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Evaluation and Influencing Factors of Nitrogen Flow Efficiency in Taihu River Basin

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Abstract: Scientifically quantifying and analyzing the nitrogen flow efficiency and its influencing factors in the Taihu Lake basin is of great significance to promote its pollution management and green development. Twenty-one municipalities in the Lake Tai basin were selected as the research objects from 2018 to 2022, and the Super-SBM model was used to reveal the changing characteristics of the nitrogen flow efficiency in the Lake Tai basin from 2 perspectives, namely static and dynamic, and the key factors affecting the nitrogen flow efficiency of the basin were explored through the Tobit model. The results show that (1) from 2018 to 2022, the overall nitrogen flow efficiency of the Lake Tai basin is at a low level, and there is still a large space for nitrogen reduction potential. (2) In terms of dynamic efficiency, the Malmquist trend indicates that the overall trend of nitrogen flow efficiency in the Lake Tai Basin is favorable, and that technological progress remains an important driving force to promote the improvement of nitrogen flow efficiency in the Lake Tai Basin. (3) In terms of influencing factors, environmental regulation and energy structure show positive and significant effects in improving the nitrogen flow efficiency of the basin. Finally, from the commonalities and differences, relevant policy suggestions for improving the efficiency of nitrogen flow in the basin are proposed.

Keywords: Nitrogen Flow Efficiency, Super-SBM, Non-expected outputs

1. Introduction

As a major project of Jiangsu's ecological civilization construction and people's livelihood project, the Taihu Lake Basin has a wide area of crop cultivation, a large amount of nitrogen fertilizer use and low utilization rate, and the sewage treatment rate of some of the industrial enterprises in the region is not up to the standard, which aggravates the problem of pollution in the watershed, and is not conducive to sustainable development. Meanwhile, the State Council indicating that the situation of eutrophication in Lake Taihu has not fundamentally improved, and the concentration of N and P in the water body of Lake Taihu is far more than the threshold of the cyanobacteria outbreaks, and the risk of large-scale outbreaks still exists. At the same time, with the acceleration of global industrialization and the acceleration of agricultural modernization, increasing the productivity of the system and meeting human needs, it has also led to a dramatic increase in the application of nitrogen fertilizers, which has resulted in the influx of large amounts of reactive nitrogen (all forms of nitrogen except nitrogen gas) into the environment, which has a profound impact on the nitrogen cycling process in terrestrial ecosystems. Therefore, in order to further strengthen the environmental management of the basin, it is an urgent task to promote the solution of the increasingly prominent nitrogen and phosphorus pollution problems by evaluating the nitrogen flow efficiency of the Taihu Lake Basin.

At present, scholars at home and abroad focus on nitrogen flow efficiency mainly include nitrogen flow law and spatio-temporal characteristics and their influencing factors, etc. Some scholars also take some special regions such as specific watersheds and production systems as the research scale. Zhou Xing et al[1]took the nitrogen footprint of oilseed rape planting process in Hubei Province as the data base, and analyzed the impact of different farming methods on nitrogen ladder utilization efficiency. Xia Yuling[2] evaluated the nitrogen utilization efficiency in the three ladder segments of agroecosystems, animal husbandry systems, and human consumption systems based on the per capita food nitrogen footprint of Shanghai city using an ARIMA model. Zou Caiyu et al[3] established an agroecosystem nitrogen balance model based on the material flow analysis method, studied and analyzed the nitrogen flux trends, nitrogen flow efficiency, and environmental loads of the agricultural production system in three townships in Fujian Province during the period of 2002-2016. Dukes et al[4]took the community as the entry point to simulate the nitrogen footprint flow process of Baltimore urban system, and analyzed and summarized the nitrogen flow law, while Noll et al[5]selected organic food industry and traditional food industry based on the nitrogen footprint model, quantitatively analyzed the nitrogen output fluxes of the two systems, as well as the comparative analysis of nitrogen flow efficiency. Meanwhile, using academic institutions as a scale innovation has become a new research hotspot. MacDonald[6]analyzed the reactive nitrogen emissions of two universities in Montreal by selecting them for comparison, and regarded the multiple institutional environmental effects as a key factor in the difference of nitrogen footprint results.

As can be seen from the above studies, certain results have been achieved for nitrogen flow efficiency. However, most of the above studies on nitrogen flow efficiency are based on quantitative analysis from the perspective of nitrogen footprint, ignoring the key factors affecting the improvement of regional nitrogen flow efficiency, such as environmental protection inputs. In addition, there is a lack of research on nitrogen flow efficiency in the Taihu Lake basin. Therefore, this study combines the reality of the Taihu Lake basin, measures the nitrogen flow efficiency based on the SBM model of non-expected output, and reveals the main influencing factors of the nitrogen flow efficiency of the Taihu Lake basin through the Tobit model, in order to provide a reasonable basis and decision-making reference for improving the nitrogen flow efficiency of the Taihu Lake basin and formulating a targeted nitrogen emission reduction strategy, and to help the basin's high-quality development.

2. Research Methodology and Data Sources

2.1. Research Area

The Taihu Lake basin is located in the hinterland of the Yangtze River Delta, with the Yangtze River in the north, the East China Sea in the east, the Qiantang River in the south, and the Tianmu and Maoshan Mountains in the west. Among them, the basin flows through the southern part of Jiangsu Province, Zhejiang Province (except the Poyang Lake basin), the central part of Shanghai Municipality, Fujian Province (except the Hanjiang River basin), Shangrao City of Jiangxi Province, Huangshan City and Xuancheng City of Anhui Province, with an area of 246,000 square kilometers, which is one of the most dynamic economies, the highest degree of openness, and the strongest innovation ability in China. Therefore, strengthening the comprehensive management and protection of the ecological environment of the Taihu Lake basin is an important task for the coordinated

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economic and social development of the Yangtze River Delta region and the coordinated development of the regional economy.

