industrial wastewater discharge	−0.039	0.544	0.025	0.129	0.153	0.134
Zhuzhou economic urbanization	0.218	−0.035	0.139	0.008	0.148	0.129
Xiangtan large livestock inventory	0.215	0.166	0.137	0.039	0.177	0.154
Xiangtan fertilizer application rate	0.162	0.234	0.104	0.055	0.159	0.139
Xiangtan urban sewage discharge	−0.141	0.437	0.090	0.103	0.193	0.169
Loudi urban sewage discharge	0.190	0.170	0.121	0.040	0.162	0.141
Characteristic root F	4.475	1.656				
Variance contribution rate E	63.926	23.653				
Cumulative variance contribution rate $\triangle E$	63.926	87.579				
KMO	0.779					
Bartlett Sig,	0.000					

Table 10 | Weights of driving factors in Changsha

Driver	a_1	W_1	W_i^0
Changsha large livestock inventory	−0.197	0.131	0.170
Changsha urban sewage discharge	0.472	0.314	0.408
Changsha's population urbanization	0.489	0.325	0.422
Characteristic root F	1.996		
Variance contribution rate E	66.531		
Cumulative variance contribution rate $\triangle E$	66.531		
KMO	0.55		
Bartlett Sig.	0.001		

'responsible' identification of driving factors, while also ensuring an accurate calculation of the contribution rate of driving factors to the water environment impact.

The contribution rate of the water environment driving force in the tributary city of Chenzhou (Table 3) is the highest, with the large livestock population reaching 0.305, followed by a population urbanization contribution rate of 0.277.

The contribution rate of the two agricultural indicators of chemical fertilizer application and large livestock inventory in Loudi (Table 4) is higher than 0.428, followed by the two urbanization indicators of spatial urbanization and economic urbanization. The contribution rate reached 0.4.

The main driving factor of Pingxiang (Table 5) City is the contribution rate of the agricultural index of chemical fertilizer consumption, which is 0.308, followed by the two urbanization indicators of spatial urbanization and population city, with a combined contribution rate of 0.540. The main driving forces of the abovementioned tributary cities are mainly agricultural factors and the influence of urbanization. In particular, the urbanization contribution rate of Pingxiang City reached 0.540, accounting for 63.7% of all driving forces.

Agricultural factors in Yongzhou (Table 6) City, the mainstream of the Xiang River, are the main driving forces for the water environment. The contribution rate of chemical fertilizer application and large livestock population is 0.650, and the contribution rate of industrial wastewater discharge is 0.318.

Hengyang (Table 7) City takes urbanization as the main driving force, the contribution rate of the urbanization index reaches 0.693 and the contribution rate of the chemical fertilizer application amount is 0.166.

The driving forces of the water environment in Zhuzhou (Table 8) City are agriculture and urbanization, and the contribution rates of the two are equal.

The driving factors of Xiangtan (Table 9) City are relatively complex. The contribution rate of agricultural factors in this city is 0.336, the contribution rate of industrialization factors (industrial wastewater discharge) is 0.153 and the contribution rate of urbanization factors in Xiangtan is 0.347. The contribution rates of the urbanization of Zhuzhou and Loudi to the water environment in Xiangtan are 0.148 and 0.162, respectively.

The urbanization of Changsha (Table 10) is the main driving force of the water environment. The main factor is the urbanization index. The contribution rate of population urbanization is 0.325, the contribution rate of urban sewage discharge is 0.314, and the contribution rate of agricultural factors is 0.131.

4. DISCUSSION

Chen Mingxia's study (Chen *et al.* 2019) showed that the concentration of NH_3-N and TP increased from the upstream to the downstream of the Xiang River. This study, based on the above research during the period from 1990 to 2020, NH_3-N and TP of Chunling River, and tributaries of the Xiang River, showed an upward trend, which was mainly affected by the number of large livestock in Chenzhou. The urban sewage discharge in Chenzhou has a significant impact on BOD_5. The urbanization of Chenzhou is the main driving force of the water environment, with a contribution rate of 0.475, accounting for 60.9% of all driving forces.

Some results (Liu *et al.* 2018; Chen *et al.* 2019) showed that the water environment of the Xiao River is better than other areas of the Xiang River Basin. This study shows that the water environment of the mainstream of the Xiang River in Yongzhou and its tributary, the Xiao River, is better than that in other areas, and the main pollution indicators show a downward trend as a whole. The BOD_5 pollution of Hengyang, Xiangtan, and the tributaries Chen River and Zheng River is more serious; the Changsha area (the mouth of the Laodao River) and the tributary Lian River are seriously polluted by NH_3-N. Zhang *et al.* (2021) also considered that the NH_3-N pollution in Changsha is serious.

