land

MDPI

Article

Distribution Patterns of Sediment Organic Carbon Stocks in Shallow Lakes and the Significance for Sustainable Lake Management: Chaohu Lake in Eastern China as a Case Study

Wenguang Luo [1,*], Yan Pan [1], Yangzhen Fan [2], Jing Lu [1] and Senlin Zhu [3,*]

[1] State Key Laboratory of Water Resources Engineering and Management, Wuhan University, Wuhan 430072, China; pan7457@whu.edu.cn (Y.P.); lujing@whu.edu.cn (J.L.)
[2] Hubei Water Resources and Hydropower Science and Technology Promotion Center, Hubei Water Resources Research Institute, Wuhan 430070, China; fyz@whu.edu.cn
[3] College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China
* Correspondence: wgluo@whu.edu.cn (W.L.); slzhu@yzu.edu.cn (S.Z.)

Abstract: Shallow lake sediments have huge potential for carbon storage, but they are vulnerable to various environmental changes and are highly susceptible to becoming a source of carbon emissions. Understanding the amount of sediment carbon storage can provide information about the potential of shallow lakes in mitigating climate change. In this study, sediment sampling was conducted at 12 study sites in Chaohu Lake, China, and sediment water content, grain size, bulk density, and sediments organic carbon (SOC) content were examined in five layers along the vertical direction, respectively, and the distribution and storage of SOC were estimated. The results showed that the surface sediments in the west lake area of Chaohu Lake would release 66,300 t of SOC to the overlying water body in the future. The sediments in the middle lake area and the east lake area will absorb another 15,900 t and 17,300 t of TOC from the water body in the future, respectively. Overall, the lake-wide sediments will release 33,100 t of SOC into the water body in the future. In addition, the results of the study also indicate that human activities are another major influence on the change in organic carbon stocks in lake sediments, and therefore, proactive measures for the restoration and protection of lake sediments are essential because increasing the SOC stocks in the sediments and maintaining the lakes in a sustainable manner can contribute to the crucial role they play in mitigating climate change.

Keywords: shallow lakes; bottom sediments; carbon source; carbon sink; carbon emissions

check for updates

Citation: Luo, W.; Pan, Y.; Fan, Y.; Lu, J.; Zhu, S. Distribution Patterns of Sediment Organic Carbon Stocks in Shallow Lakes and the Significance for Sustainable Lake Management: Chaohu Lake in Eastern China as a Case Study. *Land* **2024**, *13*, 507. https://doi.org/10.3390/land13040507

Academic Editor: Frédéric Frappart

Received: 5 March 2024
Revised: 10 April 2024
Accepted: 10 April 2024
Published: 12 April 2024

1. Introduction

With the increasing prominence of various climatic and environmental issues such as the greenhouse effect, as well as the objectives needed for the assessment of carbon sources and sinks in international climate negotiations, the issue of the carbon cycle is receiving increasing amounts of public attention [1,2]. Although lakes account for a small fraction of the Earth's surface, a growing number of studies have shown that lakes are carbon sinks that have a disproportionate impact on the global carbon cycle [3–5]. This is mainly due to the fact that sediment organic carbon (SOC) in lakes plays an important role in the carbon cycle of terrestrial ecosystems [6,7]. Therefore, sediments have great potential for carbon storage, which allows for the removal of SOC from the active recycling pool. However, SOC is vulnerable to various environmental changes and can easily become a source of carbon emissions.

Factors affecting SOC storage in lakes mainly include lake hydrological conditions, climate change, biological activities, and human activities [8,9]. Among them, changes in hydrological and climatic conditions can easily affect the formation, distribution, and SOC storage, and this phenomenon is particularly prominent in shallow lakes [10,11]. It can be seen that sediments are long-term reservoirs and important transit stations for SOC in shallow lakes. On the one hand, sediments can transport and bury large amounts of organic carbon (OC) produced in situ or obtained from the terrestrial environment [12,13]. On the other hand, sediments, when externally perturbed, can transfer OC to the overlying water column [14]. Therefore, there is a great need to seek a technical paradigm for probing the carbon storage in sediments of large shallow lakes, and to provide techniques for analyzing the carbon storage potential of lake sediments.

Regarding the study of SOC in shallow lakes, there are various research methods, and at present, scholars mainly adopt the methods of sediment sampling and laboratory analysis, but there are limitations in terms of precision and reliability [15,16]. Grabs or other samplers may disturb the sediment and alter the sediment structure and sequence, meaning that they cannot adequately represent the entire sediment profile or deep sediment characteristics, as well as vertical distribution. Currently, the most reliable method is the use of column core sampling analysis [17]. Studies have shown that column core sampling can provide a continuous record of sediment depositional history, maintain the natural stratigraphic structure of sediments, help to maintain the original state of organic matter and microbial communities in the sediments, and is of great value in understanding the historical changes in sediments and environmental processes, with a high degree of accuracy and reliability [18,19].

Chaohu Lake is one of the five major freshwater lakes in China. In recent years, due to natural and anthropogenic factors, eutrophication of the lake is serious, and the accumulation of SOC has intensified, which has seriously constrained the sustainable development of the socio-economy in the basin [20,21]. At present, SOC research mainly focuses on the water body or the lakeside green belt in Chaohu Lake; however, the prominent characteristic of the eco-environment is that there are open water, shallow groundwater, and strong surface runoff activities near it [22]. Therefore, lake sediment is closely related to the atmospheric environment, surface water environment, and groundwater environment. Organic carbon in sediments exhaust CO_2 to the atmosphere through mineralization, and dissolved organic carbon (DOC) enters the water body from the sediment, causing pollution [23]. In addition, organic carbon in sediment has a significant effect on the distribution of pollutants such as polychlorinated biphenyls (PCBs) [24]. It can be seen that it is necessary to study the organic carbon distribution characteristics in lake sediments. In this paper, the relationship between the amounts of SOC stored, its distribution characteristics, and its impacting factors was investigated for Chaohu Lake. This study can help to understand the amount of carbon stored in shallow lake sediments, provide information about the potential of lakes in mitigating climate change, and provide a scientific basis for understanding and grasping the status of endogenous pollution in shallow lakes.

2. Study Area and Methodology

2.1. Study Area

Chaohu Lake is located in Hefei City (31.60° N, 117.87° E), Anhui Province, and Eastern China. It has an average water level of 8.37 m, a lake basin length of 61.7 km, a width of 12.47 km, a water area of 769.55 km^2, and an average depth of 2.89 m. The average flow velocity in the lake ranges from 0.02 to 0.07 m/s, and the maximum flow velocity is around 0.62 m/s [25]. Due to the unique shape of Chaohu Lake, it is artificially divided into three lake regions: western, central, and eastern. Generally, the flow velocity in the eastern lake region is larger than that in the western lake region, and the maximum flow velocity usually occurs in the central lake region. As a result, this has led to uneven sediment distribution in the three regions.

In order to estimate carbon storage in the lake sediments, 12 sediment core sampling sites are selected, which are distributed in the western (represented by "W"), central (represented by "C"), and eastern (represented by "E") lake regions (Figure 1 and Table 1). Although the lake-wide SOC content cannot be accurately simulated, the results are in fact representative. Moreover, they can explain the trend of sediment distribution and estimate

SOC content to some extent. In this regard, the experimental results of SOC could represent the overall situation of the lake.