Considering that agricultural production on N fertilizer utilization and feed N utilization is the key link in the nitrogen flow process, this paper takes the four functional areas of Lake Xi, Yangcheng Dian Mao, Wucheng Xiyu and Hangjiahu as the study area, and selects 18 county-level cities and three administrative districts in Huzhou, Jiaxing, Suzhou, Wuxi, Changzhou, Taizhou, and Zhenjiang City, which are mainly engaged in agricultural and animal husbandry production, as the research objects to compare and analyze the evolution of nitrogen flow efficiency and the differences in the factors affecting nitrogen flow in the watersheds. We analyzed the evolution of nitrogen flow efficiency and the differences of influencing factors in the watershed, which is of practical significance for the government to formulate the nitrogen emission reduction policy in the watershed and to promote the green and sustainable development of the watershed.

2.2. Research Methodology

2.2.1. Super-DEA

Tone[7]combined the advantages of the Super-DEA model and the SBM model to construct the Super-SBM model, which enables decision units with efficiency values up to 1 to display specific values beyond 1 and to rank them to achieve horizontal comparison between decision units, thus dealing with efficiency evaluation studies containing non-expected outputs in a more targeted way.Therefore, the Taihu Lake Basin was selected as the study area to evaluate the nitrogen flow efficiency of the basin based on the Super-SBM model with non-expected outputs, which was set as follows:

$x \in S^L, y^a \in S^M, y^b \in S^N$; x、y^a、y^b are of matrix form; $X = [x_1 \cdots x_n] \in S^{L\times l}, Y^a = [y_1^a \cdots y_n^a] \in S^{M\times l}$ and $Y^b = [y_1^b \cdots y_n^b] \in S^{N\times l}$。where L, M, N are the number of input indicators, desired and undesired output indicators.

The construction of the super-efficient SBM model is shown below:

$$\rho^* = \min \frac{1 - \frac{1}{L}\sum_{l=1}^{L} \frac{S_l^x}{x_{kl}^t}}{1 + \frac{1}{M+1}\left(\sum_{m=1}^{M} \frac{s_m^y}{y_{km}^t} + \sum_{n=1}^{N} \frac{S_n^b}{b_{kn}^t}\right)}$$

$$s.t. \begin{cases} \sum_{k=1,k\neq j}^{K} Z_k^t x_{kl}^t + s_l^x = x_{kl}^t, l = 1,\cdots L \\ \sum_{k=1,k\neq j}^{K} Z_k^t x_{kl}^t + s_m^y = y_{kl}^t, m = 1,\cdots M \\ \sum_{k=1,k\neq j}^{K} Z_k^t b_{kn}^t + s_n^b = b_{kn}^t, n = 1,\cdots N \\ Z_k^t \geq 0, s_l^x \geq 0, s_m^y \geq 0, s_n^b \geq 0, k = 1,\cdots K \end{cases}$$

where $x_{kl}^t, y_{kl}^t, b_{kn}^t$ represents the value of inputs and outputs in the nitrogen flow process of the decision unit in period t, and s_l^x, s_m^y, s_n^b represents the slack variable.

2.2.2. Malmquist exponentiation

In reality, the dynamic nature of specific production behaviors and activities, such as process upgrades, results in fluctuations in the efficiency of the process over time, leading to increases or decreases. The Malmquist Index methodology is used to improve and guide efficiency evaluation by analyzing the causes of changes in efficiency.

Assuming constant returns to scale, its Malmquist index is expressed as:

$$M(x^{t+1}, y^{t+1}, x^{t}, y^{t}) = \sqrt{\frac{D^{t}(x_{t+1}, y_{t+1})}{D^{t}(x_{t}, y_{t})} \times \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^{t+1}(x_{t}, y_{t})}}$$

In the above equation, $D^t(x_t, y_t)$ denotes the DMU efficiency value at period t; $D^{t+1}(x_{t+1}, y_{t+1})$ denotes the DMU efficiency value at period t+1; $D^t(x_{t+1}, y_{t+1})$ denotes the DMU efficiency value at period t+1 using the technology level of period t; and $D^{t+1}(x_t, y_t)$ denotes the DMU efficiency value at period t using the technology level of period t+1.Finally, it is concluded that if M<1 then it represents a decrease in the efficiency level of the DMU; if M=1 then it represents no change in the efficiency level of the DMU; and if M>1 then it represents an increase in the efficiency level of the DMU.

2.2.3. Tobit Model

In this study, the measured nitrogen flow efficiency was used as the explanatory variable of the study based on the non-expected outputs, the results of which were in the range of 0-2. The explanatory variables were limited in their values, and the results would have produced a large error if the conventional discrete and continuous variable models were used for the regression analysis, therefore, the Tobit regression model, which is specifically designed to deal with the constrained factors, was selected for the regression analysis. The Tobit model used[8]is as follows:

$$NFE_{it} = \beta_0 + \beta_1 ED_{it} + \beta_2 IA_{it} + \beta_3 ER_{it} + \beta_4 Urb_{it} + \beta_5 GE_{it} + \varepsilon_{it}$$

NFEit is the nitrogen flow efficiency of the ith region in year t, β_0 is a constant, β_t is a vector of estimated coefficients, and ε_{it} is a random error.

