

INFORMATION MINING OF SPATIO-TEMPORAL EVOLUTION OF LAKES BASED ON MULTIPLE DYNAMIC MEASUREMENTS

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ABSTRACT:

Lakes are important water resources and integral parts of the natural ecosystem, and it is of great significance to study the evolution of lakes. The area of each lake increased and decreased at the same time in natural condition, only but the net change of lakes' area is the result of the bidirectional evolution of lakes. In this paper, considering the effects of net fragmentation, net attenuation, swap change and spatial invariant part in lake evolution, a comprehensive evaluation indexes of lake dynamic evolution were defined. Such degree contains three levels of measurement: 1) the swap dynamic degree (SDD) reflects the space activity of lakes in the study period. 2) the attenuation dynamic degree (ADD) reflects the net attenuation of lakes into non-lake areas. 3) the fragmentation dynamic degree (FDD) reflects the trend of lakes to be divided and broken into smaller lakes. Three levels of dynamic measurement constitute the three-dimensional "Swap - attenuation - fragmentation" dynamic evolution measurement system of lakes. To show its effectiveness, the dynamic measurement was applied to lakes in Jiangnan Plain, the middle Yangtze region of China for a more detailed analysis of lakes from 1984 to 2014. In combination with spatial-temporal location characteristics of lakes, the hidden information in lake evolution in the past 30 years can be revealed.

1. INTRODUCTION

Lakes are important water resources and integral parts of the natural ecosystem. Since ancient times, lakes are closely related with human survival and development and play an irreplaceable role in runoff regulation, agricultural irrigation, transportation, urban and rural water supply, aquaculture, and maintaining ecological balance (Johnson et al., 2001). The lake evolution here is mainly affected by both natural factors (crustal movement, sediment deposition, and climate change) (Shadkam et al., 2016) and human activity (reclaiming farmland from lakes, urban expansion, and construction of large-scale water conservancy projects) (Yao et al., 2006; Wei et al., 2005a). Along with the population growth and the development of productive forces, the effects of human intervention on nature and ecological environment increased, which accelerated the evolution of lakes (Xiao et al., 2012).

A number of studies have been proposed for the evolution of lakes, studies on lake mainly focus on the lake changes at different time scales (Sironić et al., 2016), the landscape pattern evolution (Liu et al., 2014; Wu et al., 2016), the evolving types and causes of lakes (Jambrina-Enríquez et al., 2017; Shadkam et al., 2016), the impact of water pollution (Grochowska et al., 2015; Sevindik et al., 2014; Williamson et al., 2009), the management of water resources (Li et al., 2017; Zębek, 2014), and so on. The core concept of most methods is to calculate the total change of the lakes' area. However, the area of each lake increased and decreased at the same time in natural condition, only but the net change of lakes' area is the result of the bidirectional evolution of lakes. Considering the growth and decay of lakes in spatial evolution, the definition and calculation model of the swap dynamic degree (SDD), the attenuation dynamic degree (ADD), and the fragmentation dynamic degree (FDD) were proposed, which can efficiently judge the process of the spatial evolution of lakes. The comprehensive evaluation indexes are of great significance to the improvement and

restoration of the ecological environment and the sustainable utilization of lake resources.

2. RESEARCH METHODS

2.1 Classified lake transfer matrix

The classified lake transfer matrix reflects the dynamic process of the mutual transformation of the lake area in a certain period of time (Sánchez-Soto et al., 2012). It not only includes the information of all graded lakes at a certain time, but also contains more abundant information about the conversion from lakes since the beginning and the transferred quantity to lakes until the ending (Liu and Zhu, 2010). The general form of classified lake transfer matrix is:

$$a_{ij} = \begin{bmatrix} a_{00} & a_{01} & \dots & a_{0n} \\ a_{10} & a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots & \dots \\ a_{n0} & a_{n1} & \dots & a_{nn} \end{bmatrix}$$

where \mathbf{a} = area of lakes; \mathbf{n} is the number of lake grades
 $i, j (i, j = 0, 1, 2, \dots, n)$ represent the type of lake grade before and after the transfer, respectively, of which 0 value represents non lake areas
 a_{ij} = area of i^{st} lakes that converted into j^{st} lakes during the study period
 a_{0j} = area of non-lake areas that converted into j^{st} lakes during the study period
 a_{i0} = area of i^{st} lakes that converted into non lake areas during the study period
 i^{st} row in the matrix = the flow information of the i^{st} lakes to other lakes and non-lake areas
 j^{st} column in the matrix = the source information of j^{st}

lakes from the other lakes and non-lake areas at the ending of the study.