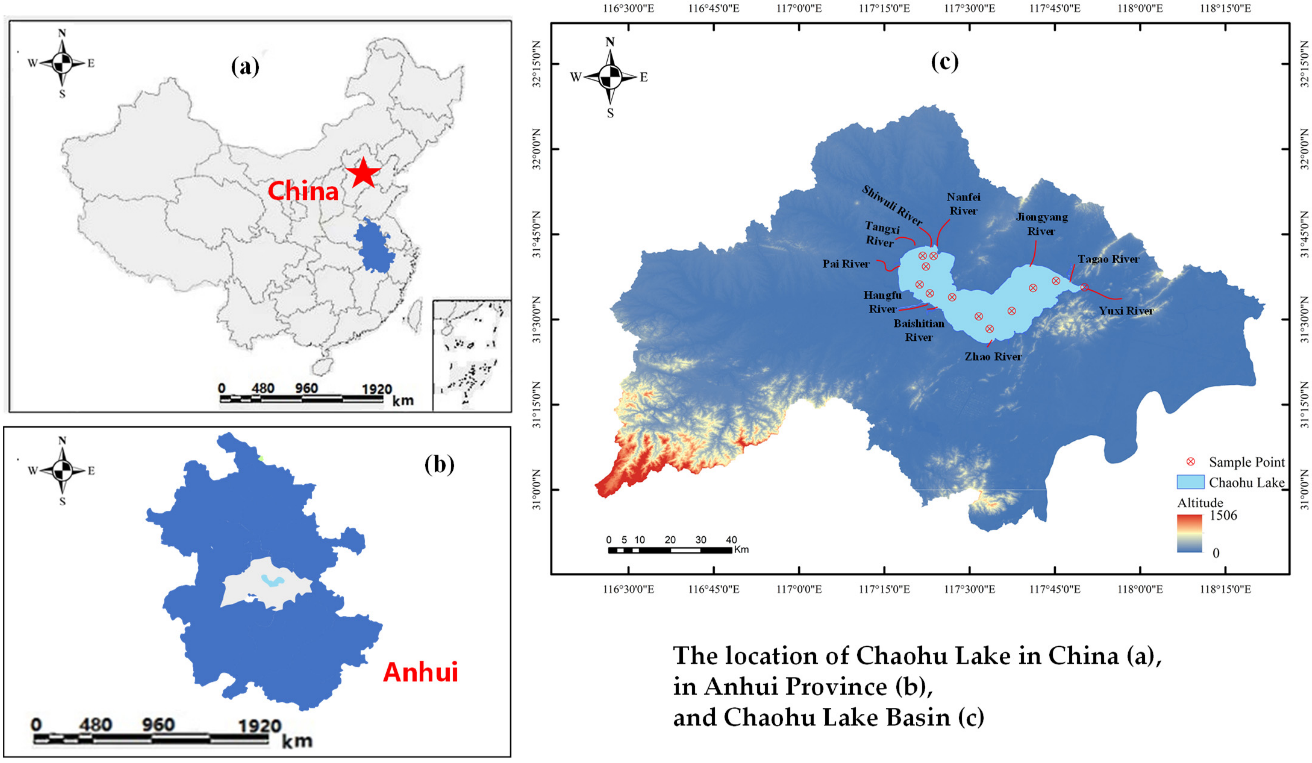

Figure 1. Sampling locations of the original sediment column cores of Chaohu Lake.

Table 1. Basic information of the original sediment column cores in Chaohu Lake.

Serial Number	Area	Sample Number	Latitude (°N)	Longitude (°E)	Sediment Thickness (cm)
1	Western	W1	31.7292	117.4065	50
2		W2	31.7289	117.3795	99
3		W3	31.7083	117.3868	88
4		W4	31.6729	117.3700	135
5	Central	C1	31.6548	117.3955	100
6		C2	31.6473	117.4524	88
7		C3	31.6078	117.5196	50
8		C4	31.5842	117.5466	42
9	Eastern	E1	31.6188	117.6038	100
10		E2	31.6644	117.6615	123
11		E3	31.6798	117.7191	100
12		E4	31.6661	117.7881	70

As can be seen from Figure 1, the water in Chaohu Lake flows from west to east and enters the Yangtze River from Yuxi River. Several surrounding tributaries flow into Chaohu Lake. The larger tributaries include Hangfu River, Pai River, Nanfei River, Tagao River, Baishitian River, and Zhao River. A large number of studies have shown that watershed land use is the main factor affecting lake sediments [26]. The cultivated land and water area accounted for more than 60% of the longitudinal surface of the basin, and the forage area was the smallest. However, with the development of economy and society, the decrease rate of cultivated land area increases rapidly, which is much higher than the change value of other land types, accounting for about 40% of the absolute change value of all land types, and it is the main part of land use [27].

2.2. Sample Collection and Analysis

The Core-60 sampler and supporting equipment from UWITEC, Austria, used in this study are sufficient to collect the sediment samples needed for the study [28,29]. The equipment is highly efficient and adaptable for sampling and can collect columnar samples of substrate at large depths as required.

Studies have shown that water content, bulk weight, and porosity are important properties of soils and substrates. Whereas SOC is different from terrestrial soils, these properties are uniquely interrelated [30,31]. This is mainly due to the fact that sediments actually contain only two phases, solid particles and water that fills all the pores. In some cases, some air bubbles become trapped, but these are secondary to the overall properties of the sediments. The presence of only two phases leads to an intrinsic dependence between water content, bulk dry density, and porosity. In order to analyze the distribution pattern of SOC, it is therefore also necessary to examine the content of physical indicators such as water content, wet density, and particle size in the sediments.

2.3. Sample Processing Methods

In this study, column–core sediment samples were collected at 12 sites in Chaohu Lake in the spring of 2019. In the process of samplings, in order to avoid the difference in the channels, the samples were sampled at the surrounding sampling points in this study to ensure that the sediment samples represented the average sediment level in the region. Based on the specific height of the column sediment samples, we split the sediment samples into five layers to test them separately. Two layers of column samples from top to bottom with heights of 0–5 cm and 5–10 cm were selected as fixed detection objects, and in addition, three layers of detected sediment samples were selected between the 5 and 10 cm layer and the bottom in accordance with the principle of the equidistant equal division. In principle, the height of the first three layers of detected sediment samples should be more than half of the entire sample height.

The segmented core sample needs to be air-dried before inspection. Then, analysis and detection are carried out in the laboratory through the detection instrument, and the detection methods are carried out in accordance with the relevant detection specifications. In this study, sediment detection indicators include the following: particle size, wet density, water content, and SOC, as well as other indicators. The stratified detection operation of sediment indexes is shown in Figure 2.

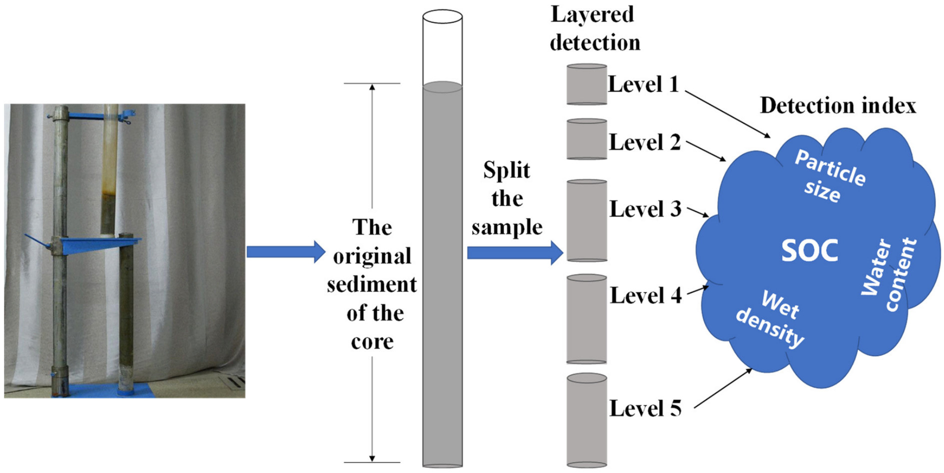

Figure 2. A schematic diagram showing sediment stratification detection.

