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Quantitative Study on Morphological Change Characteristics of Tonle Sap Lake Based on DEM

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Abstract

Lake is an important part of the natural ecosystem, and its morphological characteristics reflect the capacity of lake regulation and storage, the strength of material migration, and the characteristics of shoreline development. In most existing studies, remote sensing images are used to quantify the morphological characteristics of lakes. However, the extraction accuracy of lake water is greatly affected by cloud cover and vegetation cover, and the inversion accuracy of lake elevation data is poor, which cannot accurately describe the response relationship of lake landscape morphology with water level change. Therefore, this paper takes Tonle Sap Lake as the research object, which is the largest natural freshwater lake in Southeast Asia. DEM is constructed based on high-resolution measured topographic data, and morphological indicators such as lake area, lake shoreline length, perimeter area ratio, longest axis length, maximum width, shoreline development index, lake shape complexity, compactness ratio and form ratio are adopted to researching the evolution law of high water overflows and low water outbursts quantitatively, and clarifying the variation characteristics of landscape morphology with water level gradient in Tonle Sap Lake. The research results have important theoretical significance for the scientific utilization of Tonle Sap Lake water resources and the protection of the lake ecosystem.

Keywords

Tonle Sap Lake, DEM, Geometrical Morphology, Variation Characteristic

1. Introduction

Lakes are the most important part of the hydrosphere, the regulator of river runoff [1], the stabilizer of ecological balance [2], and the indicator of climate change [3]. Tonle Sap Lake, the research object of this paper, is the largest natural freshwater lake in Southeast Asia with a watershed area of 86,000 km^2. It is known as the natural storage site of the Mekong River as the most important buffer zone when the Mekong River floods come [4]. When Tonle Sap Lake alleviates the flood threat of the Mekong River and increases the dry water flow of the Mekong River, it is also necessary to pay attention to the impact of the Mekong River hydrological regime changes on the ecological environment of the Tonle Sap Lake area, especially to clarify the law of high water overflow and low water exposure in the Tonle Sap Lake area, that is, to give a scientific qualitative description and quantitative evaluation of the landscape form of the Tonle Sap Lake.

Morphology is often used to describe the characteristics of things in water-related disciplines [5]. After calculating and obtaining the flood inundated range of natural lakes, the flood overflow results can be visually seen in space. However, it is still difficult to quantitatively grasp the morphological change characteristics of lakes and explore the morphological change law, so a series of quantitative morphological indicators are needed to evaluate the morphological characteristics of lakes. At present, some achievements have been made in the study of lake morphological characteristics.Shi Yuming *et al.* calculated lake area, perimeter and shoreline development index based on Landsat data to study the dynamic change of morphology in flood period of Jianghan Plain in central China [6]. Huo Yu conducted a quantitative analysis on the dynamic change characteristics of the shoreline of Poyang Lake in the past 30 years, and the results showed that the length of the shoreline of Poyang Lake was shortened and its geometric shape tended to be simpler [7]. Based on satellite image data, Yuan Yangyang *et al.* analyzed and summarized the morphological characteristics of landscape water bodies in 28 lakes by using basic geometry, fractal geometry and European geometry morphological indexes [8]. Zhang Fengtai *et al.* made a comparative analysis of the morphological characteristics of typical natural lakes and artificial lakes in the world with morphological indices such as shoreline development Index, perimeter/area ratio and fractal dimension as indicators [9].

On the whole, at present, scholars mostly use remote sensing images with wide coverage, high monitoring frequency and easy access to evaluate the dynamic change characteristics of lake morphology. On the one hand, the extraction accuracy of water area based on remote sensing images is easily affected by cloud cover and vegetation, especially for Tonle Sap Lake in this study [10]. On the other hand, the accuracy of remote sensing image inversion for elevation data is poor, especially in plain river network areas, which can not accurately depict the response relationship of lake landscape morphology with water level change. In addition, there are few studies on the rate of change of lake landscape morphology with water level gradient, which makes it difficult to directly present the river-lake facies characteristics. Therefore, this paper intends to use measured high-precision terrain data to draw DEM, and use multi-disciplinary cartography [11] and mathematical statistics methods to clarify the landscape morphological characteristics and differences in flood and blight changes of Tonle Sap Lake under different water levels, so as to help deepen the study of the relationship between Mekong River and Tonle Sap Lake and the comprehensive water resources management of Tonle Sap Lake.