2.2 "Swap - attenuation - fragmentation" dynamic evolution measurement system

The traditional dynamic degree evaluation only considers the net change between lakes and other non-lake areas (Ciancio and Verhás, 2009), it tends not to involve much with the spatial interaction of lakes. In the existing dynamic researches (Liu and Zhu, 2010; Wang and Li, 2002), the parts of lakes that did not change in space in the transfer period are often neglected. Under the same net changes of lakes' area, the smaller the invariant parts of lakes in space, the greater the dynamic degree during this period. On the basis of traditional dynamic degree, this paper presents the formulas for calculating the swap dynamic degree (SDD), the attenuation dynamic degree (ADD), and the fragmentation dynamic degree (FDD). The effects of net change, exchange change and space invariant in the dynamic degree evaluation are considered.

2.2.1 Swap Dynamic Degree (SDD)

SDD considers the situation that lakes turn into other classes in certain areas, and transfer from other classes in other areas at the same time. The degree is determined by the ratio of the offsets of the shift and the spatial invariant, the value reflects the activity of spatial location shift of lakes in study period. For kst lakes, the function is shown as follows:

$$A'_k - A_k = \sum_{i=0}^n a_{ik} - \sum_{j=0}^n a_{kj} = (\sum_{i=0}^n a_{ik} - a_{kk}) - (\sum_{j=0}^n a_{kj} - a_{kk}) = I_k - D_k \quad (1)$$

$$SDD_k = \frac{2 \times \text{MIN}(I_k, D_k)}{a_{kk}} \times \frac{1}{T} \times 100\% \quad (2)$$

where $A_i = \sum_{j=0}^n a_{ij}$ ($i \neq 0$) is the sum of the elements of i^{st} row

in the $n+1$ order matrix, which represents the area of the i^{st} lakes at the beginning of the study

$A'_j = \sum_{i=0}^n a_{ij}$ ($j \neq 0$) is the sum of the elements of j^{st}

column in the $n+1$ order matrix, which represents the area of the j^{st} lakes at the ending of the study

$I_j = A'_j - a_{jj}$ ($j \neq 0$) is the additional area of j^{st} lakes

during the study period

$D_i = A_i - a_{ii}$ ($i \neq 0$) is the reduced area of i^{st} lakes

during the study period

a_{ij} ($i = j \neq 0$) = the elements in the main diagonal except

a_{00} in the $n+1$ order matrix, which represents the spatially invariant part of i^{st} lakes during the study period.

2.2.2 Attenuation Dynamic Degree (ADD)

ADD refers to the absolute dynamic change that lakes transfer into beach or construction land under the influence of nature or

human activities, it is a direct measure of the demise of lakes. For kst lakes, the function is shown as follows:

$$ADD_k = \frac{|a_{k0} - a_{0k}|}{a_{kk}} \times \frac{1}{T} \times 100\% \quad (3)$$

2.2.3 Fragmentation Dynamic Degree (FDD)

Behaviors, such as human activities and urban construction, often divide the lakes. The water self-purification ability of the divided lakes weakens, and these lakes will be easily polluted and buried. The evolution dynamic of integrity of lakes is represented by FDD. For kst lakes, the function is shown as follows:

$$FDD_k = \frac{|\sum_{i=1}^n a_{ik} - a_{kk}| - |\sum_{j=1}^n a_{kj} - a_{kk}|}{a_{kk}} \times \frac{1}{T} \times 100\% = \frac{|\sum_{i=1}^n a_{ik} - \sum_{j=1}^n a_{kj}|}{a_{kk}} \times \frac{1}{T} \times 100\% \quad (4)$$

3. SPATIO-TEMPORAL EVOLUTION OF JIANGHAN LAKE GROUP

3.1 Study area

The Jiangnan Plain is located in the northern part of the Central Yangtze River drainage basin, Hubei Province, China, and ranges from $28^{\circ} 08'$ to $30^{\circ} 08'$ N in latitude and from $111^{\circ} 12'$ to $114^{\circ} 47'$ E in longitude, with an altitude of <40 m in most parts. It is the largest plain in south China, encompassing a total area of 45456 km^2 and 25 counties/cities (Gao et al., 2011). Geologically, it stems from the lower Yangtze and Hunan-Hubei-Guizhou platform and the old Jiangnan basin of the late Paleozoic, and was formed in the past several hundred years by depositions from the Yangtze River and Han River. The climate is subtropical, with an annual precipitation of $1000\text{--}1500$ mm, and a mean annual temperature of 16.5°C . The Jiangnan Plain contains a large number of lakes, most of which are dammed and fluvial lakes. Prior to impoldering, these lakes played an important role in flood mitigation, as well as providing water for drinking, irrigation, and aquaculture.