2.4. Mathematical Fitting of SOC Content

Lake sediments and overlying water bodies consist of only two phases, liquid and solid. In fact, since all voids are filled with water, the porosity and density of sediments can be assessed directly from the water content and particle size of the sediment, which is an easily determined property. US scholars performed linear regression through a large amount of measured data (including river and fishpond sediments in Israel, fishpond sediments in Alabama, USA, and Abbassa, Egypt, lake sediments in New Zealand, alpine lake sediments in Colorado, USA, and seafloor sediments on the slopes of the Northwest African continent) and found that density correlated with organic matter and that sediment bulk weight was negatively correlated with SOC concentration [32].

$$\text{Wet density } (\text{g/cm}^3) = 1.776 - k \times \text{Ln (SOC)} \quad (1)$$

where SOC is the organic carbon concentration in the sediments (g/kg), and k is a coefficient related to water content and particle size.

The verification results of the above formula with the measured data are good. The similar response of aquatic sediments in ponds, rivers, and lakes, in different climatic and edaphic regions, suggests that the conclusions drawn from this formula have a practical value in a wide range of aquatic systems. Therefore, in this study, we applied this formula to the estimation of SOC in Chaohu Lake and used the measured data to further optimize the formula.

3. Results

3.1. Sediment Depth Distribution

First, the depths of the sediment column core samples were measured at 12 sampling sites, which allowed the depths of the sediments to be obtained. The depth of these sediments roughly ranged from 42 to 135 cm, with an average depth of about 87 cm (see Figure 3). The surface odor of the samples was observed, in which all of them showed a gray color, except some points (E1 and E4) where the surface, 10 cm of the sediments, appeared to be a yellowish-brown color. All the sediments had odor, only in a degree of difference; there were fewer mildly odorous sediment collection points.

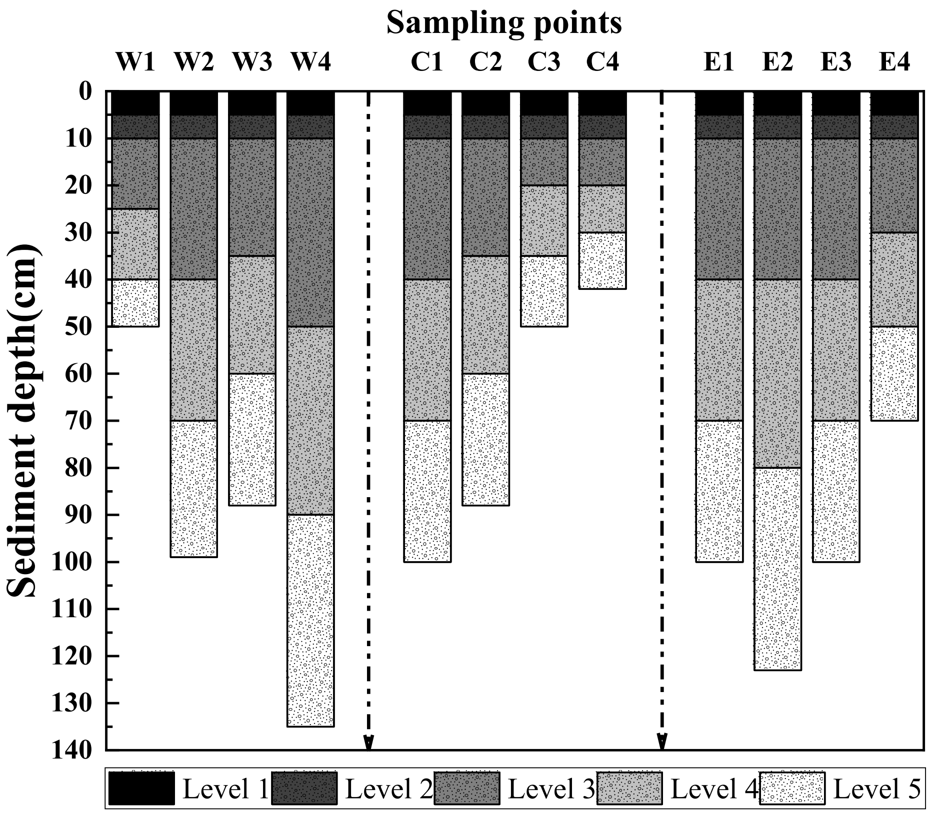

Figure 3. Sediment depth and stratification at sampling points.

As seen from Figure 2, the deepest point of sediment is W4, the shallowest place of sediment is C4, and most of the sediment is concentrated in the area of E1~E4. This is mainly due to the fact that the water flow direction of Chaohu Lake is from west to east, and there are rivers entering the lake in the area of W1 and C4, so the sediments in the lake will be mainly concentrated in the area far away from the rivers.

3.2. Wet Density, Water Content, and Particle Size Distribution

3.2.1. Vertical Distribution Pattern of Sediment Wet Density

The wet density of the sampled sediments along the vertical direction is an important indicator to determine the physical properties of the sediments and is also a direct influencing factor that can respond to SOC content in the sediments. This phenomenon is obvious in the vertical direction of the sediments, so in this study, the vertical density of the sediment was examined, and the results of the vertical density distribution were obtained (see Figure 4).

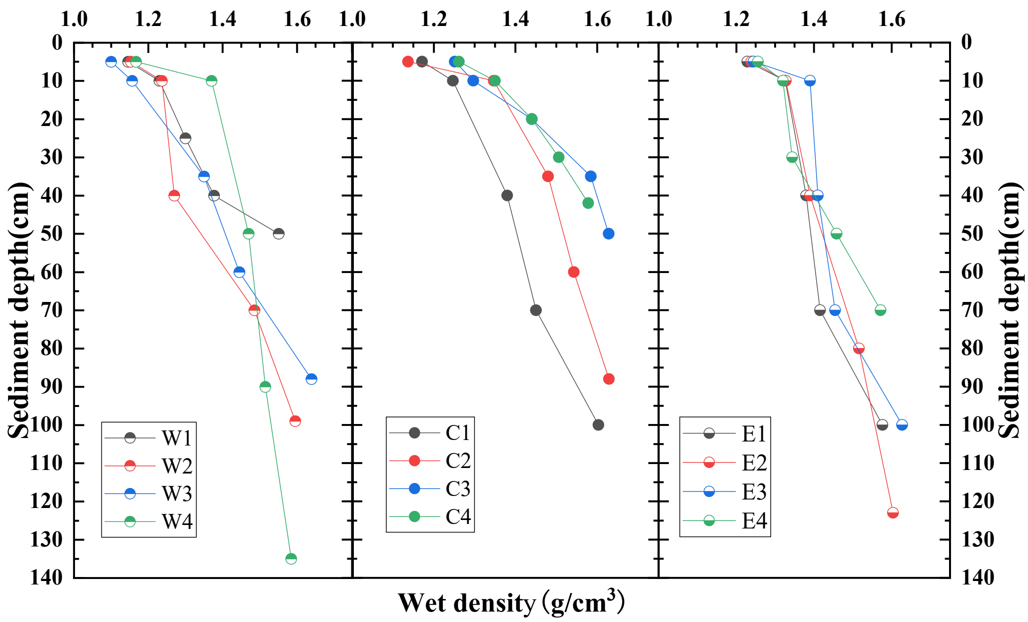

Figure 4. Vertical distribution of sediments wet density.