2. Data and Methods

2.1. Study Area Profile

Tonle Sap Lake is located in the northwest of Cambodia, on the north bank of Phnom Penh reach of the Mekong River Delta which is known as the heart of Cambodia and the "lake of life" of the people [12]. Tonle Sap Lake is a freshwater lake of overflow type, hugging-and-putting-type and seasonal, which is controlled by multiple influences of tributaries of the lake and Mekong River. The changes of incoming water from tributaries and the changes of water level of Mekong River main stream during flood and dry season lead to great differences in lake area and volume. The measured largest lake area (15,261 km^2) and volume (78.7 billion m^3) are 7 times and 101 times of the measured minimum area (2053 km^2) and volume (780 million m^3) respectively [13]. Under constant water level, Tonle Sap Lake presents a narrow and long oval shape with the northwest and southeast as the long axis. In order to further investigate the variation law of Tonle Sap Lake's morphology with the fluctuation of water level during flood and dry season, the area above the outlet control station of Tonle Sap Lake, Kampong Chhnang Station, was selected as the research object according to the topographic characteristics and flooding characteristics of the lake, as shown in **Figure 1**.

2.2. Data

The 1:100,000 underwater topographic map of Tonle Sap Lake, 1:20,000 underwater topographic map of Tonle Sap River and 1:50,000 land topographic data of Tonle Sap Lake basin were used.

2.3. Methods

The technical route of this paper includes the following steps: 1) data collection, 2) data processing, 3) construction of digital elevation model, 4) calculation of water range under different water levels, and 5) assessment of lake morphological changes. The main research methods are as follows.

2.3.1. Construction Method of Digital Elevation Model

A Digital Elevation Model (DEM) is a data set of plane coordinates (X, Y) and their elevation (Z) of regular grid points within a certain range. It is formed

