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Review

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Posted Date: 25 March 2024

doi: 10.20944/preprints202403.1445.v1

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Review

A Review on Watershed Environment Study with Lake Sediment Records in China

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Abstract: Lake sediment records are of great importance for understanding the evolution of watershed environments. Various studies have been carried out to constrain the depositional ages of lake sediments and examine their physical, chemical, and biological characteristics, aiming to construct historical vegetation, environment and climate patterns in Chinese lake watersheds. In this study, we obtained relevant literature on lake sediment records by searching the key word 'age-depth' from the databases – Web of Science and China National Knowledge Infrastructure (CNKI, the largest Chinese academic database). We analyzed the literature based on its type (published in a Chinese/English journal or as a Master's/PhD thesis), period of publication, journal (if published in a journal), key authors, study area, dating scale, and main aims. The results suggest that the lakes in the plateau regions are the most popular research topic typically covering 100–200 years (short-term) and 500–30,000 years (long-term). The literature focuses on a wide range of topics, from past environmental evolution in the watershed to lake ecology, and provides a solid foundation for better understanding regional climate change and the preservation of lake environments and ecosystems. In the future, resulting data from environmental reconstruction with lake sediments will be needed to integrate with emerging information processing technologies (e.g., artificial intelligence and meta-analysis), to disentangle the complex interplay between Earth surface processes and global climate change; furthermore, strengthening interdisciplinary collaboration will deepen our comprehension of man-land relationship and promote the sustainable management of lake ecosystems in the context of global climate change.

Keywords: literature review; lake sediments; lake ecosystems; paleoenvironment; paleoclimate; paleovegetation

1. Introduction

Lakes, within the terrestrial hydrosphere, crucially regulate regional hydrological climates and ecological environments, and play a key role in linking Earth's surface systems [1,2]; they can provide substantial natural resources and ecological services, and thus support the development of our economy and society. As such, the study of lakes is of great importance across various multidisciplinary fields. Excellent continuity and high resolution offered by lake sediments shape unique depositional environments of lakes [3]; thus the deposits in lakes are valuable records for unravelling past environmental change in the watersheds, the evolution of lake ecosystems, and human impacts on environments [4,5].

Research on lake sediments can be dated back to the late 19th century with the systematic investigations conducted by Russel and Gilbert on lakes in the western United States [1]. Subsequently, in the 1960s, the first batch of international initiatives for the collection and characterization of lake sediments were undertaken [4]. Concurrently, Chinese scientists began to embark on expeditions and hydrological measurements of lakes such as Lop Nor and Qinghai Lake [6,7]. The 1970s and 1980s witnessed a focus of study on late Quaternary stratigraphy of lake sediments, alongside investigations into evolution of paleoclimate and geological units of basins

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during the Meso–Cenozoic with stratigraphy [8]. The studies on lake sediments expanded further with its burgeoning importance on the implications of global climate and environmental change. Scientists reconstructed regional environmental successions with physical, chemical, and biological information derived from lake sediments [9,10]; moreover, they established databases to facilitate comparative analyses [11] with records from ice cores and the ocean [12], and thereby began to elucidate environmental disparities among regions. In recent years, people have gradually become aware of the impact of human activities on lake environments [13] based on the anthropogenic record in lake sediments. With high-resolution data derived from lake sediments, researchers have reconstructed the evolutionary history of lake environments driven by human activities [14,15]. These efforts aim to unveil the extent of impacts of human activities and climate change on the evolution of lake ecology and environments [16,17].

Due to the complexity of the studies on lake sediments, they are usually related to knowledge and methods from different disciplines, including geology, geography, ecology and environmental science. Indicators of environmental change for lake sediments include physical (e.g., grain size composition and magnetic susceptibility [18]), chemical (e.g., organic matter, isotopes, carbonates, and various geochemical elements [19]) and, biological (e.g., pollen, alkanes, and diatoms [20–22]) proxies. By analyzing these proxies, we can obtain key information on environmental evolution of lakes, including paleoclimate changes, evolution of ecosystems, biodiversity variation, the adaptation of lake ecosystems to environmental change [23], and the impact of human activities on lake environments [24]. Furthermore, by analyzing environmental indicators (e.g., pollutants and nutrients from lake sediments), we can evaluate the health of lake ecosystems; this will place a solid basis for developing strategies to protect and manage lake resources.