2.3. Selection of indicators and data sources

2.3.1. Indicator Construction for Nitrogen Flow Efficiency

The N-Calculator nitrogen footprint model proposed by Hutton et al[9]has been widely used by later scholars, who established a nitrogen gradient flow model by analyzing the reactive nitrogen emission fluxes in human consumption and energy production systems, with the U.S. production system as the data background. Based on the coupled human-nature system (CHANS), Gu Baojing[10]subdivided the nitrogen flow model into four functional groups for the nitrogen flow process, so as to quantitatively calculate and analyze the nitrogen gradient flow fluxes and flow efficiencies at different regional scales, and Vries et al.[11]took the lead in narrowing the scale down to a regional perspective, focusing on reactive nitrogen emissions, and establishing the INITIATOR model to calculate and analyze nitrogen flow efficiency. It can be seen that scholars mainly focus on nitrogen flux and nitrogen input and output, and do not take into account the government's environmental governance, capital policy inputs and other factors on the nitrogen flow efficiency, therefore, this paper will be environmental protection inputs, policy impacts, and other non-nitrogen flow fluxes as a consideration of the indicators, the introduction of the DEA method, the watershed of the nitrogen flow efficiency of in-depth research.

Drawing on the research ideas of Gu Baojing, Zou Caiyu and other scholars[3,10,12-13], this paper defines the nitrogen flow efficiency of the watershed from the perspective of the total factor indicators as the ratio of the inputs and the actual outputs of the resource elements in the process of nitrogen cycling within a certain period of time under the consideration of the reactive nitrogen flux. The indicator system of basin nitrogen flow efficiency is constructed as follows: (i) Input indicators:

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mainly including resource, capital and environmental protection inputs. Among them, the resource input is expressed by the input of nitrogen in the basin, which is calculated by the input of nitrogen in the three systems of agriculture, animal husbandry, industry and human consumption; the capital input is referred to the government's financial expenditures and the expenditures of the industrial enterprises; the environmental protection input is chosen to measure the strength of the environmental protection, which is quantitatively calculated by the number of nitrogen emission reduction policies, laws and regulations, and the number of activities introduced. (ii) Output indicators: divided into two categories: desired output and non-desired output. Desired output is expressed by the nitrogen content of the main products in the agricultural and animal husbandry and industrial systems, and is obtained by converting the output of grains, potatoes, beans, vegetables, pigs, sheep and beef, and the output of the main industrial products. The non-expected outputs are mainly obtained by summing the reactive nitrogen fluxes by adding the nitrogen loss from agricultural land, industrial nitrogen oxides, industrial ammonia nitrogen and nitrogen loss from domestic sewage.

Table 1: Input-output index system for nitrogen flow efficiency in the Taihu Lake basin.

Type of indicator	Level 1 indicators	Level 2 indicators	Explicit explanation
Input indicators	Resource inputs	Basin nitrogen inputs	FLINtotal+IDINtotal+HCI Ntotal
	Capital inputs	Expenditure	Investment in environmental protection
	Environmental inputs	Environmental protection efforts	Number of Nitrogen Emission Reduction Policies and Regulations
Output indicators	Expected outputs	Total nitrogenous products	FLOUTtotal+IDOUTtotal
	Non-expected outputs	Reactive nitrogen flux	

2.3.2. Selection of indicators for factors influencing nitrogen flow efficiency

The influencing factors of nitrogen flow efficiency have complexity and are the result of the joint action of various factors, therefore, in order to effectively manage the situation of water environment pollution in the Taihu Lake Basin, it is of great research significance to study and analyze other factors affecting the efficiency of nitrogen flow in the basin. Therefore, this paper in reference to the relevant research literature on the basis of[14-16], based on the actual situation of the Taihu Lake Basin region, combined with the characteristics of the nitrogen flow link in the Taihu Lake Basin to build the indicator system, specifically the level of economic development, urbanization level, the level of environmental regulation, the level of green ecological level, the energy structure and agricultural mechanization of the six aspects, as shown in Table 2, the use of the Tobit model to carry out correlation Analysis.

Table 2: Factors affecting nitrogen flow efficiency in the Taihu Lake basin.

Variable name	Notation	Definition or description	Unit (of measure)
Level of economic development	ED	GDP per capita	Million dollars/person
Environmental regulation	ER	Investment in environmental pollution as a percentage of GDP	%
Urbanization level	Urb	Share of urban population	%

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Table 2: (continued).

Green ecologization	GE	Percentage of green space	%
Energy structure	ES	Industrial electricity consumption/social electricity consumption	%
Mechanization of agriculture	AM	Gross power of agricultural machinery	Kilowatt (unit of electric power)

2.3.3. Data sources

In this paper, 21 municipal jurisdictions are selected as Hangjiahu District (Huzhou Deqing , Huzhou Changxing, Huzhou Anji and Jiaxing Jiashan, Jiaxing Haining, Jiaxing Pinghu, Jiaxing Tongxiang), Yangcheng Dianmao District (Suzhou Wujiang, Suzhou Changshu, Suzhou Zhangjiagang, Suzhou Kunshan, Suzhou Taicang), Wucheng Xiyu District (Wuxi Jiangyin, Wuxi Yixing, and Changzhou Wujin, Changzhou Liyang), and Huxi District (Taizhou Jingjiang, Taizhou Taixing, and Zhenjiang Danyang, Zhenjiang Yangzhong, Zhenjiang Jurong). The relevant data are extracted from the reports of the statistical yearbooks, national economic and social development statistical bulletins and other reports of the provinces (autonomous regions) and municipalities in the Lake Tai Basin in the years 2019-2023, and the missing data are filled in by interpolation. Among them, the statistical caliber of the data in this paper exists in the case of "city district" and "county-level city", due to the continuous improvement of the administrative division system in urban areas, some county-level cities have evolved into the current city district, so this study adopts the "county-level city". The statistical caliber of the "county-level city" area is used in this study. The relevant parameters are shown in the appendix[10,16-19].