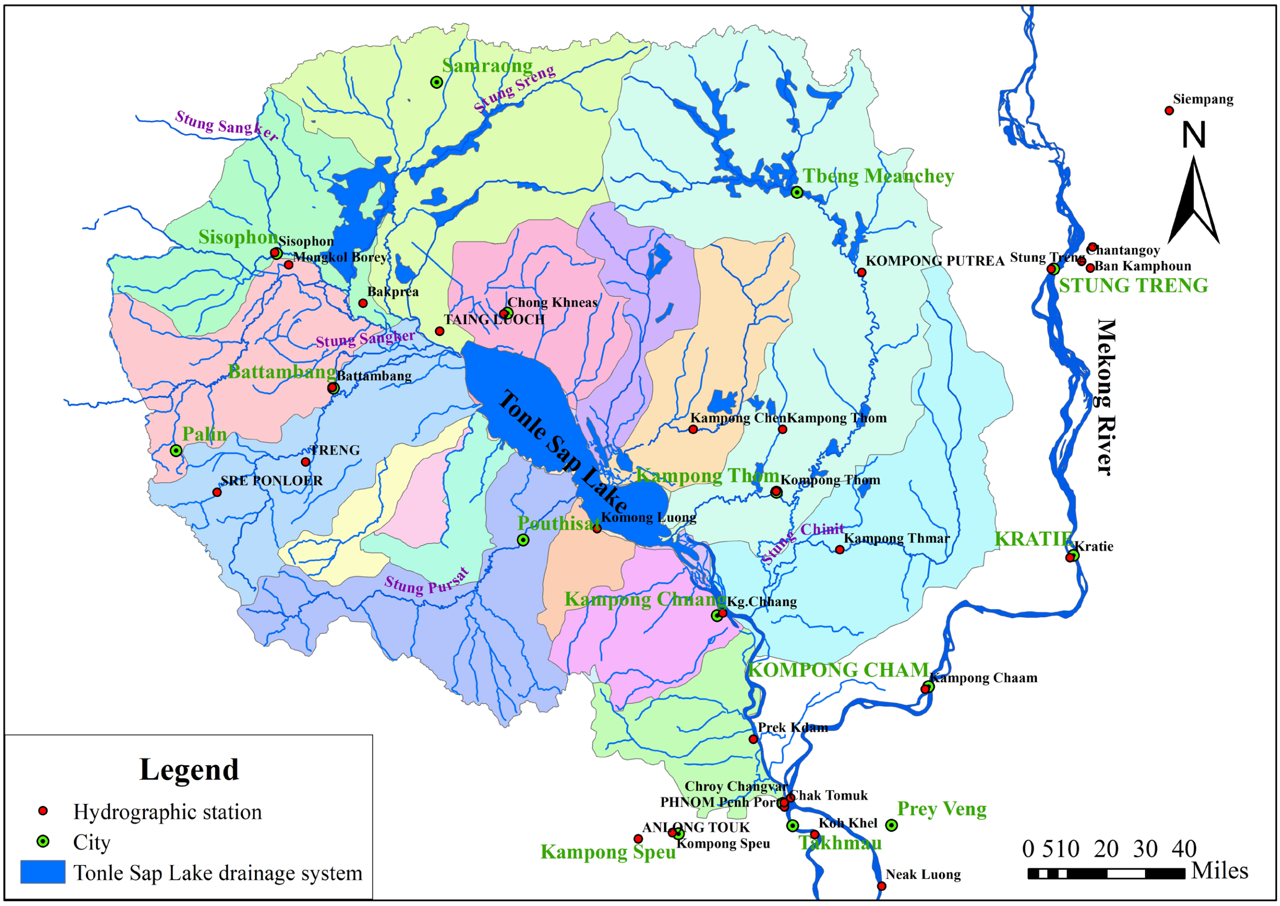

Figure 1. Water system map of Tonle Sap Lake basin.

through data interpolation of contour lines or elevation points, etc., and can be used to achieve digital simulation of terrain with limited terrain elevation data [14].

The construction of DEM in Tonle Sap Lake District is to scan paper topographic map data into digital images, then convert them into vector data, and carry out data format conversion, coordinate system conversion, data stitching and other data processing on them. Then GIS software is used to generate all vector data into irregular triangulation TIN, and then convert TIN into raster data. According to the topographic map scale, the resolution of the DEM built in this paper is 5 m.

2.3.2. Calculation Method of Water Body Range under Different Water Levels

The range of water under different water levels is calculated by the passive inundation method, that is, given a water level value, the elevation value of each grid unit in Tonle Sap Lake district and the size of the water level value are judged in turn. If the given value is greater than the elevation value of the grid unit, it is regarded as flooding and the grid unit is stored. In short, any area below a given water level is counted as a water body.

2.3.3. Characterization Methods of Lake Morphological Changes

Based on the existing research results [3] [5] [6] [7] [14], the evaluation indexes of lake morphology selected in this paper are divided into two aspects. First, the basic geometric morphological indexes include lake area (S), lake perimeter (P), perimeter/area ratio (K), longest axis length (L) and maximum width (W). The second is European geometric shape index, including shoreline development Index (SDI), lake shape complexity (e), compactness ratio (C), form ratio (F_R). The specific calculation method is shown in Table 1.

3. Results

3.1. The Variation of Lake Water Range with the Rise and Fall of Water Level

Topographic data is used to construct the DEM of Tonle Sap Lake area, and the results are shown in Figure 2. Then, the water body range under the water level of 1 - 11 m of Tonle Sap Lake was obtained by the passive inundation method. The water body range under different water levels is shown in Figure 3. It can be seen that the area of Tonle Sap Lake grows rapidly with the water level, and the water body range expands significantly along the northwest and southeast directions, among which the expansion is the largest in the provinces of Battambang and Kampong Thom. In Battambang Province, the water area of Tonle Sap Lake increased from 182 km^2 at 1 m to 3523 km^2 at 11 m, and the water level of the lake area changed by 334 km^2 per meter. In Kampong Thom Province, the water area of Tonle Sap Lake increased from 212 km^2 at 1 m to 2740 km^2 at 11 m, and the water level of the lake area changed by 253 km^2 per meter.

3.2. The Change of Lake Morphology Index with the Rise and Fall of Water Level

According to the quantitative evaluation index calculation method of landscape water morphology of Tonle Sap Lake, the morphological indices of different water levels from 1 to 11 m were obtained, and the calculation results are shown in Table 2 and Table 3.

Table 1. Quantitative evaluation index of landscape water morphology in Tonle Sap Lake.