In this study, with a retrospective literature review on lake sediments in China over the past thirty years, we aim to provide valuable information and a reference from different aspects for further promoting the comprehensive development of the research on lake sediments in the future, by quantitative analyses, summarizing its research status (including methods), and examining its deficiencies.

2. Data Collection and Methods

Bibliometrics serves as an objective, comprehensive, and systematic approach for examining the current status and trends in the field of lake sediment research from multiple perspectives [25,26]. The bibliometric analysis on the literature compiled (categorized by type of literature, date of publication, journal published, key authors, and studied region) can uncover the development tendencies within this field, evaluate academic achievement and its influence, identify opportunities for collaboration, and aid in the optimization of academic resources [27,28]. By analyzing the dating scale and content of related literature, this study seeks to attain a better understanding of evolution patterns of the Earth's environments, changes in lake environments, and the research topics and the cutting edge in the research field of lake sediments across different regions.

We employed 'lake sediment*' and 'China' as keywords for a literature search in Web of Science (https://www.webofscience.com/) and CNKI databases (China National Knowledge Infrastructure, the largest Chinese academic database, https://www.cnki.net/). We initially identified 5,181 articles with the criterion that the article must contain a detailed sedimentological description on the lake core profile. To ensure that the lake sediments were age-constrained, we then manually checked the literature, screened those with 'age-depth' models, and obtained 413 articles as datapoints for statistical analysis for this study. We classified these lake sedimentary profiles based on the length of their dated age intervals to understand their temporal resolution and coverage.

3. Results and Discussion

3.1. Number of Literature and Dates of Publication

The statistical analysis of literature types from 1994 to 2023 indicates that Chinese articles (35), English articles (315) and Master's/PhD dissertations (65) account for 8.5%, 76.2%, and 15.3%

respectively (Figure 1a). The articles on lake sediments published during 1994–2023 increase year by year based on the summary of quantity and date of the publications, with a particularly marked surge from 2006 onwards; this suggests that the study on lake sediments has received more attention in the past two decades. Notably, the number of English articles also increased evidently from 2006, indicating the development and increasing influence of Chinese research on lake sediments in the international academic community (Figure 1b). 2016–2019 are the peak years for publications on lake sediment research, particularly during 2018–2019 the number of publications reaches a peak of 80 per year. The results indicate that lake sediment research in China has received widespread attention, and related researchers have made significant progress both domestically and internationally.