In this study, we focused on natural lakes recorded in *Lake in Hubei Province* (Guo et al., 2015). To obtain a more detailed analysis of the changes of lakes in Hubei from 1984 to 2014, the lakes were divided into four levels according to their areas (Wei et al., 2005b). The four great lakes (who cover an area of more than 100 km^2) in Hubei: Liangzihu Lake, Honghu Lake, Futouhu Lake, and Changhu Lake (the areas of the corresponding lakes in 1984 are 245.173 km^2 , 214.777 km^2 , 140.096 km^2 , and 121.416 km^2 , respectively). The lakes that cover an area of $10\text{--}100 \text{ km}^2$, $1\text{--}10 \text{ km}^2$, and $<1 \text{ km}^2$ are large lakes, medium lakes, and small lakes in Hubei Province, respectively. Figure 1 shows the lakes noted in the *Lake in Hubei Province*, which are basically concentrated in the plain area.

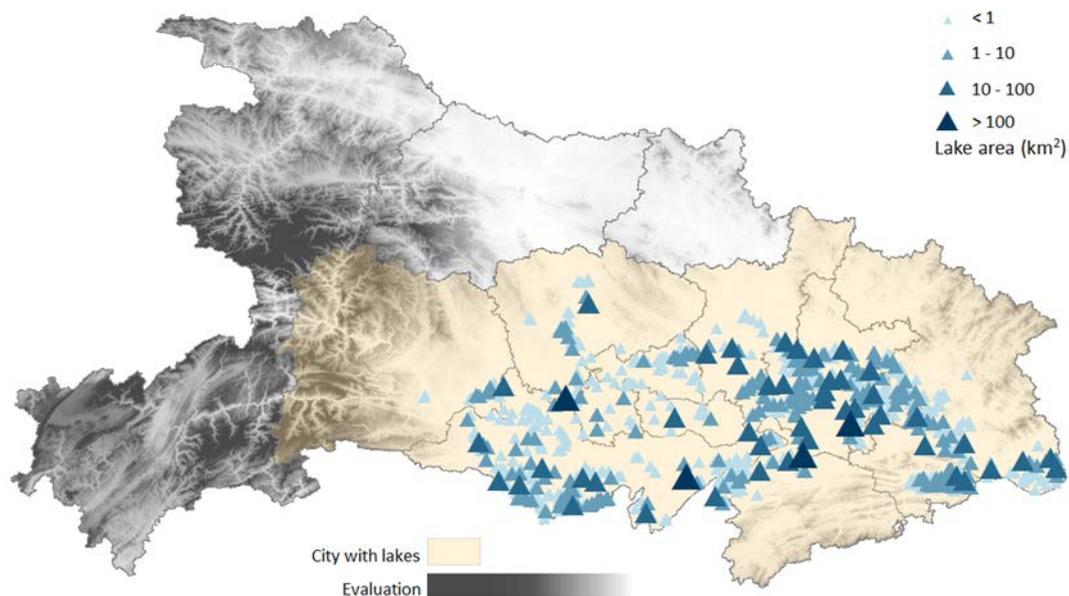


Figure 1. Distribution of the Jiangnan Lake Group in 2014

3.2 Experimental data

The surface area measurements of lakes in 1984, 1989, 1995, 2000, 2005, and 2010 were acquired from Landsat TM remote-sensing data and lakes in 2014 were acquired from Landsat-8 images. The geometric correction, mosaic and enhancement of the remote sensing images in study area were carried out by ERDAS. And 7 phases of water information were extracted from remote sensing images by NDWI (Normalized Difference Water Index)(McFEETERS, 1996).

The time of year (e.g. dry or rainy season) significantly affects topographies and remote sensing imagery. Data on the lake were obtained during specific periods: most of the images used in this study were obtained from the wet season (June–September), and a few were obtained from October.