As can be seen from Figure 4, along the depth direction, the deeper the sediments, the greater the wet density. The main reason for this may be because as the sediment is deposited for a longer time period, the lower layer of sediment will contain more solids (sediment), which will squeeze the interstitial space between the sediment particles. This also indicates that the amount of organic matter that can be held in interstitial spaces will decrease.

3.2.2. Distribution Pattern of Water Content and Particle Size

The capacity of interstitial space between sediments to accommodate SOC determines its content. The two indicators used to characterize the capacity of the interstitial space of sediments chosen for use in this study were water content and particle size [33,34]. This is because a smaller sediment water content indicates that the sediment contains more solid particles, while a smaller sediment particle size indicates a small particle-to-particle void space. Therefore, the two in a single void space size and number determine the sediment interstitial space accommodation capacity. The results of the water content and particle size distribution of sediments along the vertical direction in this study are shown in Figure 5.

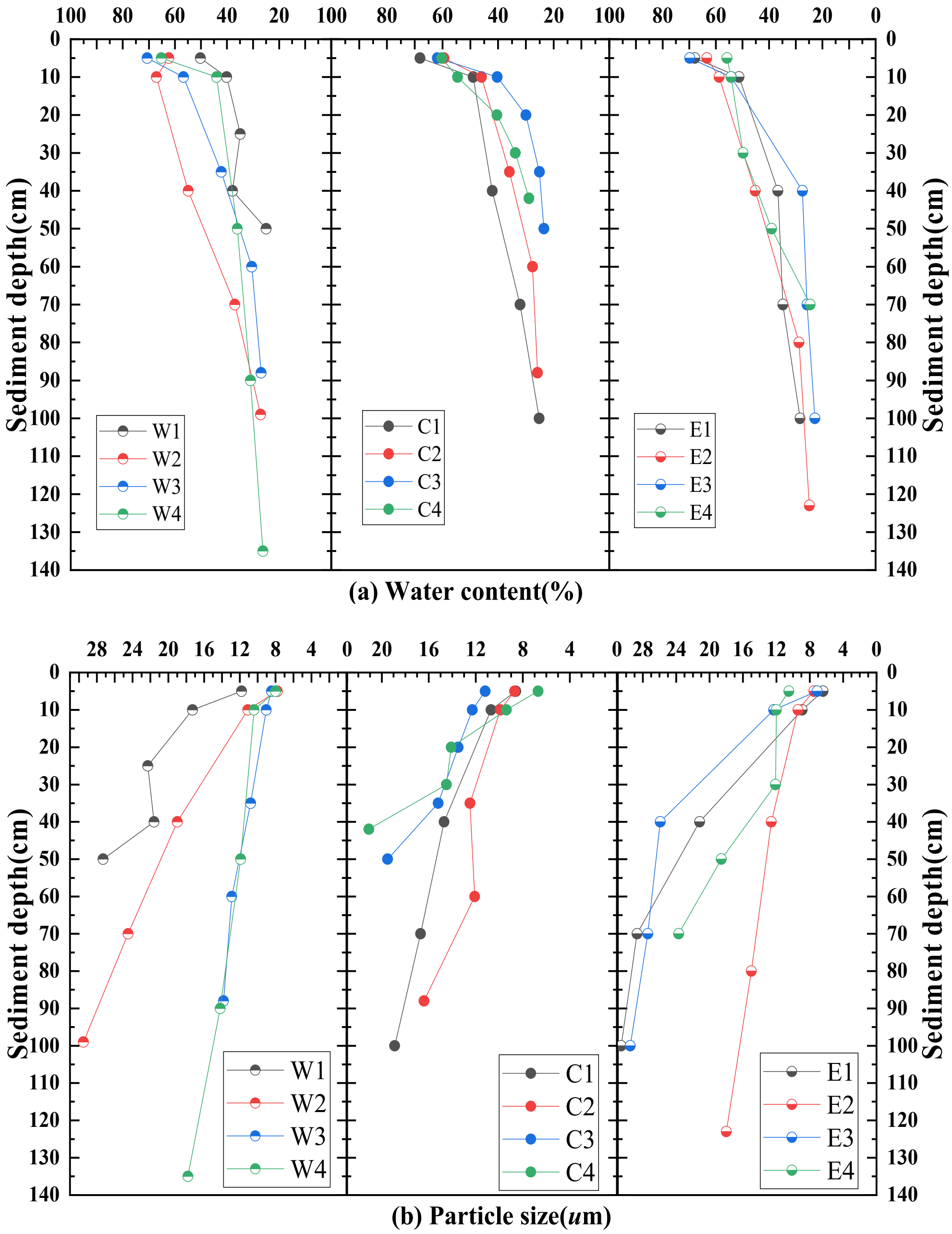

Figure 5. Distribution of water content and particle size along the vertical direction.

Along the depth direction, the water content in the sediment decreases with the increase in depth (Figure 5a), and this law is basically consistent in all 12 monitoring sites in Chaohu Lake. The particle size of the sediment is above 10 cm in the surface layer, because the particles in the floating mud layer of the sediment are relatively loose, and it is very easy to be re-suspended by hydrodynamic disturbance. The larger the sediment particles, the easier it is to settle down. In 10 cm below the surface layer, because the part of the sediment is fixed, sediments will not be re-suspended. Therefore, the particle size of the sediments also shows an increase with increasing depth (Figure 5b).

3.3. Distribution of Sediment Organic Carbon Content

SOC was determined in this study mainly by titration, once the sediments were pretreated, by oxidizing or decomposing the carbon-containing substances into CO_2. The distribution of SOC content in Chaohu Lake sediments was determined by efficient and fast reading (see Figure 6).

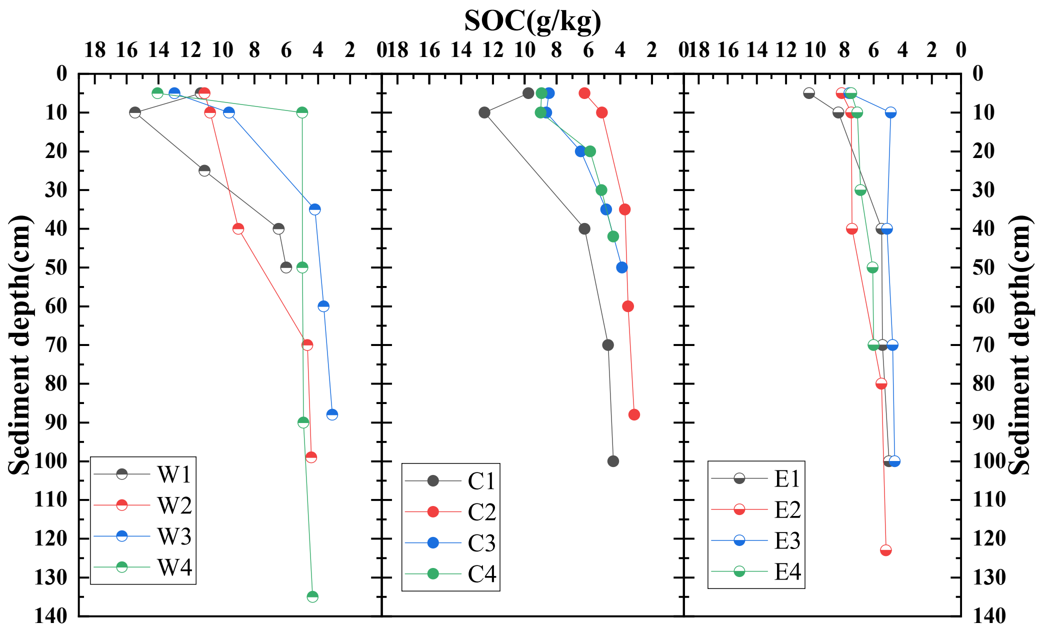

Figure 6. Distribution of organic carbon along the vertical direction.