Morphological index	Index 1	Index 2	Index 3	Index 4	Index 5
Basic Geometric Morphological	Area (km^2) S	Perimeter (km) P	K = Perimeter (P)/ Area (S)	Longest Axis Length (km) L	Maximum Width (km) W
European Geometric Shape	Shoreline Development Index $\mathrm{SDI} = P/2\sqrt{\pi S}$ (1)	Lake Shape Complexity $e = P^2/S$ (2)	Compactness Ratio $C = S/S_0$ (3) (S_0 is the minimum circumscribed circle area)	Form ratio $F_R = S/L^2$ (4)	

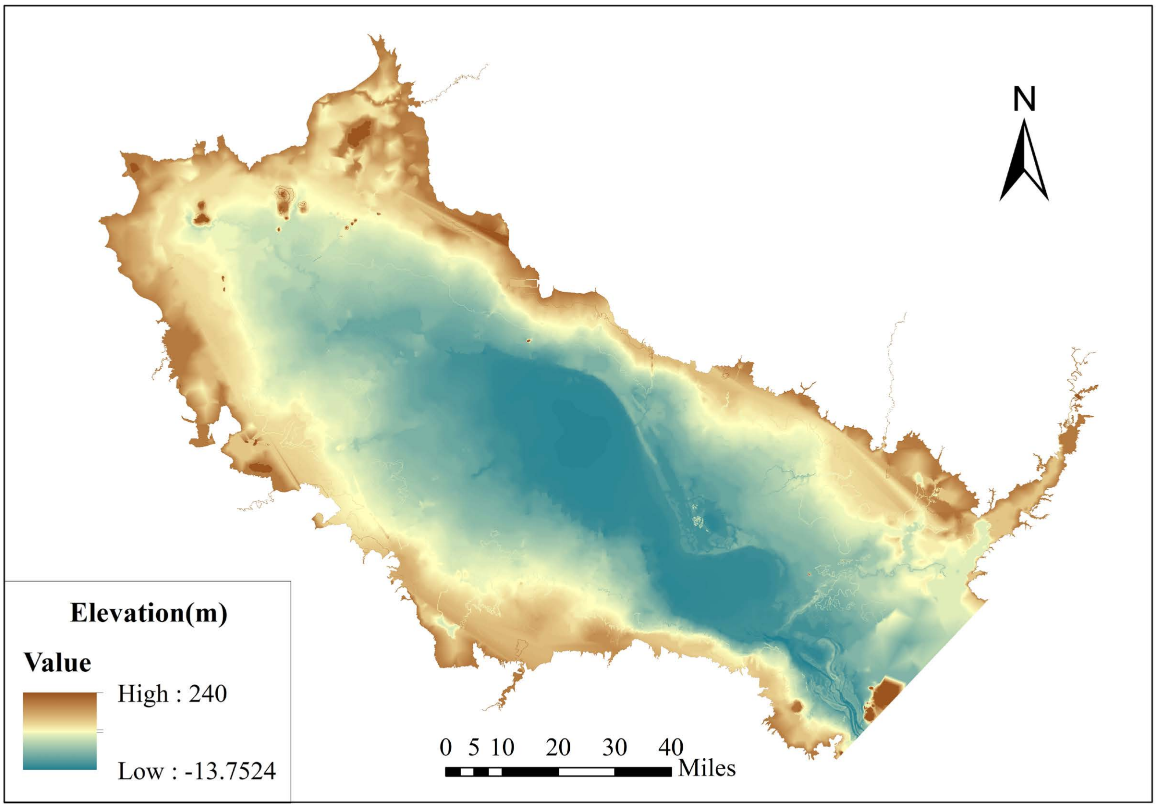

Figure 2. Digital elevation model of Tonle Sap Lake area.