3. Analysis of nitrogen flow efficiency results

3.1. Static analysis of nitrogen flow efficiency in the Taihu Lake basin

3.1.1. Characterization of time-series evolution

According to the above SBM model considering non-desired output, the nitrogen flow efficiency of each region in the Taihu Lake basin is measured using Matlab software, and the specific calculation results are shown in Table 3 below. It can be seen that the vast majority of decision-making units in the period from 2018 to 2022 the average value of efficiency did not exceed 1. Among them, Jiaxing Tongxiang City has the highest value of efficiency, reaching 1.093; Zhenjiang Yangzhong City has the second highest average value of nitrogen flow efficiency in the county-level cities within the Taihu Lake, at 1.067; at the same time, the nitrogen flow efficiencies in Wujiang District and Kunshan, Suzhou, are very close to 1. However, the efficiency values of the other counties and cities are still low, and the efficiency values of the other counties are still low, especially in Pinghu City. Especially, the mean value of Pinghu City can only reach 0.263, which is very far away from the frontier surface.

It is worth noting that the decision-making units with the highest and lowest efficiency values are Pinghu City and Tongxiang City, which both belong to Jiaxing City, due to the important role played by environmental protection efforts. Since Jiaxing City began piloting a horizontal ecological protection compensation mechanism for watersheds within the city, Tongxiang City has responded quickly and achieved remarkable results, such as conducting activities and programs such as watershed-wide sampling, installing ecological ditches, and diverting rainwater and sewage to monitor discharges in key areas, such as agriculture, industry, and human life, with the direction of

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"adapting to local conditions". In addition, a comprehensive management of the watershed environment has been carried out with the aim of reducing the total N and P concentrations.

Table 3: Nitrogen flow efficiencies by region in the Taihu Lake Basin, 2018-2022.

District	2018	2019	2020	2021	2022	Mean value of statistical intervals
Suzhou Wujiang	0.817	1.043	1.011	1.009	1.004	0.273
Suzhou Changshu	0.729	0.564	0.601	0.629	1.058	0.337
Suzhou Zhangjiagang	0.799	1.259	1.057	0.750	0.668	0.719
Suzhou Kunshan	1.043	0.924	1.021	0.919	1.032	1.004
Suzhou Taicang,	0.310	0.601	0.347	0.354	0.234	1.788
Huzhou Deqing	0.523	0.495	0.901	1.134	1.050	1.188
Huzhou Changxing	0.433	0.249	0.280	0.273	0.284	0.423
Huzhou Anji	1.030	0.712	0.728	1.037	0.733	0.650
Wuxi Jiangyin	0.343	0.527	0.427	0.373	0.428	0.430
Wuxi Yixing	0.477	0.612	1.055	1.006	1.008	0.483
Changzhou Wujin	0.509	0.242	0.310	0.296	0.223	0.291
Changzhou Liyang	0.402	0.557	0.801	1.081	0.641	0.488
Taizhou Jingjiang	1.051	1.014	1.089	1.048	1.016	0.790
Taizhou Taixing	0.391	0.244	0.263	0.247	0.249	1.029
Zhenjiang Danyang	0.346	0.642	0.602	0.433	0.284	0.747
Zhenjiang Yangzhong	1.053	1.075	1.014	1.147	1.045	0.944
Zhenjiang Jurong	0.403	0.596	0.442	0.995	0.386	0.914
Jiaxing Jiashan	1.004	1.016	0.828	1.027	0.442	0.742
Jiaxing Haining	0.431	0.338	0.457	0.473	0.499	0.439
Jiaxing Pinghu	0.523	0.212	0.235	0.175	0.169	0.263
Jiaxing Tongxiang	1.023	0.938	1.367	1.060	1.075	1.118

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3.1.2. Characterization of regional evolution

The results showed that the overall efficiency values of Mao Yangcheng and West Lake areas were stable over time, while Hangjiahu and Wucheng and Xiyu areas showed an increasing curve. Meanwhile, the average nitrogen flow efficiency of Taihu Lake basin was only 0.674, which could not meet the requirement of frontier efficiency, which indicated that there was still some room for improvement in nitrogen flow efficiency in Taihu Lake basin.

In comparison, the average nitrogen flow efficiencies of the four major areas, namely Hangjiahu, Yangcheng Dianmao, Wucheng Xiyu, and Huxi, were 0.661, 0.791, 0.566, and 0.679, respectively, and the rankings of the efficiencies were: Yangcheng Dianmao, Huxi, Hangjiahu, and Wucheng Xiyu. It can be seen that the efficiency value of Wucheng Xiyu District is below the average value, mainly due to the fact that since the "13th Five-Year Plan", the maximum area of cyanobacterial outbreaks and the average area of cyanobacterial outbreaks in the Taihu Lake Basin have been at a high level, of which the maximum area of outbreaks in 2017 was more than 1,000 square kilometers or more. And in the cyanobacteria outbreak of the "hardest hit" and "Wu battlefield" Wucheng Xiyu District has also been affected. Although its nitrogen flow efficiency has been steadily increasing since 2018, it remains low compared to other regions.