As can be seen from Figure 6, SOC at all levels basically has a decreasing trend along the depth direction, with the highest content occurring at the surface layer (except for an anomaly on W_1 and C_1, respectively). This is also mainly due to the fact that the inlet rivers bring a large number of sediments, which are deposited and silted in the three lake areas of Chaohu Lake, resulting in higher SOC content in the surface layer. It is only in the three lake areas of Chaohu Lake that the vertical distribution of the SOC content may be different due to different sediment deposition conditions.

4. Discussion

4.1. Differences from Existing Studies

The relationship between sediment water content, particle size, wet density, and SOC described here can be used as a simple method to estimate organic carbon content in sediments by simply measuring sediment wet density, water content, and particle size.

The formula for the coefficient *k* can be derived from Equation (1):

$$k = (1.776 - \text{Wet density } (\text{g/cm}^3))/\text{Ln (SOC)} \quad (2)$$

In addition, the coefficient *k* is considered to be a parameter that is related to sediment water content and particle size. According to the measured data, SOC has a dual effect with particle size and water content. Therefore, in this study, an auxiliary coefficient *k*′ is used:

$$k' = w^*(D/D_{\text{low}}) \quad (3)$$

where w is the water content in the sediments (%), D is the median particle size of the sediment (μm), and D_{low} is the particle size of the bottom-most particle in the sediment at the sampling point (also the particle size of the Lever 5 layer).

Based on the measured wet density and SOC along the vertical direction of the 12 sampled sediments in Chaohu Lake, as well as water content and particle size, *k* and *k*′ can be obtained, respectively, and their correlations are clearly linear (see Figure 7):

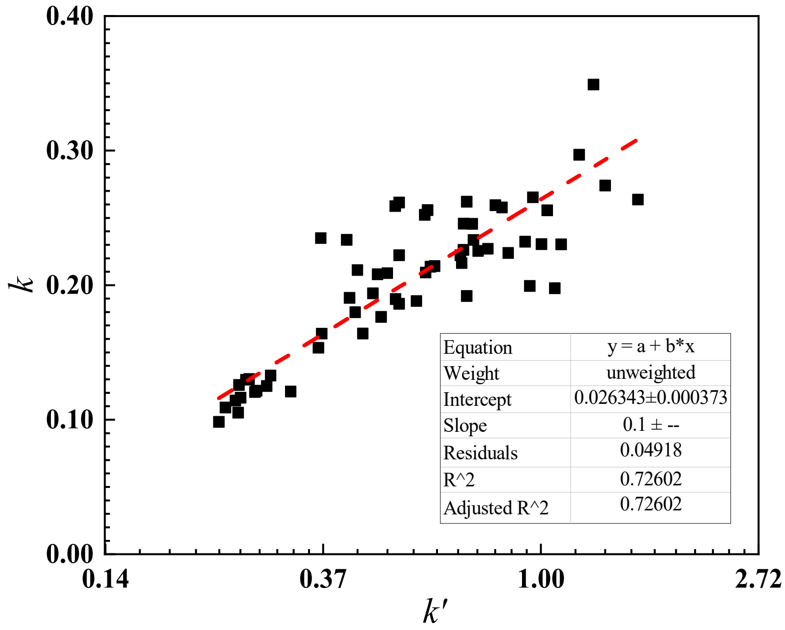

Figure 7. Linear relationship between k' and k.

Since the relevant data in Figure 7 show a log-linear relationship (the horizontal coordinates in the figure are the logarithmic coordinates taken), a mathematical expression for the coefficient k can be obtained:

$$k = 0.263 + 0.1 \times \text{Ln}\,(w^*(D/D_{\text{low}})) \tag{4}$$

From Equation (4), we can obtain the theoretical plot between k and $(w^*(D/D_{\text{low}})$ (Figure 8).

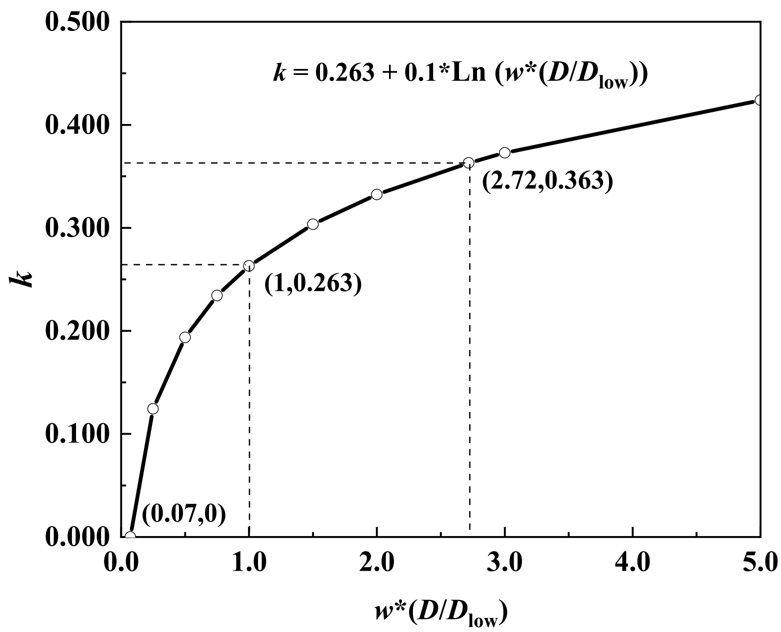

Figure 8. Theoretical calculation curve of k.

As shown in Figure 8, when $(w^*(D/D_{\text{low}})) = 0.07$, the sediment will essentially contain no organic carbon. This state can be defined as the lowest layer of the sediment having a water content of no more than 7%, and it is conceivable that it is indeed more difficult to hold organic carbon in this state. When $(w^*(D/D_{\text{low}})) = 1$, it is the threshold value of the sediment content factor at a constant factor of 0.263. We can also consider that when the water content of the lowest layer of the sediment is 100%, it is the lowest state of the existence of the SOC saturated content. When (w*(D/D_{low})) = 2.72, the k value is around 0.363, which is the same as the coefficient in the research results of Avnimelech et al. [30]. However, such extreme conditions are generally reached only when the sediment is saturated with organic carbon (e.g., at 100% water content, surface particles are about 2.72 times more abundant than bottom particles). Obviously, it is difficult to reach this saturation state in the natural state of shallow lakes, and the density of the sediment is often larger than the calculation results, so it would be more reasonable to use this coefficient after correction in the fitting formula.

In this study, the relationship between measured sediment wet density and k*Ln(SOC) was further re-fitted according to Equation (1), which showed a clear linear relationship (see Figure 9).