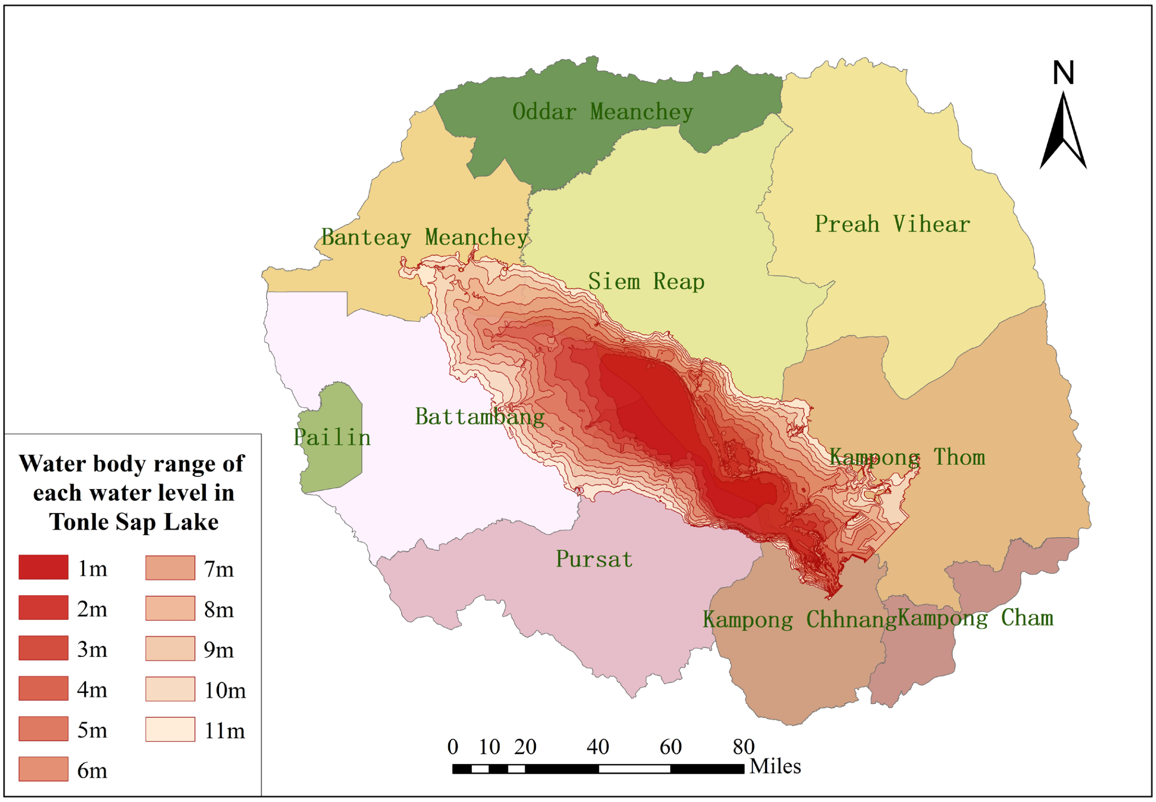

Figure 3. The range of water bodies at different levels in Tonle Sap Lake.

Table 2. The calculated value of the basic geometric shape index of Tonle Sap Lake.

Water Level/m	Area (S)/km^2	Perimeter (P)/km	Perimeter/ Area(K)	Longest Axis Length (L)/km	Maximum Width (W)/km
1	1830	325	0.178	101	34
2	3076	761	0.247	146	43
3	3920	681	0.174	153	44
4	5042	988	0.196	189	50
5	6352	844	0.133	199	56
6	7731	706	0.091	205	62
7	8954	744	0.083	212	65
8	10,220	789	0.077	224	68
9	11,491	888	0.077	237	73
10	12,879	990	0.077	252	82
11	14,035	1005	0.072	253	84

Table 3. The calculated value of European geometric shape index of Tonle Sap Lake.

Water Level/m	Shoreline Development Index (SDI)	Lake Shape Complexity (e)	Compactness Ratio (C)	Form Ratio (F_R)
1	2.144	57.781	0.230	0.181
2	3.871	188.312	0.183	0.144
3	3.067	118.235	0.214	0.168
4	3.925	193.595	0.179	0.141
5	2.988	112.172	0.204	0.160
6	2.264	64.400	0.235	0.185
7	2.219	61.888	0.253	0.199
8	2.203	60.991	0.260	0.204
9	2.338	68.682	0.261	0.205
10	2.461	76.117	0.259	0.203
11	2.392	71.904	0.279	0.219

4. Discussion

4.1. Analysis of Lake Morphological Change

In order to find out the causes of changes in landscape morphological characteristics of Tonle Sap Lake under different water levels and the difference degree of flood and blight changes, the change rule of the quantitative evaluation index of landscape water morphology of Tonle Sap Lake was analyzed, as shown in Figure 4, and combined with the water morphology of Tonle Sap Lake under different water levels as shown in Figure 5, As can be seen:

1) The area (S) of Tonle Sap Lake increases linearly with the change of water level. The area corresponding to 1 m water level is 1830 km^2, and the area corresponding to 11 m water level is 14,035 km^2, which is about 8 times that at 1 m, and the increase is 12,205 km^2. The regression equation is $S = 1028.357 + 814.149H + 65.127H^2 - 2.863H^3$ (S is the lake area and H is the water level).