3.3 Analysis of spatial evolution of lakes

To identify an overall trend of the changes in these lakes, we classified the lakes and accounted the corresponding changes in 30 years (see Figure 2). The total area of lakes in the Jiangnan Plain exhibited a decreasing trend from 1984 to 2014, and the intensity of decrease varies in different periods of time. Since 1980s, with the process of reform and opening up in China, industrial and agricultural production has exhibited rapid development. Driven by economic interests, the water management in the middle Yangtze reaches experienced a chaotic period. Blindly reclaiming land from lakes led to severe attenuation of lakes in this period. Before the year 2000, the water surface area of the natural lakes significantly declined, and the total area decreased by 272.282 km² from 2459.807 km² in 1984 to 2187.524 km² in 2000. Since 2000, under the strategy of "leveling protective embankment to divert water, retreating the land to lakes", the area decay is relatively gentle. A total area of 96.903 km² was lost until 2014, indicating that the strong reduction of the lakes in the 1980s was curbed. From 1984 to 2014, the lake area reduced by 369.186 km².

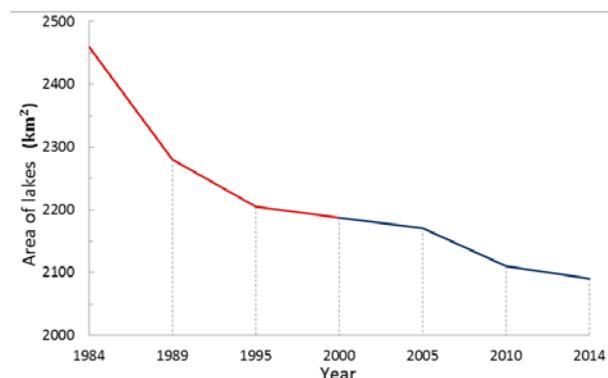


Figure 2. Changes of the total area of the Jiangnan Lake Group from 1984 to 2014

3.4 Classified lake transfer matrix in Jiangnan Plain

Throughout the study period that spans 30 years, the lake area in Jiangnan Plain continued to decrease. However, the area of each lake increased and decreased in natural condition, only but the total growth in lake area is less than the reduction. To determine the actual spatial characteristics of the changes of lakes, this study analyzed the growth and decay of lakes, respectively. The calm middle period in 2000 was set as the boundary, and the data can be divided into two periods: 1984-2000 and 2000-2014. In order to explore the increase and decrease in lake evolution, classified lake transfer matrices for lakes in Jiangnan Plain were obtained. Table 1 and Table 2 show the transition in lake distinct during 1984-2000 and 2000-2014, respectively. The value 0 represents non-lake areas, and value 1-4 represent four great lakes, large, medium and small lakes, respectively.

By analyzing and arranging the classified lake transfer matrix, lake evolution guidance during the study period can be gain (see Figure 3 and Figure 4). The variation of each level of lake consists of two sets of data. Taking the large lakes for example, the red line and blue line represent the total area of lakes at the beginning and end of the study period. The blue area represents the invariable part in space during 1984-2000. The distance between the red line and blue line reflects the net change of

large lakes during the study period, while the distance between the blue line and blue area indicates the amount of swap change in the large lakes. The second column shows the interactive evolution between large lakes and other types. The increase of other types into large lakes during the study period is shown above the horizontal axis, and the reduction of large lakes into other types is overlay displayed below the horizontal axis.

	2000_0	2000_1	2000_2	2000_3	2000_4
1984_0		59.653	178.762	81.283	40.053
1984_1	88.249	632.676	0.510		0.226
1984_2	255.329		766.701	53.611	7.544
1984_3	210.437	7.746	27.014	249.353	25.231
1984_4	77.448	0.079	0.568	11.254	45.788

Table 1 Classified lake transfer matrix from 1984 to 2000 (Unit: km²)

	2014_0	2014_1	2014_2	2014_3	2014_4
2000_0		52.948	158.809	100.766	48.324
2000_1	101.483	591.701		6.789	0.180
2000_2	189.562	0.172	726.290	51.177	6.355
2000_3	109.033		31.696	238.088	16.685
2000_4	57.830	0.193	4.775	13.539	42.505

Table 2 Classified lake transfer matrix from 2000 to 2014 (Unit: km²)