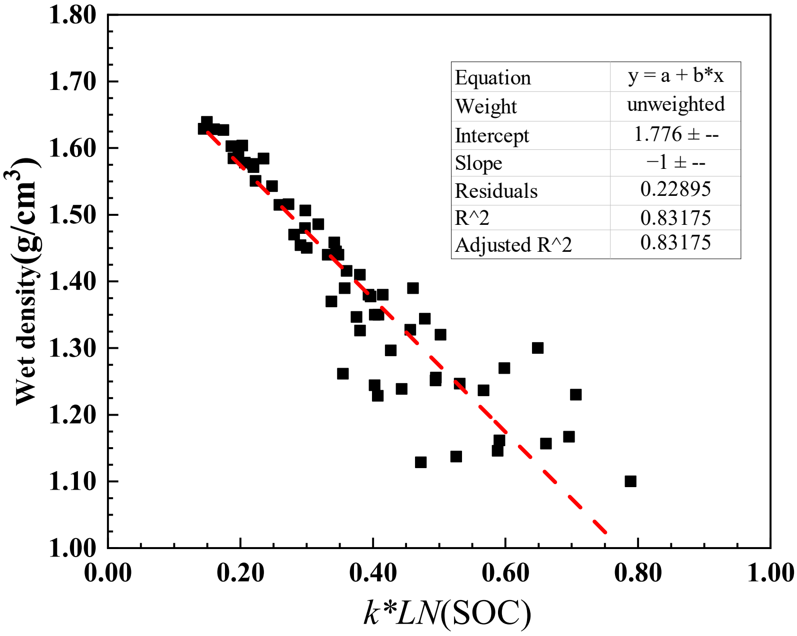

Figure 9. Linear relationship between wet density and k*Ln (SOC).

From Figure 9, it can be seen that the modified Equation (1) is in accordance with the law after the test of the measured data. Moreover, the R^2 of the linear fitting of the modified Formula (1) reaches 0.83, which is better than $R^2 = 0.70$ in the original equation in Avnimelech et al.'s study [30]. This also fully demonstrates that the revised fitting formula is more reasonable.

Compared with previous research methods, our method improves the interaction mechanism between sediment organic carbon distribution and sediment physical properties. The quantitative method of sediment carbon sink is further proposed with reference to the sediment organic matter balance theory. Although this method still needs further scientific definition and different academic viewpoints in the analysis of stable organic carbon content and carbon equivalent calculation, its progressive significance lies in the fact that it puts forward an operable quantitative accounting method. In a future investigation of lake sediment organic carbon emissions, there will be some progressive value or enlightenment to provide a quantitative accounting tool.

4.2. Prediction of Release Potential of Sediments Organic Carbon

A large number of studies have shown that the surface layer of shallow lake sediments below 10~20 cm is a fixed layer, in which the state is relatively stable. The sediments above this layer are susceptible to external disturbances, and the materials in the sediments are easily released into the overlying water [35]. Therefore, in this study, the first and second layers of sediments are considered to be the unstable state layer of SOC, and only when the sediment settling state of this part of the sediments tends to be similar to that of the following three layers (i.e., the average wet density, water content, and particle size are equal) is it considered that SOC tends to be saturated with the storage state of the whole shallow lake.

In addition, the calculation methods of lake sediment organic carbon content and SOC density are shown in Equations (5) and (6).

$$TC = C_{\mathrm{d}} \times S \quad (5)$$

$$C_{\mathrm{d}} = \sum(\text{Wet density}_i \times \text{SOC}_i \times H_{\mathrm{i}}) \quad (6)$$

where TC is SOC stock under a certain thickness (10^4 t); C_{d} is the carbon density of the sediment under a certain thickness (kg/m^2); wet density$_i$ is the wet density of the i-layer (g/cm^3); SOC$_i$ is the organic carbon content of the i-layer (g/kg); H_i is the sampling thickness of the i-layer (cm); and S is the area (km^2).

In this study, the thickness of the SOC unstable state layer H_{i} = 10 cm [36], which is the top two layers (Lever 1 and Level 2) of the sediments in the 12 sampling points, which each equal 5 cm, while the wet density and SOC of the SOC unstable state layer are the average wet density of the two layers (Lever 1 and Level 2) and the average SOC of the two layers, respectively. Based on these three indicators, the carbon density C_{d} of the organic carbon unstable layer in the current state at each sampling point can be calculated according to Equation (6).

When the unstable layer of the SOC of the 12 sampling points finally tends to be stable, the wet density, water content, and particle size of the sediments should be close to the average wet density, average water content, and average particle size of the lower three layers (Lever 3, Lever 4, and Level 5) of the sediments of the similar sampling points, and then according to Equation (1), the SOC content of the unstable layer, when it finally tends to be stable, is obtained. SOC, when the unstable layer of organic carbon eventually tends to be stable, can be calculated according to Equation (1), and finally the carbon density, C_{d} when the unstable layer of SOC tends to be stable, can be calculated according to Equation (6) at each sampling point.

In this study, the carbon densities C_{d} of W1~W4, C_{d} of C1~C4, and C_{d} of E1~E4 were arithmetically averaged to obtain the carbon densities C_{d} of the three regions (W, C, and E), and SOC in the unstable state of the sediment could be calculated based on the area of the three layers (see Table 2).

Table 2. Prediction of surface organic carbon storage in sediments.

District	Area (km^2)	Present		Saturation		Release Potential (10^4 t)
		C_{d} (kg/m^2)	TC (10^4 t)	C_{d} (kg/m^2)	TC (10^4 t)	
W	190.79	1.34	25.61	0.99	18.98	−6.63
C	293.80	1.08	31.66	1.13	33.26	1.59
E	284.96	0.99	28.31	1.05	30.04	1.73
All	769.55	1.14	85.58	1.06	82.28	−3.31

As can be seen from Table 2, the surface sediments in the west lake region of Chaohu Lake will release 66.3 thousand tons of OC to the overlying water body when they converge to lower sediments in the future under the condition of little change in the status quo. This also indicates that the SOC unstable state layer in the west lake belongs to the supersaturated storage state, and the sediment eutrophication is serious, which is consistent with the current pollution status exhibited by Chaohu Lake at this stage [37]. In the middle and east lakes of Chaohu Lake, the SOC unstable state layer belongs to the under-saturated storage state and will absorb 15.9 thousand tons and 17.3 thousand tons of OC from the water body in the future when it converges to the middle and lower layers of the sediment, respectively.

From the perspective of the whole lake, 33.1 thousand tons of SOC will be released to the water body in the future. This also indicates the existence of eutrophication pollution in Chaohu Lake sediments, which is also corroborated to the current phenomenon of water in Chaohu Lake [38].

4.3. Implication for Sustainable Management of Lakes

Are shallow lake sediments a carbon source or sink? This is obviously a complex question that cannot be answered simply. First, from a temporal point of view, based on the calculations in Table 2, it can be seen that the sediments of Chaohu Lake are a source of carbon in the future without transitional interference from human activities. However, this is a dynamic process on an exceptionally long-time scale, and SOC stock in the sediments fluctuates during this process. This is also why we are concerned about the inter-annual time scale of SOC, and SOC will sometimes be shown in the carbon source and sink between the repeated sawing, which is mainly related to the release rate of SOC by external interference. Studies have shown that the release rate of SOC is mainly related to environmental factors such as water temperature, pH, hydrodynamic conditions, dissolved SOC concentration, and aquatic ecosystems in the sediments, in addition to sediment particle properties [39].