2) The length of the shoreline (P) of Tonle Sap Lake generally increases with the water level, with a minimum of 325 km at 1 m and a maximum of 1005 km at 11 m. Combined with the morphologic changes of water body at different water

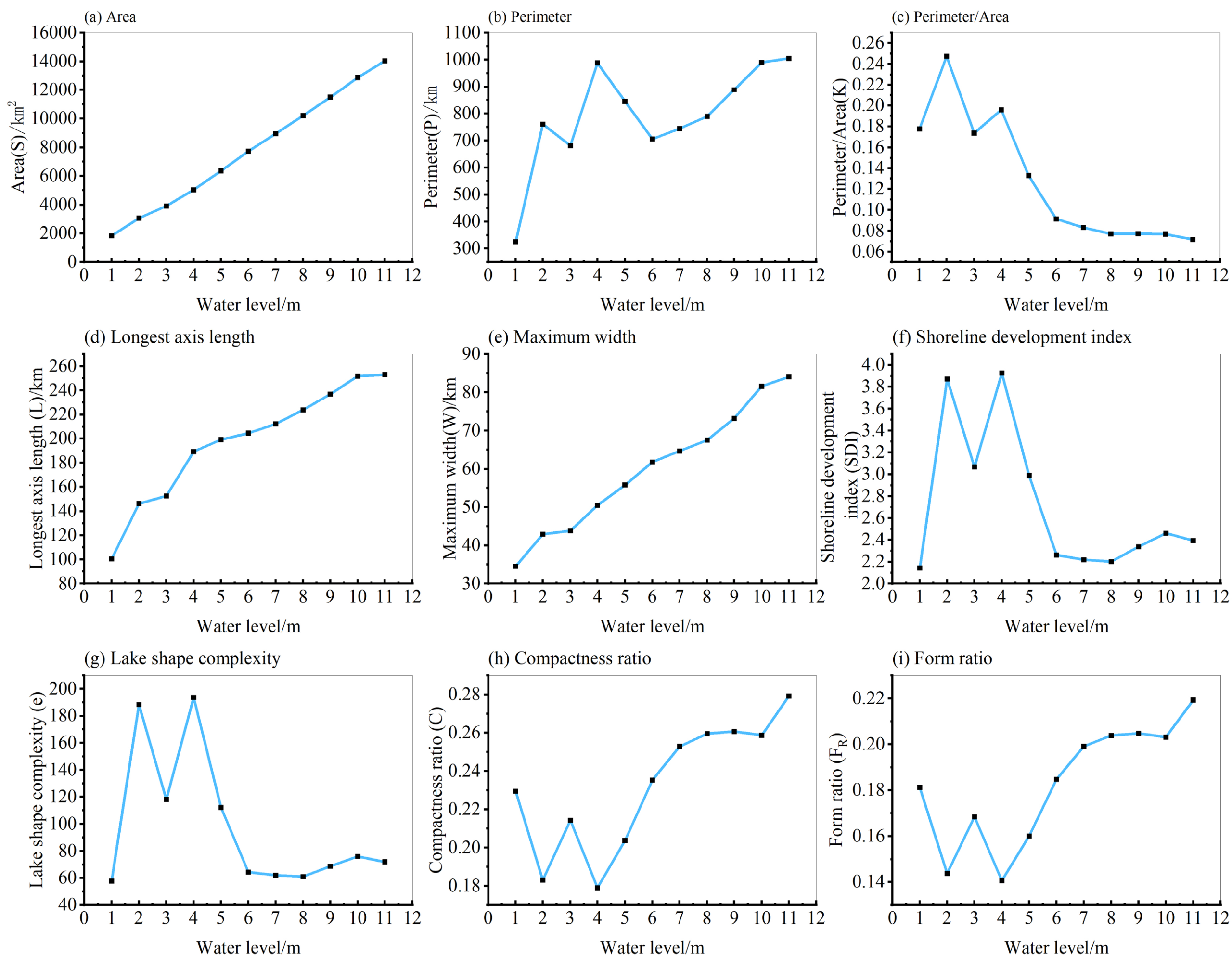

Figure 4. Change of quantitative evaluation index of landscape water morphology in Tonle Sap Lake.