A study by Chen *et al.* (2019) showed that the Lu River environment is mainly influenced by agriculture and residents. This study found that the water environment of the Lu River tributaries is significantly affected by Pingxiang City. Among them, the urbanization contribution rate of Pingxiang City reached 0.540, accounting for 63.7% of all driving forces. Because Pingxiang City is under the jurisdiction of Jiangxi Province, it is necessary to strengthen the water environment management measures in interprovincial river basins.

The water environment of the Lian River tributaries is obviously driven by Loudi City. The regression model adjusted R^2 is 0.655–1, and the linear regression model had a good fit. Urbanization in Loudi drives changes in NH_3-N and COD_{Mn}. Urban sewage discharge affects many water quality indicators. In the process of driving by the water environment, the urbanization contribution rate of Loudi is 0.579, accounting for 1% of all driving forces. The contribution rate of agriculture is 0.428, and all driving forces are 35.8%. The industrial contribution rate is 0.187, and all driving forces are 15.7%.

In the Xiang River Basin, there are few cross city quantitative analysis studies on the impact of upstream cities on the water environment of downstream cities. Most studies qualitatively point out that the pollutant emissions from upstream cities affect downstream cities (Liu *et al.* 2019). This study quantitatively analyzes the degree of impact of upstream cities on the water environment of downstream cities. The urbanization of Zhuzhou City and the urban sewage discharge of Loudi City not only have an impact on the water environment of the city, but also have a driving effect on the water environment of the downstream Xiangtan area, with their contribution rates reaching 12.9 and 16.9%, respectively. Zeng *et al.* (2023) analyzed that the poor water quality in Xiangtan City may be attributed to Zhuzhou City. But this study did not quantify the impact of Zhuzhou on the water quality of Xiangtan.

In the Yongzhou region, the mainstream of the Xiang River, agricultural factors are the main driving force, with a contribution rate of 0.650. Urbanization in Hengyang is the main driving force, with a contribution rate of 0.693. Agricultural factors and urbanization factors jointly drive the water environment in Zhuzhou City, with equal contribution rates. The driving factors of Xiangtan City are relatively complex. The contribution rate of agricultural factors in this city is 0.336, the contribution rate of industrialization factors (industrial wastewater discharge) is 0.153, and the contribution rate of urbanization factors in Xiangtan is 0.347. At the same time, the urbanization contribution rate of upstream Zhuzhou city was 0.148, and the urban sewage discharge contribution rate of upstream Loudi city reached 0.162. Loudi's urban sewage management and control work are not only of great significance to the city's water environment, but also play an important role in the downstream Xiangtan city's water environment. As the capital city of Changsha, the main driving force of the water environment is urbanization, the contribution rate of urbanization reaches 0.639, and the contribution rate of agricultural factors is 0.131.

Integrating the urban sewage discharge with the contribution rate of population, economy, and spatial urbanization indicators to the impact of the water environment, we can obtain the following: the proportion of urbanization in each driving force is as follows: Changsha (83%) > Hengyang (80.7%) > Pingxiang (63.7%) > Chenzhou (60.9%) > Xiangtan (57.4%) > Zhuzhou (50%) > Loudi (48.5%); Urbanization has a greater impact on the driving process of the water environment in the Xiang River Basin.

Based on the above data, it can be found that urbanization is the main influencing factor on the water environment change in the Xiang River Basin. This contradicts Chen Mingxia's belief that economic factors, such as urban development, will no longer be the main factors affecting the water environment of the Xiang River Basin after 2008. Referring to the research results of other watersheds (Zhang *et al.* 2019; Wu *et al.* 2021; Wang *et al.* 2022), this study believes that as the urbanization process of watersheds accelerates, urban development factors play an increasingly important role in the water environment process of watersheds.

5. CONCLUSION

This paper analyzes the changing trend of water environment indicators in the Xiang River Basin from 1990 to 2020 and uses the stepwise regression analysis method to trace the cross-city driving factors of each indicator based on the panel data of the social and economic developments of the basin.

In the water environment protection work in the Xiang River Basin, it is necessary to strengthen the joint governance measures of the water environment between provinces and cities. The urban development in the upper reaches of the river basin has a certain impact on the water environment of the downstream cities. In the process of urban development and expansion, it is necessary to consider the needs of the downstream water environment. Urban sewage discharge is the driving force of multiple water quality indicators and multiregional water environmental pollution, and it is necessary to further strengthen the management of urban sewage discharge in river basins.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Yanmin Cao and Dongyue Qian contributed to writing and editing; Chongyu Wang contributed to chart editing; and Dongyue Qian contributed to preliminary data collection. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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