From a spatial perspective, even in the same lake, different areas will behave differently in terms of whether SOC is a carbon source or sink (this is obvious in the three lake areas of Chaohu Lake). This is mainly because with social and economic development, frequent human activities lead to changes in the nature of land use in Chaohu Lake Basin (the most obvious one is the reduction in cultivated land and the increase in urban land), resulting in an increase in impervious underlying surface, which inputs a large amount of nutrients originally left in cultivated land into the lake, thus affecting the nutrient status of the lake. In eutrophic regions of lakes with increased humus content, there is more rapid and steady decomposition as humus absorbs light and heat [40]. In addition, as eutrophic lakes are stabilized in order to more closely resemble the mineralized sediments at the bottom, it is possible to release OC to the water column to achieve this purpose [41].

Lakes are highly relevant players in the global carbon cycle, as they can store large amounts of SOC, thus removing OC from active circulation pools. However, SOC may also be releasable to pore water and diffuse into the overlying water bodies in areas of high eutrophication [42]. Therefore, the carbon balance of lake ecosystems can be largely influenced by human activities, such as industrial wastewater, agricultural activities, or aquaculture activities. In order to improve the sustainability of lake water environments and to cope with the mitigation of global climate change, environmental protection measures can be targeted to the aforementioned pollution pathways to reduce carbon emissions, increase the carbon storage capacity in sediments, and improve lake water ecosystems [43]. For example, heavily contaminated sediments can be vitrified and then woven together to cover the original sediment surface [44]. In this way, the pore space of the larger-sized ceramic grains can enhance the carbon storage capacity of the surface layer. On the other hand, the coverage of ceramic grains can greatly impede the re-emission of carbon from the lower layer of sediments.

5. Conclusions

Studies have shown that shallow lake sediments have large carbon stocks and interrelationships and dependencies between water content, SOC, wet density, and porosity (particle size) in the sediments. By knowing any one of these attributes, the values of the others can be estimated. Correcting the estimation formula of using water content, porosity, and bulk density of sediments to estimate SOC content makes the calculation results more accurate. By comparing and analyzing the future trends of SOC on different areas of the lake, it was found that SOC stocks differed significantly among different study sites, indicating that environmental conditions and human activities (land use and land cover) have an impact on SOC stocks. Moreover, the accumulation of organic matter in the sediments of the areas subjected to severe anthropogenic activities and carbon emissions to the water body will occur after long-term accumulation. The results of this study confirm a strong responsive relationship between human activities, SOC stocks, and lake trophic status. It is thus evident that maintaining the sustainability of lake water bodies and sediments is necessary. The process of the sequestration of atmospheric carbon emissions can be reduced through the restoration of contaminated lake sediments to support global climate change mitigation.

Author Contributions: Conceptualization, W.L. and S.Z.; methodology, W.L. and Y.P.; validation, Y.F. and J.L.; investigation, W.L. and Y.P.; resources, J.L.; data curation, W.L. and J.L.; writing—original draft preparation, W.L. and Y.P.; writing—review and editing, W.L., S.Z. and J.L.; supervision, W.L. and J.L.; project administration, W.L.; funding acquisition, W.L., Y.F. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study is supported by the National Natural Science Foundation of China (Grant No. 52109099, 52079094) and the Water Resource Scientific Research Project of Hubei Province (HBSLKY202301; ZB01XZ-202306-ZCFW0685).

Data Availability Statement: All data generated or analyzed in this study are included in this manuscript. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

References

1. Bastviken, D.; Tranvik, L.J.; Downing, J.A.; Crill, P.M.; Enrich-Prast, A. Freshwater methane emissions offset the continental carbon sink. *Science* **2011**, *331*, 50. [CrossRef] [PubMed]
2. Peter, S.; Isidorova, A.; Sobek, S. Enhanced carbon loss from anoxic lake sediment through diffusion of dissolved organic carbon. *J. Geophys. Res.-Biogeo.* **2016**, *121*, 1959–1977. [CrossRef]
3. Cole, J.J.; Prairie, Y.T.; Caraco, N.F.; McDowell, W.H.; Tranvik, L.J.; Striegl, R.G.; Duarte, C.M.; Kortelainen, P.; Downing, J.A.; Middelburg, J.J.; et al. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* **2007**, *10*, 171–184. [CrossRef]
4. Alkhatib, M.; del Giorgio, P.; Gelinas, Y.; Lehmann, M. Benthic fluxes of dissolved organic nitrogen in the lower St. Lawrence estuary and implications for selective organic matter degradation. *Biogeosciences* **2013**, *10*, 7609–7622. [CrossRef]
5. Luo, W.; Zhu, S.; Wu, S.; Dai, J. Comparing artificial intelligence techniques for chlorophyll-a prediction in US lakes. *Environ. Sci. Pollut. Res.* **2019**, *26*, 30524–30532. [CrossRef] [PubMed]
6. Bianchi, T.S.; Cui, X.; Blair, N.E.; Burdige, D.J.; Eglinton, T.I.; Galy, V. Centers of organic carbon burial and oxidation at the land-ocean interface. *Org. Geochem.* **2018**, *115*, 138–155. [CrossRef]
7. Wu, Y.; Eglinton, T.I.; Zhang, J.; Montlucon, D.B. Spatiotemporal variation of the quality, origin, and age of particulate organic matter transported by the Yangtze River (Changjiang). *J. Geophys. Res.-Biogeo.* **2018**, *123*, 2908–2921. [CrossRef]
8. Yadav, V.; Malanson, G.P. Modeling impacts of erosion and deposition on soil organic carbon in the Big Creek Basin of southern Illinois. *Geomorphology* **2009**, *106*, 304–314. [CrossRef]
9. Xia, X.; Dong, J.; Wang, M.; Xie, H.; Xia, N.; Li, H.; Zhang, X.; Mou, X.; Wen, J.; Bao, Y. Effect of water-sediment regulation of the Xiaolangdi reservoir on the concentrations, characteristics, and fluxes of suspended sediment and organic carbon in the Yellow River. *Sci. Total Environ.* **2016**, *571*, 487–497. [CrossRef]
10. Yu, H.; Wu, Y.; Zhang, J.; Deng, B.; Zhu, Z. Impact of extreme drought and the Three Gorges Dam on transport of particulate terrestrial organic carbon in the Changjiang (Yangtze) River. *J. Geophys. Res.-Earth* **2011**, *116*, F04029. [CrossRef]
11. Poulin, B.A.; Ryan, J.N.; Aiken, G.R. Effects of iron on optical properties of dissolved organic matter. *Environ. Sci. Technol.* **2014**, *48*, 10098–10106. [CrossRef] [PubMed]
12. Wagai, R.; Mayer, L.M. Sorptive stabilization of organic matter in soils by hydrous iron oxides. *Geochim. Cosmochim. Acta* **2007**, *71*, 25–35. [CrossRef]
13. Riedel, T.; Zak, D.; Biester, H.; Dittmar, T. Iron traps terrestrially derived dissolved organic matter at redox interfaces. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 10101–10105. [CrossRef] [PubMed]
14. Yang, L.; Choi, J.H.; Hur, J. Benthic flux of dissolved organic matter from lake sediment at different redox conditions and the possible effects of biogeochemical processes. *Water Res.* **2014**, *61*, 97–107. [CrossRef]
15. Chadwick, S.P.; Babiarz, C.L.; Hurley, J.P.; Armstrong, D.E. Influences of iron, manganese, and dissolved organic carbon on the hypolimnetic cycling of amended mercury. *Sci. Total Environ.* **2006**, *368*, 177–188. [CrossRef] [PubMed]