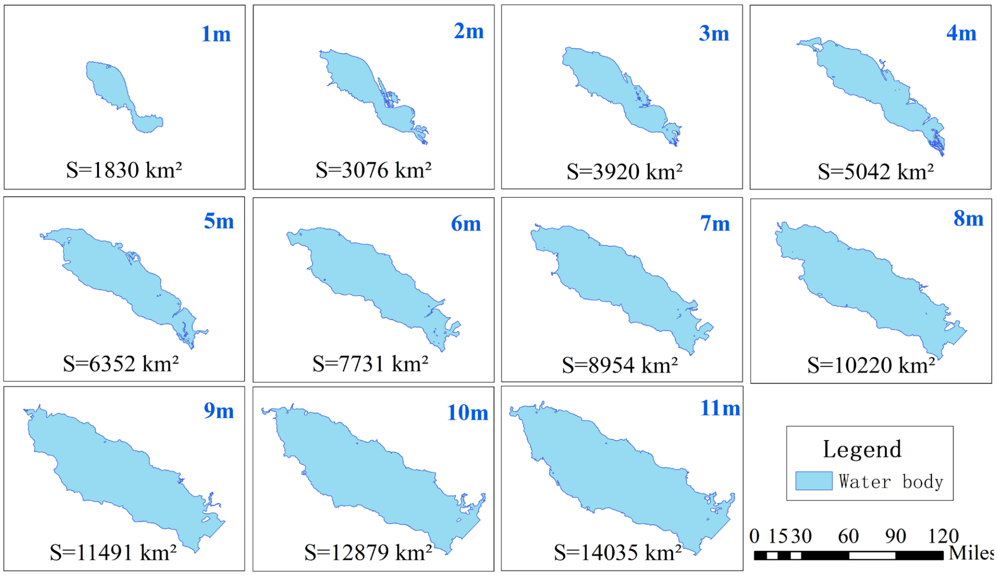

Figure 5. Morphological changes of water body under different water levels in Tonle Sap Lake.

levels of Tonle Sap Lake, it can be seen that when the water level is from 1 m to 2 m, the length of the shoreline increases abruptly. First, the sudden increase in the length of the shoreline is due to the inundation of part of the shoreline and the connection with the small lakes in the neighboring area, which forms a long and narrow shoreline protrusion. Second, the sudden increase in the length of the shoreline is due to the formation of multiple channels along the direction of the Kampong Chhnang estuary. The slight decrease in the length of the shoreline when the water level is 2 m to 3 m is mainly due to the rising water level of the lake, which makes the main lake of Tonle Sap Lake merge with the neighboring small lakes, resulting in some of the narrow shore has been converted to a small number of mid-lake island. The sudden increase of shoreline length from 3 m to 4 m is mainly due to the formation of braided rivers. When the water level is from 4 m to 6 m, the length of the shoreline decreases because the braided river gradually changes from river facies to lake facies. After the water level is 6 m, the lake shoreline length increases approximately steadily and linearly because the central island in Tonle Sap Lake is submerged, and the "low water level forms a line" changes to the "High water level forms a surface". At this time, the lake surface steadily expands outward in an approximate elliptical shape.

3) Lake perimeter/area ratio (K) indicates whether the lake is narrow and long and whether the shape of the shoreline is complex. Tonle Sap Lake generally shows a downward trend with the increase of the water level, and gradually becomes stable after 6 m, indicating that the lake gradually changes from a narrow and complex shape to a simple and regular oval shape after 6 m.

4) The longest axis length (L) and maximum width (W) of Tonle Sap Lake generally increase steadily with the increase of water level. The minimum L appears at 1 m water level (101 km) and the maximum L appears at 11 m water level (253 km), and the variation value is 152 km. The minimum W appears at 1

m (34 km) and the maximum W appears at 11 m (84 km), and the variation value is 50 km. The longest axis length is roughly 2 - 3 times of the maximum width, which indirectly reflects that the water body of Tonle Sap Lake is narrow and long from 1 m to 11 m.

5) The more irregular the shoreline, the more tortuous and changeable the shoreline, the greater the shoreline development Index (SDI) and the lake shape complexity (e). The shoreline development Index and lake shape complexity of Tonle Sap Lake are larger when the water level is 2 - 4 m. Combined with the water body morphological changes at different water levels of Tonle Sap Lake, it can be seen that at 2 m, part of the bottomland is submerged and thus forms a narrow and long landbank protruding; at 3 m, part of the narrow and long landbank is submerged and a few mid-lake island are formed; at 4 m, braided rivers are formed due to the rising water level. The species diversity of the coastal zone of the lake is higher, and the shoreline development Index and the lake shape complexity change little when the water level exceeds 4 m. When the water level is 4 - 15 m, he shoreline development Index decreases and tends to be stable, indicating that the smoother the lake shoreline is, the simpler the geometric form is.