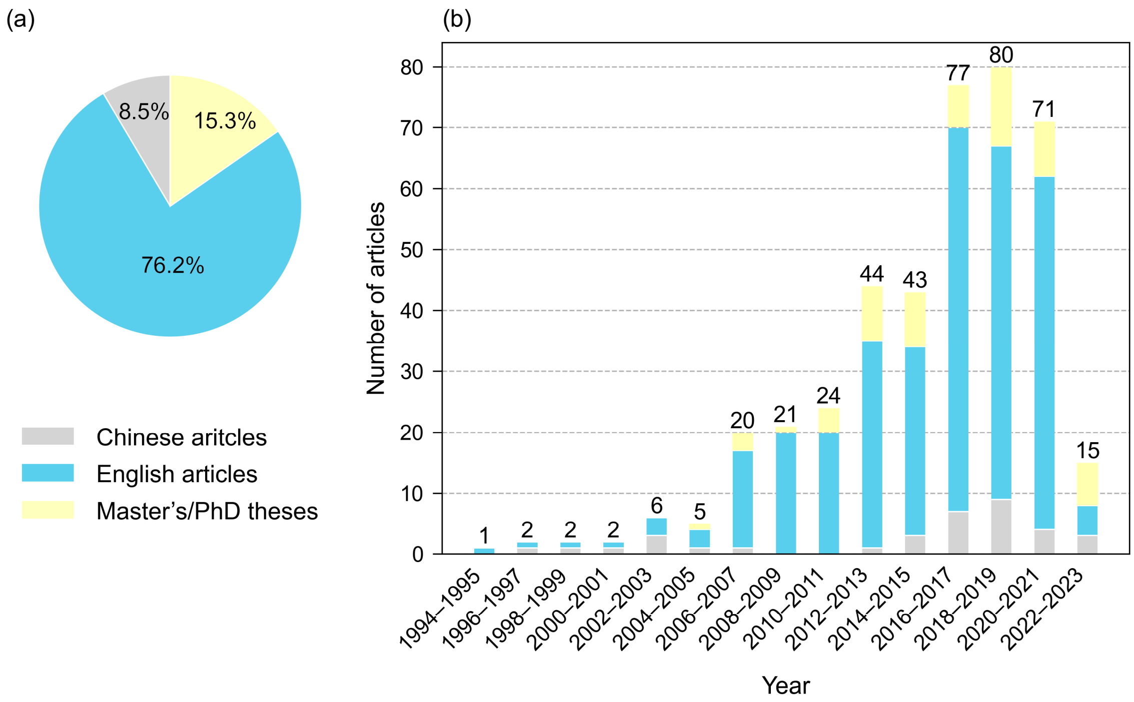

Figure 1. Type of literature and its accounted percentage (a) and number of different publication type (b) on lake sediment research in China during 1994–2023.

3.2. Journals Published

An analysis of publication sources across Chinese and English journals, with a particular focus on the top 10 journals by frequency of publication, identifies '*Palaeogeography, Palaeoclimatology, Palaeoecology*', '*Quaternary Science Reviews*', and '*Quaternary International*' as leading journals in lake sediment research in China (Table 1). Among them, '*Palaeogeography, Palaeoclimatology, Palaeoecology*' stands out with the highest number of publications, totaling 41 articles. This highlights the journal's substantial influence within the lake sediment research community, which attracts a diverse range of researchers to publish their findings there. This is attributed to the journal's broad interdisciplinary scope, encompassing fields such as geology, climatology, and paleoecology; this makes it an important platform for the academic exchange of lake sediment research. Similarly, '*Quaternary Science Reviews*' and '*Quaternary International*' are comprehensive journals and cover a wide range of topics on Quaternary geology (including climate change, geomorphic and biological evolution); the number of their publications is second only to '*Palaeogeography, Palaeoclimatology, Palaeoecology*', and has also received widespread attention. From the above journal names, we can see that long-term scale lake sediment research in China has been primarily published in domestic and international journals focused on themes of paleoenvironments and Quaternary.

Table 1. Top 10 journals in terms of number of published articles on lake sediment research in China from 1994 to 2023. NA = not applicable.

Journal name	Number of articles	Impact factor (2022)
Palaeogeography, Palaeoclimatology, Palaeoecology	41	3.0
Quaternary Science Reviews	33	4.0
Quaternary International	29	2.2
Journal of Paleolimnology	28	2.1
The Holocene	22	2.4
Quaternary Research	17	2.3
Chinese Science Bulletin (科学通报)	8	NA
Quaternary Sciences (第四纪研究)	7	NA
Boreas	6	2.2
Global and Planetary Change	6	3.9
Hydrobiologia	6	2.6
Journal of Asian Earth Sciences	6	3.0
Earth and Planetary Science Letters	6	5.3
Review of Palaeobotany and Palynology	5	1.9
Journal of Lake Sciences (湖泊科学)	5	NA

3.3. Key Authors

An analysis of authors (with > 8 articles) and their affiliations during 1994–2023 indicates that Ji Shen, Enlou Zhang, and Liping Zhu have published the most articles (20, 17, and 17; Table 2). Researchers who publish a large number of articles in the field of lake sediment research typically possess excellent knowledge and experience, and their affiliated institutions often have strong research teams and resources. The result of the analysis on the affiliations of key authors shows that Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (CAS) has published the most lake sediment literature, suggesting its strong research capabilities in this field of lake sediment research. Additionally, several researchers from Tibetan Plateau Research Institute (CAS), Institute of Geographic Sciences and Resources (CAS), the School of Resources, Environment, and Tourism at Capital Normal University, and the School of Resources and Environment at Lanzhou University, have also published a significant amount of articles in the field of lake sediment research. The author list also includes some foreign researchers, such as Ulrike Herzschuh and Steffen Mischke, affiliated with the Helmholtz Center for Polar and Marine Research at the Alfred Wegener Institute in Germany and the School of Geosciences at the University of Iceland, respectively, suggesting extensive international collaboration in this field. China, as a country rich in lake resources, possesses various types of lakes including freshwater, salt, and plateau lakes. These lakes have unique geographical locations, hydrological characteristics, and sedimentary processes, and attract attention from researchers worldwide. Domestic and international collaboration has provided a broader perspective and resource support for lake sediment research.