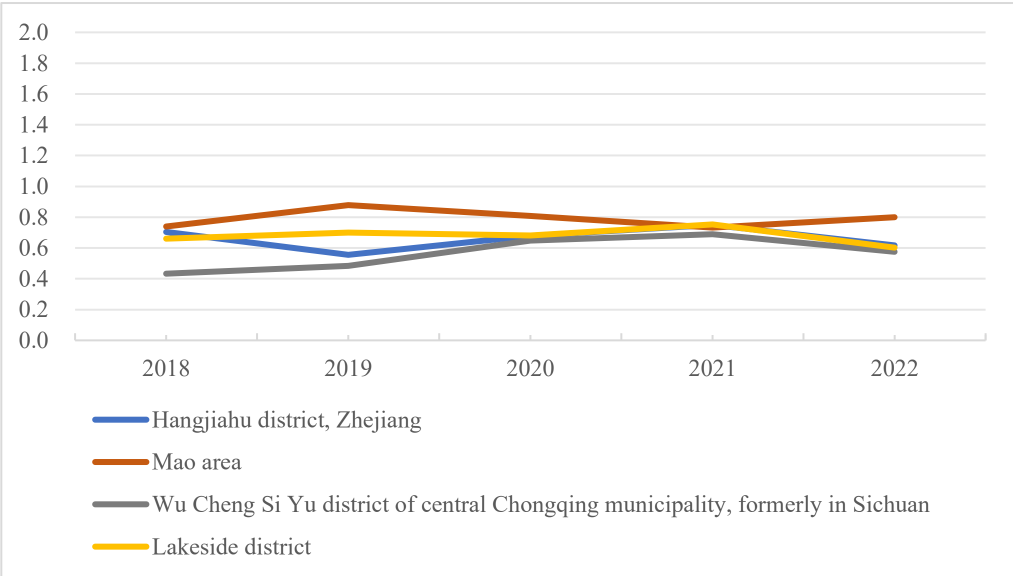

Figure 1: Nitrogen flow efficiencies by region in the Lake Tai Basin, 2018-2022.

As for the overall trend, the difference in the mean nitrogen flow efficiency of the four regions is 0.225, and one of the reasons for this regional difference is the difference in the average trophic index of Lake Taihu. According to the report on the health status of Lake Taihu, East Taihu Lake has changed from moderate to mild eutrophication since 2018, while the trophic status of the other lakes has not changed, so the nitrogen flow efficiency of Mao Yangchengdian area, which is located in the East Taihu Lake basin, has been at a higher level. Meanwhile, the report also gives the data of total phosphorus and total nitrogen pollution loads into the lake from the rivers around Lake Taihu, which shows that the total nitrogen pollution loads of the districts are much more than the total phosphorus pollution loads, which is one of the reasons why the average value of nitrogen flow efficiency of the districts has not yet reached the effective value.

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3.2. Dynamic analysis of nitrogen flow efficiency in the Taihu Lake basin

In order to further analyze the changes of nitrogen flow efficiency in the Lake Tai Basin and to dynamically analyze the average changes of nitrogen flow efficiency, the nitrogen flow efficiency and its decomposition index were measured based on the ML index (Table 4).In the four years, there were 14 ML indices greater than 1 in Yangchengyangdian Mao zone, 17 ML indices greater than 1 in Hangjiahu zone, 12 ML indices greater than 1 in Wuchengxiu zone, and 11 ML indices greater than 1 in Huxi zone. There are 11 ML indices greater than 1 in Huxi District. It can be seen that the ML indexes of all regions in the Taihu Lake Basin have increased more than decreased, indicating that the overall trend of nitrogen flow efficiency in the Taihu Lake Basin is favorable.

Table 4: Malmquist index for each region of the Taihu Lake basin.

District	2018-2019	2019-2020	2020-2021	2021-2022
Suzhou Wujiang	1.278	0.969	0.998	0.994
Suzhou Changshu	0.773	1.066	1.046	1.684
Suzhou Zhangjiagang	1.576	0.840	0.710	0.890
Suzhou Kunshan	0.886	1.104	0.900	1.123
Suzhou Taicang,	1.942	0.577	1.021	0.659
Huzhou Deqing	0.946	1.820	1.260	0.925
Huzhou Changxing	0.574	1.125	0.975	1.040
Huzhou Anji	0.691	1.024	1.424	0.707
Wuxi Jiangyin	1.539	0.810	0.875	1.146
Wuxi Yixing	1.281	1.725	0.954	1.001
Changzhou Wujin	0.475	1.281	0.956	0.754
Changzhou Liyang	1.383	1.439	1.349	0.593
Taizhou Jingjiang	0.965	1.074	0.962	0.970
Taizhou Taixing	0.625	1.077	0.939	1.005
Zhenjiang Danyang	1.856	0.937	0.719	0.656
Zhenjiang Yangzhong	1.020	0.943	1.131	0.912
Zhenjiang Jurong	1.480	0.740	2.253	0.388
Jiaxing Jiashan	1.012	0.815	1.240	0.430
Jiaxing Haining	0.784	1.353	1.037	1.054
Jiaxing Pinghu	0.405	1.112	0.744	0.967
Jiaxing Tongxiang	0.917	1.457	0.776	1.013

As can be seen from Figure 2, the Malmquist index of nitrogen flow efficiency in the Taihu Lake basin is in a stable state in 2018-2022 as a whole, and slightly fluctuates and declines in 2021-2022, which is attributed to the fact that China has upgraded the concept of ecological civilization into the strategy of ecological civilization, and that the green economy is developing rapidly in the whole country, with rapid upgrading of the industrial structure, in which the agricultural structure is also gradually upgraded, and therefore the Taihu Lake basin In recent years, we have also continued to promote pollution prevention in the basin, aiming at the synergistic progress of environmental protection and economic development, and the construction of ecological civilization is imperative.