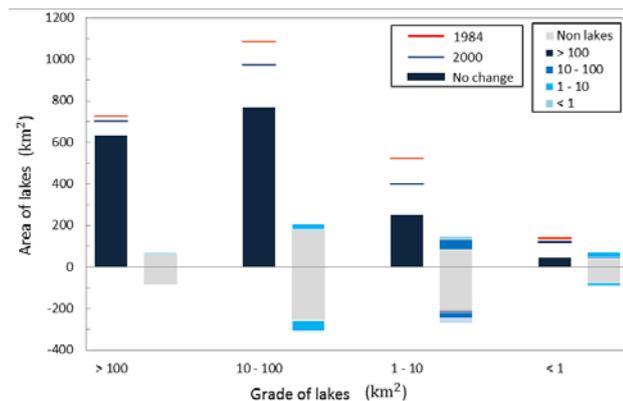


Figure 3. Guide map of lake evolution in 1984-2000

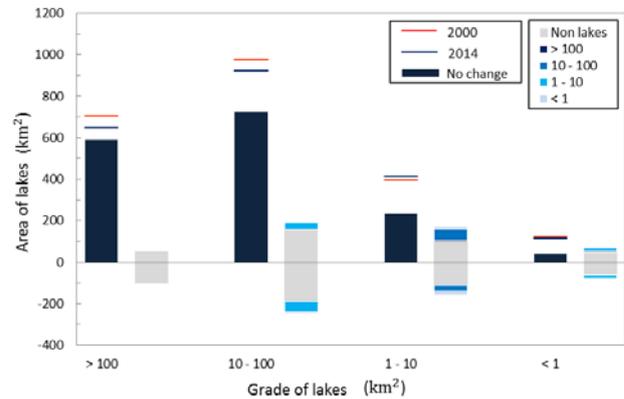


Figure 4. Guide map of lake evolution in 2000-2014

Combined with the transfer matrix, the lake transfer situation in 1984-2000 and in 2000-2014 was analyzed. The related conclusions were as follows:

(1) There is a certain degree of decay in lakes with all grades. The spatial dynamics of lakes are dominated by interactive change, in which the conversion between lakes and non-lake regions is the most significant, showing a high degree of spatial activity. In addition to the net attenuation of lakes, there have been a lot of conversion and recovery in the past thirty years. With the development of urbanization, the interaction between lakes and lands has been more frequent as the swap dynamic degree appeared significant increase.

(2) The interactive evolution in lakes is mainly reflected on conversion between large and medium lakes, mostly for large lakes converted to medium lakes by decomposition or landfill, (53.611 km²) with a certain degree of restoration of medium lakes to large lakes (27.014 km²). The dominant trend was that larger lakes are segmented. As an exception, the Four-lakes Watershed plays an important role in flood control, drainage, and runoff regulation. Considering its high stability, it basically did not be decomposed into smaller lakes.

4. DYNAMIC EVOLUTION ANALYSIS IN JIANGHAN PLAIN

On the basis of two transfer matrixes, the amount of spatial invariant, increase, decrease and multiple variations of lakes at all grades in 1984-2000 and in 2000-2014 can be analyzed. The SDD (Equation (2)), ADD (Equation (3)), FDD (Equation (4)) of lakes were calculated, and the statistical result is shown in Table 5. The visual comparison of SDD, ADD, and FDD in 1984-2000 and in 2000-2014 is essential to further assess the evolution of lakes in Jianghan Plain (see Figure 5).

	a_{kk}	$a_{k0} - a_{0k}$	$\sum_{i=1}^n a_{ik} - \sum_{j=1}^n a_{kj}$	D_k	I_k	$I_k - D_k$
1	632.676	28.596	7.089	88.985	67.478	-21.507
2	766.701	76.567	187.355	316.484	206.855	-109.630
3	249.353	129.154	331.157	270.427	146.148	-124.279
4	45.788	37.395	582.812	89.348	73.054	-16.294

Table 3 Information of lake dynamic evolution from 1984 to 2000 (Unit: km²)

	a_{kk}	$a_{k0} - a_{0k}$	$\sum_{i=1}^n a_{ik} - \sum_{j=1}^n a_{kj}$	D_k	I_k	$I_k - D_k$
1	591.992	48.535	6.604	108.162	53.312	-54.850
2	726.219	30.753	191.928	247.337	195.280	-52.057
3	237.868	8.267	305.597	157.633	172.271	14.638
4	42.329	9.506	531.054	76.513	71.544	-4.969

Table 4 Information of lake dynamic evolution from 2000 to 2014 (Unit: km²)

Area (km ²)	1984 - 2000			2000 - 2014		
	SDD	ADD	FDD	SDD	ADD	FDD
> 100	0.013	0.003	0.001	0.013	0.006	0.001
10 - 100	0.034	0.006	0.015	0.038	0.003	0.019
1 - 10	0.073	0.032	0.083	0.095	0.002	0.092
< 1	0.199	0.051	0.796	0.241	0.016	0.896