Table 2. The author with > 8 publications on the study of lake sediments in China from 1994 to 2023. CAS = Chinese Academy of Sciences.

Author	No. of articles	Institution
Ji Shen	20	Nanjing Institute of Geography and Limnology, CAS
Enlou Zhang	17	Nanjing Institute of Geography and Limnology, CAS
Liping Zhu	17	Institute of Tibetan Plateau Research, CAS
Junbo Wang	14	Institute of Geographic Sciences and Natural Resources Research, CAS
Xingqi Liu	13	College of Resources Environment and Tourism, Capital Normal University

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Ulrike Herzschuh	12	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research
Xiangdong Yang	12	Nanjing Institute of Geography and Limnology, CAS
Fahu Chen	11	College of Earth and Environmental Sciences, Lanzhou University
Aifeng Zhou	10	College of Earth and Environmental Sciences, Lanzhou University
Guoqiang Chu	9	Institute of Geology and Geophysics, CAS
Steffen Mischke	9	Faculty of Earth Sciences, University of Iceland

3.4. The Five Lake Regions

Lake sediment records were divided into five lake regions: Qinghai-Tibetan Plateau (QTP), Yunnan-Guizhou Plateau (YGP), Mongolia-Xinjiang Plateau (MXP), East Plain (EP), and Northeast Region (NR), according to the localities of the lakes in the literature [29] (Figure 2). The result of analysis on lake distribution data suggests that there are relatively more articles on the QTP (124), MXP (117), and YGP (108). In contrast, there are fewer articles on the EP (40) and NR (24). This may be related to the distribution of lakes in China: Plateau regions typically possess more abundant lake resources and unique climatic conditions, and attract a significant number of researchers, while lake resources in plains are relatively limited.

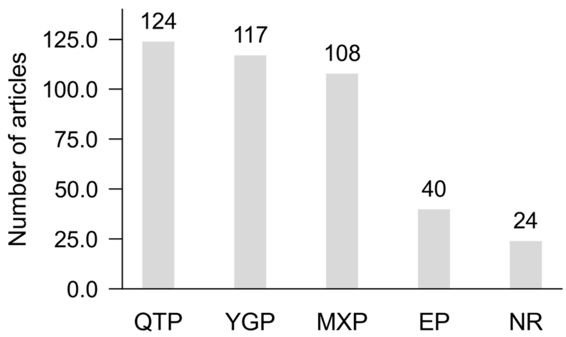

Figure 2. Number of articles published with lake sediments from the five lake regions. Abbreviation: QTP = Qinghai-Tibetan Plateau; YGP = Yunnan-Guizhou Plateau; MXP = Mongolia-Xinjiang Plateau; EP = East Plain; NR = Northeast Region.

The data on the lake elevation show that there are 135,179, and 99 lakes with elevational ranges > 3,000 m, between 1,000 and 3,000 m, and < 1,000 m, respectively; this is related to China's specific location (at the junction of the Eurasian Plate) and the resulting hierarchical distribution of geological structures and geomorphologic formations (Figure 3a). The data on lake type suggest that there are 218 closed lakes, 172 open lakes, 18 dried-up lakes, and 5 seasonal lakes (Figure 3b). Due to topographic features and land-sea distribution patterns, closed, open, and dried-up lakes are generally concentrated in the QTP and MXP, YGP and EP, and MXP respectively, while seasonal lakes have a scattered distribution in the QTP, MXP, and EP. In the QTP, rivers and streams formed by snowmelt and rainfall converge in high-altitude areas and constitute closed lakes [30]. The MXP, located in Central Asia [31], is characterized by geographical barriers that prevent water flow directly into the ocean, leading to the formation of closed lakes in lower-lying areas. In contrast, although the YGP has a high elevation, its proximity to the ocean and large rivers facilitates the outflow of lake water and thus the formation of open lakes. The EP, with flat terrain and abundant river systems, allows water to easily flow into the ocean, forming open lakes. Additionally, the dry climate and unfavorable hydrological conditions in the MXP result in insufficient lake water maintenance and thus dried-up lakes predominate [32,33].