16. Dadi, T.; Völkner, C.; Koschorreck, M. A sediment core incubation method to measure the flux of dissolved organic carbon between sediment and water. *J. Soils Sediments* **2015**, *15*, 2350–2358. [CrossRef]
17. Knorr, K.H. DOC-dynamics in a small headwater catchment as driven by redox fluctuations and hydrological flow paths are DOC exports mediated by iron reduction/oxidation cycles? *Biogeosciences* **2013**, *10*, 891–904. [CrossRef]
18. Skoog, A.C.; Arias-Esquivel, V.A. The effect of induced anoxia and reoxygenation on benthic fluxes of organic carbon, phosphate, iron, and manganese. *Sci. Total Environ.* **2009**, *407*, 6085–6092. [CrossRef] [PubMed]
19. Pekel, J.F.; Cottam, A.; Gorelick, N.; Belward, A.S. High-resolution mapping of global surface water and its long-term changes. *Nature* **2016**, *540*, 418–422. [CrossRef]
20. Luo, W.; Yue, Y.; Lu, J.; Pang, L.; Zhu, S. Sediment phosphate release flux under hydraulic disturbances in the shallow lake of Chaohu, China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 60843–60851. [CrossRef]
21. Konoplev, A.; Wakiyama, Y.; Wada, T.; Ivanov, M.; Komissarov, M.; Nanba, K. Reconstruction of time changes in radiocesium concentrations in the river of the Fukushima Dai-ichi NPP contaminated area based on its depth distribution in dam reservoir's bottom sediments. *Environ. Res.* **2022**, *206*, 112307. [CrossRef] [PubMed]
22. Yang, P.; Yang, C.H.; Yin, H.B. Dynamics of phosphorus composition in suspended particulate matter from a turbid eutrophic shallow lake (Lake Chaohu, China): Implications for phosphorus cycling and management. *Sci. Total Environ.* **2020**, *741*, 140203. [CrossRef] [PubMed]
23. Aguilar, L.; Thibodeaux, L.J. Kinetics of peat soil dissolved organic carbon release from bed sediment to water. Part 1. Laboratory simulation. *Chemosphere* **2005**, *58*, 1309–1318. [CrossRef] [PubMed]
24. Huang, S.; Bao, J.; Shan, M.; Qin, H.; Wang, H.; Yu, X.; Chen, J.; Xu, Q. Dynamic changes of polychlorinated biphenyls (PCBs) degradation and adsorption to biochar as affected by soil organic carbon content. *Chemosphere* **2018**, *211*, 120–127. [CrossRef] [PubMed]
25. Luo, W.; Lu, J.; Zhu, S.; Yue, Y.; Xiao, L. Investigation of the impact of hydrodynamic conditions on sediment resuspension in shallow lakes. *Int. J. Digit. Earth* **2022**, *15*, 1676–1691. [CrossRef]
26. Mikhail, K.; Shin-ichiro, O. Siltation and radiocesium pollution of small lakes in different catchment types far from the Fukushima Daiichi nuclear power plant accident site. *Int. Soil Water Conserv. Res.* **2020**, *8*, 56–65.
27. Xiong, Z.Y.; Cui, L.P. Remote sensing monitoring and driving factor analysis of land use change in the Chaohu Lake Basin from 1962 to 2019. *China Flood Drought Manag.* **2024**, *34*, 55–59. (In Chinese)
28. Khim, B.K.; Jung, H.M.; Cheong, D. Recent variations in sediment organic carbon content in Lake Soyang(Korea). *Limnology* **2005**, *6*, 61–66. [CrossRef]
29. Xie, Z.L.; He, J. Organic carbon fractions and estimation of organic carbon storage in the lake sediments in Inner Mongolia Plateau, China. *Environ. Earth Sci.* **2015**, *73*, 2169–2178. [CrossRef]
30. Koelmans, A.A.; Prevo, L. Production of dissolved organic carbon in aquatic sediment suspensions. *Water Res.* **2013**, *37*, 2217–2222. [CrossRef]
31. Zhang, Y.; Shen, J.; Feng, J.M.; Li, X.Y.; Liu, H.J.; Wang, X.Z. Composition, distribution, and source of organic carbon in surface sediments of Erhai Lake, China. *Sci. Total Environ.* **2023**, *858*, 159983. [CrossRef] [PubMed]
32. Avnimelech, Y.; Ritvo, G.; Leon, E. Meijer, M.K. Water content, organic carbon and dry bulk density in flooded sediments. *Aquacult. Eng.* **2001**, *25*, 25–33. [CrossRef]
33. Ma, Y.Y.; Wang, Z.Q.; Ma, T.; Chen, S.X. Spatial distribution characteristics and influencing factors of organic carbon in sediments of Tongshun River riparian zone. *Chemosphere* **2020**, *252*, 126322. [CrossRef] [PubMed]
34. Wu, Y.Y.; Fang, H.W.; Huang, L.; Cui, Z.H. Particulate organic carbon dynamics with sediment transport in the upper Yangtze River. *Water Res.* **2020**, *184*, 116193. [CrossRef] [PubMed]
35. Chen, Y.Y.; Liu, Q.Q. On the horizontal distribution of algal-bloom in Chaohu Lake and its formation process. *Acta Mech. Sin.* **2014**, *30*, 656–666. [CrossRef]
36. Fan, C.X. Advances and prospect in sediment-water interface of lakes: A review. *J. Lake Sci.* **2019**, *31*, 1191–1218. (In Chinese)
37. Cai, Y.F.; Kong, F.X. Diversity and Dynamics of Picocyanobacteria and the Bloom-Forming Cyanobacteria in a Large Shallow Eutrophic Lake (lake Chaohu, China). *Limnology* **2013**, *72*, 38. [CrossRef]
38. Xu, J.; Zhao, B. Mechanisms of dissolved organic carbon adsorption on different typical soils in China. *Soils* **2017**, *49*, 314–320. (In Chinese)
39. May, L.; Aura, C.M.; Becker, V.; Briddon, C.L.; Carvalho, L.R.; Dobel, A.J.; Jamwal, P.; Kamphuis, B.; Marinho, M.M.; McGowan, S.; et al. Getting into hot water: Water quality in tropical lakes in relation to their utilization. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2021; Volume 789, pp. 1–22.
40. Boithias, L.; Sauvage, S.; Merlina, G.; Jean, S.; Probst, J.; Perez, J.M.S. New insight into pesticide partition coefficient K-d for modelling pesticide fluvial transport: Application to an agricultural catchment in south-western France. *Chemosphere* **2014**, *99*, 134–142. [CrossRef]
41. Gudasz, C.; Ruppenthal, M.; Kalbitz, K.; Cerli, C.; Fiedler, S.; Oelmann, Y.; Andersson, A.; Karlsson, J. Contributions of terrestrial organic carbon to northern lake sediments. *Limnol. Oceanogr. Lett.* **2017**, *2*, 218–227. [CrossRef]
42. Strauch, A.M.; MacKenzie, R.A.; Giardina, C.P.; Bruland, G.L. Influence of declining mean annual rainfall on the behavior and yield of sediment and particulate organic carbon from tropical watersheds. *Geomorphology* **2018**, *306*, 28–39. [CrossRef]

43. Jiang, C.; Zhang, H.; Wang, X.; Feng, Y.; Labzovskii, L. Challenging the land degradation in China's Loess Plateau: Benefits, limitations, sustainability, and adaptive strategies of soil and water conservation. *Ecol. Eng.* **2019**, *127*, 135–150. [CrossRef]
44. Luo, W.; Lu, J. Inhibition of in situ coating of sediment ceramsite on sediment nutrient release of eutrophic lakes. *Environ. Geochem. Health* **2020**, *4*, 13–27. [CrossRef] [PubMed]