And the decomposition of the efficiency index can also be seen, the first two years of the Taihu Lake Basin nitrogen flow efficiency change index is smaller than the technical change index outside, while the latter two years of the efficiency change index is greater than the technical change index, indicating that for the enhancement of the efficiency of nitrogen flow in the Taihu Lake Basin on the issue of the influence of the role of the technical efficiency is the largest, and technological progress of the role of the relatively weak, indicating that in the enhancement of the efficiency of nitrogen flow in the Lake Tai Basin should continue to focus on technological transformation in the future to continuously improve the efficiency of energy conservation and emission reduction.

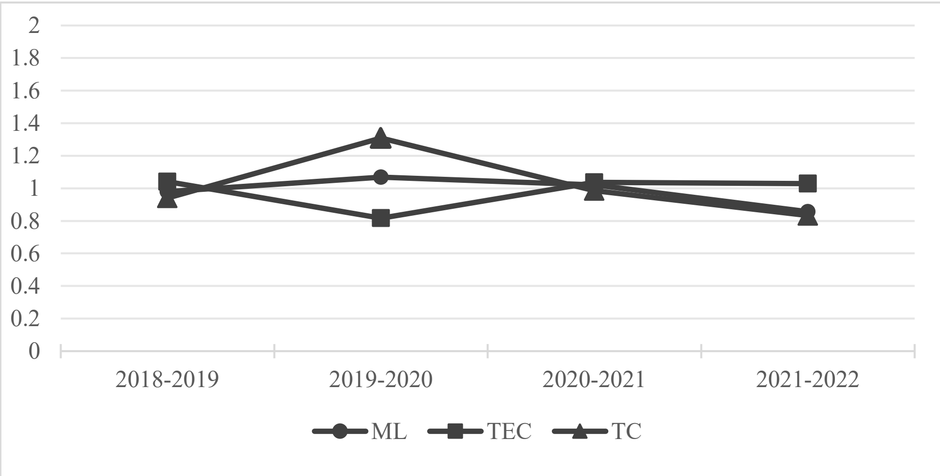

Figure 2: ML index of nitrogen flow efficiency and its decomposition in Lake Tai basin, 2018-2022.

Meanwhile, in order to further analyze the differences among regions, the changes of Malmquist index in the Taihu Lake region were refined, and Table 5 shows the changes of the average Malmquist index and its decomposition terms of each region in the Taihu Lake region from 2018 to 2022. First, from the Malmquist index, the Malmquist index of Mao Yangcheng and Wucheng Xiyu districts increased by an average of 2.3% and 0.7%, while the Malmquist index of Hangjiahu and Huxi districts decreased. Second, the decomposition terms show that the regional nitrogen flow technology change indexes are all larger than the efficiency change indexes within the study year interval, indicating that the production technology in the Taihu Lake Basin has continued to improve in recent years, and that technological advances continue to be an important driving force in promoting the efficiency of nitrogen flow in the Taihu Lake Basin. It should be noted that the change indices of nitrogen flow efficiency in the four regions are less than 1, which indicates that if we want to further improve the efficiency of nitrogen flow in the basin, we need to improve the technological efficiency first, and translate the technological progress into the improvement of technological efficiency in agriculture and industry, which can be practically applied to nitrogen flow links.

Table 5: ML index and its decomposition value for each region of Lake Tai Basin, 2018-2022.

Shore	ML	TEC	EC
Yangchengdianmao	1.023	0.960	1.065
Hangjiahu	0.965	0.967	0.998

Table 5: (continued).

Wuchengxiyu	1.007	0.952	1.058
Huxi	0.981	0.940	1.044

3.3. Analysis of Factors Affecting Watershed Nitrogen Flow Efficiency

3.3.1. Analysis of factors affecting nitrogen flow efficiency in the subregion

In order to investigate the regional heterogeneity of nitrogen flow efficiency in the Taihu Lake basin, regression analysis was conducted on the factors influencing nitrogen flow efficiency from the four major regions, namely, Hangjiahu, Yangcheng Dian Mao, Wucheng Xiyu, and Huxi, based on the results presented in Table 6, as follows:

For the Hangjiahu region, GDP per capita has a significant negative effect on nitrogen flow efficiency, indicating that in regions with a higher level of economic development, the efficiency of nitrogen utilization may be reduced due to the overuse of resources by economic activities. In contrast, green ecology and agricultural mechanization have a significant positive effect on nitrogen flow efficiency in the region, indicating that the increase in green space and the level of mechanization contribute to the optimization of nitrogen flow efficiency.

For Mao Yangchengdian, the nitrogen flow efficiency was mainly positively influenced by the urbanization level and energy structure, suggesting that the urbanization and industrialization level in the region may be related to the change in agricultural production practices and the reduction of reactive nitrogen, which may lead to the increase of regional nitrogen flow efficiency. However, other variables such as GDP per capita, environmental regulation, green ecology and agricultural mechanization did not show significance in the region, which may be related to the specific economic and environmental conditions of the region.