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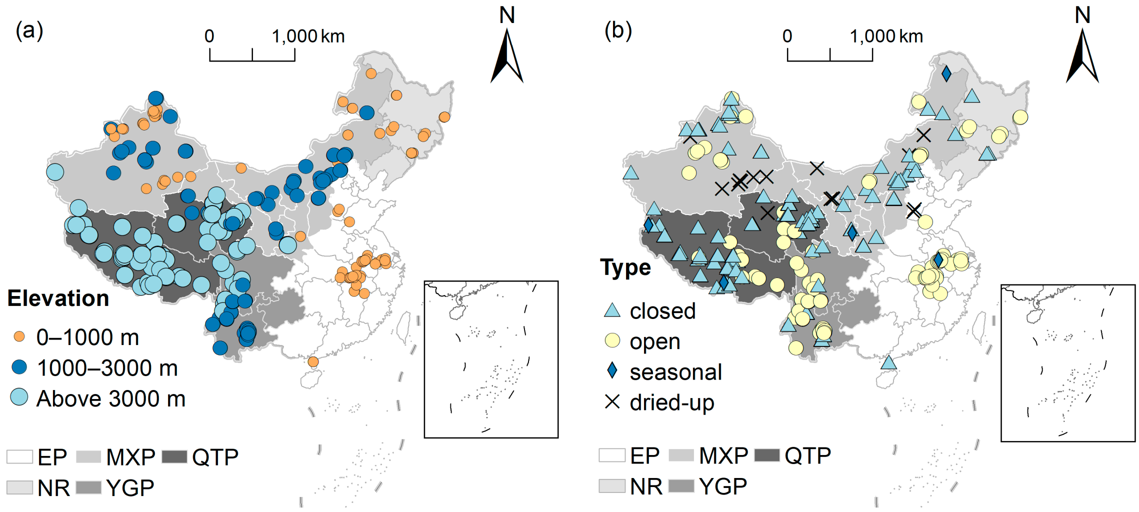

Figure 3. Elevations (a) and types (b) of the studied lakes in China. Abbreviation: EP = East Plain; MXP = Mongolia-Xinjiang Plateau; QTP = Qinghai-Tibetan Plateau; NR = Northeast Region; YGP = Yunnan-Guizhou Plateau. The base map is from 'Chinese Standard Map – Approval Number GS (2022) 1873'.

3.5. Dating Scales

The dating scale is primarily concentrated in two time-intervals: 100–200 years and 500–30,500 years. This is because literature focusing on the impact of human activities on lake environments and ecosystems tends to concentrate on short time scales, while literature studying climate and vegetation changes in lake basins emphasizes long time scales (Figure 4). The traditional methods for dating sediment mainly involve paleomagnetism, ^{14}C, ^{210}Pb and ^{137}Cs radioisotope dating [34]. Recently methods such as uranium-thorium (U/Th) dating, optically stimulated luminescence (OSL) dating, and volcanic ash dating, have been increasingly employed for determining the age of lake sediments. Different dating methods are suitable for dating at different time scales. For example, ^{137}Cs and ^{210}Pb dating methods are mainly applicable to short-term scales (e.g., 50–60 years and 100–200 years), while radiocarbon, U/Th, and OSL dating methods are typically used for longer time scale research. It is worth noting that the dating time scale of sediment profiles in 38.7% of the literature exceeds 10,000 years. This indicates that the study of long-term sedimentary processes of lakes is becoming increasingly important for understanding environmental change, and can provide a broader perspective for exploring significant time intervals and processes in Earth's history.