6) Form ratio (F_R) and compactness ratio (C) reflect the openness of the lake surface, the larger the value, the more open the lake surface, on the contrary, it means that the lake is more narrow and long. When the water level of Tonle Sap Lake is 2 - 4 m, the shape rate and compactness are small, indicating that the lake surface is relatively narrow and long, with many central islands and narrow and long island beaches exposed, which are characterized by large shoreline curvature and relatively closed local shape. When the water level is 4 - 15 m, the compactness and shape rate generally increase, indicating that the lake surface gradually opens up.

4.2. Change Rate of Lake Morphology Index with Rising and Falling Water Level

In order to further investigate the amplitude of the change of the morphological characteristics of Tonle Sap Lake with the rise and fall of the water level, the area change rate (km^2/m) is introduced, which refers to the change area (km^2) of the lake with every 1 m change of the water level.

$$\alpha = \frac{S_{i+1} - S_i}{H_{i+1} - H_i} \tag{5}$$

where, S_{i+1} and S_i is the area under the corresponding water level; H_{i+1} and H_i indicates the water level under the corresponding water level, where $i = 1$ to 10.

The calculated results are shown in **Table 4**. The area change rate from 2 m to 3 m is the lowest (844 km^2/m), while the area change rate from 9 m to 10 m is the highest (1388 km^2/m), and the average area change rate from 1 - 11 m is 1221 km^2/m.

Table 4. Variation rate of water level area from 1 to 11 m in Tonle Sap Lake.

Water level/m	1	2	3	4	5	6	7	8	9	10	11
Area (S)/km^2	1830	3076	3920	5042	6352	7731	8954	10,220	11,491	12,879	14,035
Area growth rate (α)/(km^2/m)		1246	844	1122	1311	1379	1223	1266	1271	1388	1156

5. Conclusions

Based on DEM data, nine morphological indexes including lake area (S), lake perimeter (P), perimeter/area ratio (K), longest axis length (L) and maximum width (W), shoreline development Index (SDI), lake shape complexity (e), compactness ratio (C), form ratio (F_R) were used to summarize the variation rules of these nine indexes with water level in Tonle Sap Lake. This paper expounds the landscape morphological characteristics and the difference degree of flood blight change under different water levels in Tonle Sap Lake, and draws the following conclusions:

The area of Tonle Sap Lake increases rapidly and linearly with the water level, and the area changes by 1221 km^2 when the average water level changes by 1m. The water body expanded significantly along the northwest and southeast directions, with the largest expansion in Battambang and Kampong Thom provinces. In Battambang Province, the water area of Tonle Sap Lake increased from 182 km^2 at 1m to 3523 km^2 at 11 m, and the water level of the lake area changed by 334 km^2 per meter. In Kampong Thom Province, the water area of Tonle Sap Lake increased from 212 km^2 at 1m to 2740 km^2 at 11 m, and the water level of the lake area changed by 253 km^2 per meter.

There are three reasons for the drastic changes in the six geometric shape indicators of lake shoreline perimeter, perimeter/area ratio, shoreline development Index, lake shape complexity, compactness ratio, and form ratio when the water level is below 6 m. First, during the process of lake surface uplifting, small lakes in neighboring areas and Tonle Sap Lake will first form a long and narrow shoreline protrusion, leading to the growth and complexity of the shoreline. Then the rising shore is submerged until the two lakes merge. The second is the emergence and inundation of the mid-lake island of Tonle Sap Lake under different water levels. Third, at low water levels, braided rivers will appear in the Tonle Sap Lake area, resulting in complicated shoreline and narrow lake surface. In this case, the calculated values of lake shoreline perimeter, perimeter/area ratio, shoreline development Index and lake shape complexity are larger, but the form ratio and compactness ratio are smaller.

When the water level of Tonle Sap Lake is above 6 m, its landscape morphological characteristics show regularity. The length of the lake shoreline increased steadily, the ratio of the perimeter/area, the shoreline development Index and the lake shape complexity stabilized at about 0.077, 2.3 and 66, respectively, and the compactness ratio and form ratio showed a steady growth trend in general. It shows that when the water level of Tonle Sap Lake is above 6 m, the shoreline of the lake is simple and smooth, and the lake surface is open and steadily expands outward in a regular oval shape.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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