For Wuchengxiyu District, GDP per capita has a significant negative effect on nitrogen flow efficiency, similar to Hangjiahu District, implying that excessive resource consumption or mismanagement brought about by economic development may reduce nitrogen flow efficiency. Environmental regulation and energy structure showed a significant positive effect in this region, suggesting that environmental regulation policies such as strengthening ecological compensation and industrialization level play a positive role in enhancing nitrogen use efficiency in this region. Meanwhile, green ecology showed a significant negative effect, which may be due to the expansion of green space limiting the intensification of agricultural production, resulting in lower nitrogen flow efficiency.

As for the western part of the lake, both the level of urbanization and green ecologization had a significant positive effect on nitrogen flow efficiency. The increase in the level of urbanization may be associated with more modern agricultural production methods, while the positive effect of green ecologization implies the positive contribution of the expansion of green space to nitrogen flow efficiency in the region. The other variables did not show significance in Lakes West and may be related to the particular geographical and economic conditions of the region.

In summary, the analysis of regional heterogeneity reveals that there are significant differences in the driving factors affecting nitrogen flow efficiency in different regions. Factors such as economic development, urbanization, environmental regulation and green ecologization show diverse mechanisms of action in different regions, which provides empirical evidence for the development of regionally targeted watershed nitrogen management policies. Each region should develop differentiated strategies according to its own characteristics to optimize nitrogen use efficiency and promote the sustainable development of nitrogen and phosphorus pollution control in the Taihu Lake basin.

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Table 6: Tobit regression results of factors affecting nitrogen flow efficiency in Lake Tai Basin.

Variant	Basin as a whole	Hangjiahu district	Yangchengdianmao district	Wuchengxiyu district	Huxi district
ED	0.002	-0.058**	0.000	-0.048***	0.006
	(0.25)	(-2.39)	(0.03)	(-3.10)	(0.17)
ER	0.121***	0.036	-0.041	0.340***	0.057
	(3.25)	(0.82)	(-0.82)	(3.78)	(0.61)
Urb	0.002	-0.032***	0.048***	0.035*	0.012***
	(0.83)	(-4.05)	(4.75)	(1.96)	(3.09)
GE	-0.095*	0.499***	-0.064	-0.269*	1.324**
	(-1.74)	(3.19)	(-1.34)	(-2.00)	(2.67)
ES	0.014***	0.007	0.026***	0.011**	0.002
	(4.47)	(1.53)	(5.11)	(2.86)	(0.41)
AM	0.001	0.010**	0.000	-0.004	0.001
	(0.66)	(2.44)	(0.09)	(-0.99)	(0.37)
_cons	-0.546**	1.699***	-4.751***	-1.616	-1.109*
	(-2.23)	(2.97)	(-6.55)	(-1.61)	(-2.07)
Observations	105	35	25	20	25
LR test (P)	0.000***	0.000***	0.000***	0.000***	0.000***

Note: *** p<0.01, ** p<0.05, * p<0.1

3.3.2. Impact Analysis of Overall Nitrogen Flow Efficiency in the Taihu Lake Basin

In selecting the Tobit model for the analysis, its requirement is to do a multiple covariance test for each of the influencing factors. The results of the test are presented in Table 7.The results show that the variance inflation factor (VIF) for each variable is below 2, indicating that the problem is not serious. Among them, environmental regulation has the highest VIF of 1.910 and 1/VIF of 0.523, suggesting that although there is a certain degree of correlation between it and the other independent variables, it does not pose a threat of covariance. The VIFs of the other variables are all between 1.240 and 1.670, and the 1/VIFs are all higher than 0.5, further suggesting low covariance among the variables. Overall, the average VIF is 1.480, indicating that the covariance of the explanatory variables in the model is in an acceptable range, providing a reliable basis for regression analysis.

Table 7: Impact factor VIF test results.

Variant	VIF	1/VIF
ER	1.910	0.523
AM	1.670	0.597
ES	1.470	0.680
ED	1.330	0.753
GE	1.270	0.788
Urb	1.240	0.803
Average value	1.480	

The results of the regression analysis of the nitrogen flow efficiency variables in the Lake Tai Basin are displayed in Table 6 and analyzed as follows:

(i) The regression coefficient of environmental regulation and nitrogen flow efficiency is 0.121 and passes the 1% significance level, indicating that environmental regulation plays a significant positive influence on nitrogen flow efficiency, and that inputs for environmental pollution control can effectively improve nitrogen flow efficiency. This positive relationship may be due to the fact that strict environmental regulations require enterprises and farmers to adopt more efficient nitrogen management techniques to reduce nitrogen loss and pollution and improve resource utilization efficiency. This result suggests that increasing environmental protection inputs, such as ecological compensation, is important for improving nitrogen flow efficiency.

(ii) The regression coefficient of energy structure is positive and passes the 1% significance level, indicating that energy structure also has a significant positive effect on nitrogen flow efficiency. This finding reflects that highly industrialized areas have more advanced production technologies and facilities, which can not only effectively reduce their own nitrogen emissions, but also help farmers use nitrogen fertilizers more efficiently, thus reducing nitrogen flow losses. At the same time, increased industrialization is often accompanied by agricultural modernization, leading to the optimization of nitrogen management and rationalization of resource allocation.