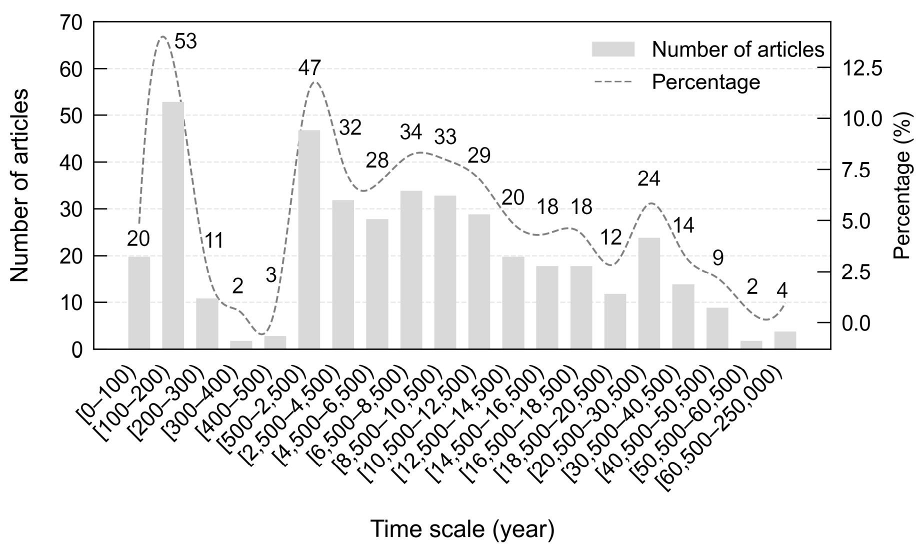

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Figure 4. Distribution of dating scales of the studied lake sediment profiles.

3.6. Key Themes

According to their key themes, the articles on lake sediment research were divided into two main categories: 1) the reconstruction of paleoenvironmental change in the watershed (301 articles, 72.9% of the total); and 2) the evolution of the lake ecosystems (91 articles, 22.0%) (Figure 5). Four subcategories were further classified and shown by representative proxies: 1) paleoclimate reconstruction (245 articles, 59.3%); 2) paleovegetation reconstruction (56 articles, 13.6%); 3) lake ecosystems (40 articles, 9.7%); and 4) lake environment (51 articles, 12.3%) (Figure 5).

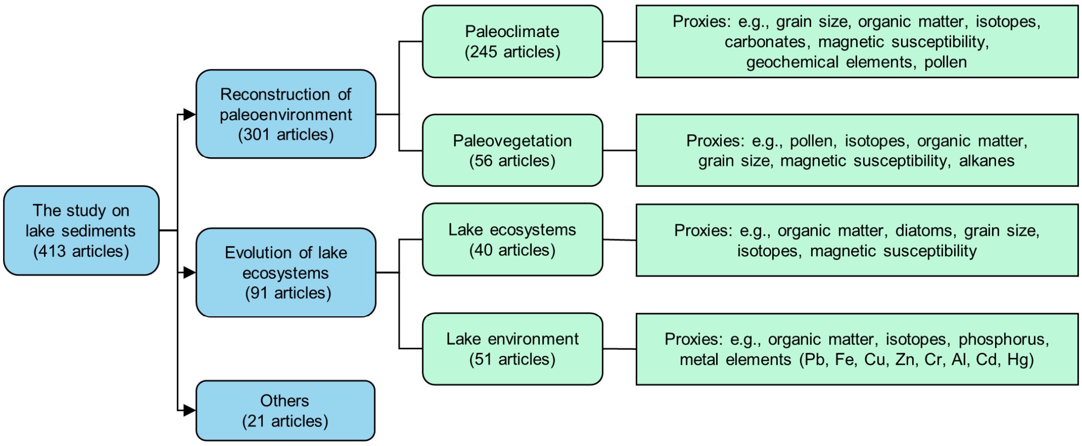

Figure 5. Key themes and their proxies of lake sediment research.