Table 5 "Swap - attenuation - fragmentation" dynamic evolution measurements of lakes in Jiangnan Plain

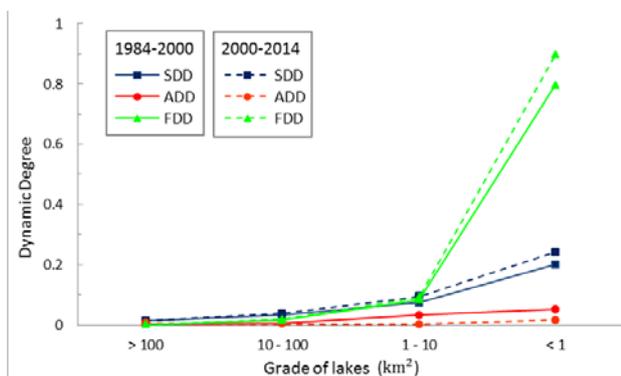


Figure 5. Comparison of dynamic degrees of lakes at all grades

(1) The Four Great Lakes exhibit an extremely low degree of dynamic levels, which are related to the high degree of emphasis on their functions of flood control and storage. Large lakes and medium-sized lakes are the main force of lake attenuation, their attenuation has been controlled since entering the new century. The overall dynamic degree of large lakes and medium lakes is also low. While the small lakes with an area of less than 1 km² showed a high degree of dynamic levels, indicating that the spatial distribution of small lakes is extremely unstable.

(2) For the Four Great Lakes and large lakes, the spatial dynamics were mainly composed of interactive changes. The SDD accounted for more than 60% of the total dynamic in 1984-2000 and in 2000-2014. The medium-sized lakes were characterized by SDD and FDD, while the small lakes were dominated by FDD. The spatial dynamics of small lakes were mainly presented as the decomposition and aggregation between the small lakes and the lagers. The attenuation of lakes in Jiangnan Plain has been curbed since 2000, and the types of lake transfer also changed along with the development of society and economy.

(3) Through the comparison of two study periods, dynamic evolution trends of lakes with all grades varied between 1984-2000 and 2000-2014. Results show that since 2000, 1) As a result of the increase in area attenuation of the Four Great Lakes, the ADD also increased, while their SDD and FDD were relatively stable. 2) For the lakes with areas less than 100 km²,

their ADD has decreased in different degrees since 2000, and the overall dynamics showed a downward trend. The net attenuation process of lakes has slowed down, and the attenuation trend has been cubed. However, both of their SDD and FDD increased to a certain extent. The proportion of interactive changes in space evolution structure is further enhanced, and the evolution flow of lakes is more complicated.

CONCLUSION

Cause the fixedness and uniqueness of lake evolution in space, analysis based on area change can not truly reflect the dynamic evolution of lakes. To truly express the changes in lake variation, it is necessary to build a comprehensive analysis system that considers the net attenuation, net decomposition and interactive changes in lakes and reveal the corresponding implied information. This paper constructs the "Swap - attenuation - fragmentation" dynamic measurement system and analyzes the lake transfer in Jiangnan Plain during 1984-2000 and 2000-2014. By comparing the lake transfer before and after 2000, the dynamic characteristics and evolution of lakes at different grades in Jiangnan Plain are more clearly identified, and the quantitative statistics of the bidirectional change and variation process in lake evolution is realized.

The overall decay in Jiangnan Plain has been eased since entering the new century. Reclaiming farmland from lakes on a large scale was under control, and the attenuation tendency of lake area was alleviated. However, with the acceleration industrialization and urbanization, some new characteristics of lake evolution have been developed in Jiangnan Plain. The development of tourism industry and wetland construction led to the rapid changes of large lakes in space. Under the influence of city construction and industrialized farming around the lake, the comprehensive activity of lake evolution increased in general.

This paper constructs the dynamic evolution measurements of lakes, mining and evaluating the hidden process of exchange, implicit conversion and decomposition in lake evolution combined with spatio-temporal location information. The proposed methods provide a new idea for understanding the spatial and temporal dynamics of lake and its driving forces, but also make up for the shortage of traditional dynamic method to judge the evolution of lakes with spatial landscape. The results of this study are of great significance for more accurate evaluation of the systematic process of lakes, the improvement of ecological environment and the sustainable utilization of lake resources.

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