(iii) On the other hand, greening had a negative effect on nitrogen flow efficiency, but did not reach the significance level. This means that although the increase of park green space area may have a potential effect on nitrogen flow efficiency, it does not play a significant role. In addition, the regression coefficients of GDP per capita, urbanization level, and agricultural mechanization were 0.002, 0.002, and 0.001, respectively, which did not pass the test of significance, but their direction and magnitude still provided relevant clues. The positive coefficient of GDP per capita suggests that the development and improvement of economic level may have a contributory effect on the efficiency of nitrogen flow, probably because richer areas are more capable of investing in modern agricultural technologies and environmental protection measures. The positive coefficient of the level of urbanization, on the other hand, reflects the process of urbanization or is associated with changes in agricultural production methods, which in turn affects nitrogen flow. The positive role of agricultural mechanization, although not significant, hints at the potential value of mechanization in driving agricultural efficiency.

4. Conclusions and recommendations

In this study, based on the county scale, 21 districts in the Taihu Lake Basin were taken as the research objects, and the nitrogen flow efficiency from 2018 to 2022 was measured by using the SBM model based on the non-expected outputs, and an in-depth study on the temporal evolution of the nitrogen flow efficiency in the Taihu Lake Basin and its influencing factors was carried out by combining with the ML index and the Tobit model, and the following conclusions were drawn:

1) In terms of the efficiency analysis of the ultra-efficiency SBM model and the Malmquist index, the results show that the nitrogen flow efficiency in the Taihu Lake Basin is at a low level in the statistical year, and there is still a large potential space for energy saving and emission reduction. Moreover, technological progress is still an important driving force to improve the efficiency of nitrogen flow in the Taihu Lake basin. Therefore, the taihu lake basin environmental governance still need for a long time for work, will further technical progress into agriculture, industrial technology efficiency of improvement, fusion "difference" blueprint, accurate positioning management target, stimulate system innovation, to achieve the realization of environmental sustainable development in taihu lake basin, improve nitrogen flow efficiency, improve governance efficiency and basin self repair force.

2) Through the empirical study of nitrogen flow efficiency in the Taihu Lake basin, the results show that environmental regulation and energy structure play a key role in influencing the enhancement of nitrogen flow efficiency. Meanwhile, Tobit regression and OLS robustness analysis consistently show that the strengthening of environmental regulation and the optimization of reasonable energy structure significantly promote the improvement of nitrogen flow efficiency, which are the key factors in the management of environmental pollution in the basin, reflecting the importance of government policies and innovative technological means in the development of the nitrogen cycle system and nitrogen emission reduction in the Lake Tai Basin.

Based on the above research conclusions, the following suggestions are proposed in order to improve the efficiency of nitrogen flow in the Taihu Lake basin:

1) As to how to further transform technological progress into improved technological efficiency in agriculture and industry, the lakeshore region should strictly implement the provisions of "reduction and substitution" for construction projects involving nitrogen and phosphorus emissions, explore the ecological transformation of farmland drainage and irrigation systems, promote the transformation and upgrading of traditional industries to green development, and take the initiative to cultivate the future of emerging industries such as green development. It should guide the orderly transfer of heavy industries to the coastal areas, optimize the ecological environment through adjustment and transformation, and gradually realize the synergistic development of the environment and the economy.

2) Emphasize the importance of government policies and technical means in the development of energy conservation and emission reduction in the Taihu Lake Basin. The government should give full play to the regulatory role of endogenous incentives, for example, by increasing investment in environmental pollution control, formulating corresponding environmental regulatory policies, encouraging farmers and enterprises to adopt efficient nitrogen management techniques, regulating limited inputs of nitrogen fertilizers, and reducing nitrogen loss in the watershed; or promoting the application of clean energy in industrial and agricultural production, subsidizing the application of organic fertilizers, and vigorously advocating green agriculture, etc., which can fundamentally reduce environmental load, help optimize nitrogen management during agricultural production, and thus further promote the improvement of nitrogen flow efficiency in the Taihu Lake basin.

However, the spatial and temporal evolution of nitrogen flow efficiency has multi-scale characteristics, and the factors affecting nitrogen flow efficiency are intricate and complex, so on the basis of fully absorbing its results, we try our best to make it as close as possible to the actual development of watershed management. Due to data limitations, this paper only considers the input and output indicators in the index system, but in reality, nitrogen flow efficiency is subject to the interaction of various factors. Therefore, the further improvement of nitrogen flow efficiency indicators in the watershed can be a key research direction for future extension, combining various factors into the pollution prevention and control work in the watershed.

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Appendix

Main parameters of agro-ecosystems [10,16].

Crop	Seed nitrogen content /%	Nitrogen content of compound fertilizer /%	Nitrogen content of irrigation water /(kg-hm^{-2})	Rate of biological nitrogen fixation /(kg-hm$^{(-2)}$-a^{-1})	Atmospheric nitrogen deposition rate /(kg-hm^{-2})
Grain	1.9	30	26.3	45	14.8
Potatoes	2.5	30	26.3	15	14.8
Legumes	1.9	30	26.3	80	14.8
Vegetable	0.9	30	26.3	15	14.8

Parameters related to main nitrogen products [17].

Principal offerings	Beef	Pork	Goat meat	Poultry	Honey	Cow's milk	Hen's egg	Chemicals prodrug	Chemotherapy fibroid	Plastics products
Nitrogen content/%	3.2	2.1	2	3	0.1	0.5	2.1	5	10	0.2

Parameters of NO_X emission factors for main fuels in industrial systems [18].

Fuels	Raw coal	Coke	Diesel	Gasoline	Diesel fuel	Petroleum
NO_X emission factor	2.3	2.7	5.1	2.3	2.9	0.6

Main parameters of the human consumption system [19].

	Per capita vegetable nitrogen consumption	Urban per capita consumption of animal nitrogen	Sewage denitrification rate
Urban population	2.2	2.6	1.25%
Rural population	3.7	0.2	1.25%