3.6.1. Paleoclimate Reconstruction

Paleoclimate reconstruction mainly focuses on multiple proxies in lake sediments, including grain size composition, organic matter, isotopic and carbonate composition, magnetic susceptibility, geochemical elements, and pollen. Among these, grain size composition is an important indicator for analyzing the physical properties of lake sediment [35]. It can provide information about past precipitation and humidity change [36], and reveal the relationship between lake hydrodynamic changes, precipitation variability, and climate change [37]. Organic matter analysis evaluates the source and composition of organic matter in lake sediment [38]. By measuring the content of total organic carbon (TOC), total nitrogen (TN), and the carbon/nitrogen ratio (C/N) in sediment, the productivity and organic matter input of ancient lakes can be evaluated [39,40]. Stable isotopes (e.g., ^{13}C, ^{15}N, ^{18}O and ^{2}H) can reveal hydrological and climatic change in paleolakes [41,42], including precipitation and compositional change of lake water in the watershed [43,44]. Isotopic and carbonate composition further aids in studying chemical characteristics of lake water and carbon cycling processes, thereby reflecting variation in water composition and temperature of the paleolake [39]. Magnetic susceptibility can be employed to infer precipitation change [45] and surface soil erosion [46] in the watershed. The content and ratios of geochemical elements [47] can be used to study the impact of climate change on weathering processes in the watershed. For example, the Climate Change Index (CCI) is represented by the ratio of concentration of elements such as iron, manganese, chromium, vanadium, to the concentration of elements including sodium and potassium [48]. Higher CCI values typically indicate warm and humid climatic conditions, whereas lower values suggest arid or semi-arid climatic conditions [49]. Pollen assemblages primarily comprise tree and shrub, meso-herbs, xero-herbs, and wetland pollen types [50], corresponding to warm and moist climates, and cold and arid climates, respectively [51,52]. Early human activities, particularly deforestation, resulted in a decline in the concentration of tree and shrub pollen, and a concurrent increase in herbaceous pollen in the assemblages. Furthermore, human settlement and agricultural expansion prompted a rise in the content of cereal grain pollen in lake sediments, indicative of the proliferation of adjacent shoreline farming practices [46]. A comprehensive analysis of these proxies is helpful for

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understanding the trends and cycles of past climate change, gaining insights into the global climate system, unveiling the driving mechanism of climate change, and predicting future climate change. Future study should be focused on integrating and analyzing climate data from various lakes on a broader spatial scale to further explore the spatial differences and driving factors of climate change.

3.6.2. Paleovegetation Reconstruction

Paleovegetation reconstruction primarily involves analyzing multiple proxies in lake sediments to reconstruct former plant composition, vegetation types and successions, and their relationship with climate change. Pollen and alkane analyses are the two principal methods for studying past vegetation composition and evolution: the former is achieved by analyzing the pollen types and their percentages in the pollen sum [49]; while the latter studies the source of organic matter and vegetation history through the distribution of alkanes and isotopes in sediments. For example, by examining the carbon isotopes (^{13}C) of individual alkanes, change in the relative abundance of C3/C4 plants during geological history can be reconstructed [53]. By combining other proxies (e.g., isotopic composition, organic matter, grain size composition, magnetic susceptibility) we can better understand vegetation dynamics and its response to environmental change. The paleovegetation reconstruction result is invaluable in understanding the response mechanisms of plants and vegetation to environmental change, predicting future ecosystem dynamics, and developing effective strategies for ecological conservation and restoration. To further understand the drivers of past vegetation change, we will need to integrate the general information from the watershed to explore both natural and anthropogenic influences, as well as analyze the impact of the vegetation change on hydrological and geomorphological processes in the watershed.

3.6.3. The Evolution of Lake Ecosystems

Several proxies in sediments (e.g., organic matter, diatoms, grain size and isotopic composition, and magnetic susceptibility) have been used to investigate the evolution of lake ecosystems to understand the changes in the internal ecosystem and biological communities, among which diatoms are one of the primary methods for studying the evolution of lake ecosystems by analyzing the concentration and relative abundance of fossil diatoms in sediments, the chemical environmental changes as well as the biological responses of paleolakes can be inferred [54]. In addition, diatoms are highly sensitive to environmental change, and thus can be used as biological indicators to study the impacts of climate change and human activities on lake waters [55]. By combining fossil diatoms and other commonly used proxies, we can better obtain the information of the chemical environment and biological response of lake water bodies and thereby understand the evolution of lake ecosystems. The study on the evolution of lake sediments is of great importance for protecting lake ecosystems, maintaining biodiversity, and sustainably utilizing lake resources. To better understand the dynamic changes in lake ecosystems, we will also need to consider the nutrient element input into lakes from watershed surface water and soil development, and link the dynamic changes in lake ecosystems with surface process in the watershed.

3.6.4. Environmental Change of Lakes

The study of environmental change in lakes mainly focuses on issues such as heavy metal pollution, eutrophication, and anthropogenic-related pollution. By analyzing multiple proxies in lake sediments, including organic matter, isotopes, phosphorus, and metal elements, the quality and health status of lake environments can be assessed. Specifically, the total phosphorus content and metal element concentration are important indicators for assessing change in lake environments. Total phosphorus content is a key indicator used to assess the trophic status and degree of eutrophication of lakes [56]. The analysis on metal elements can facilitate the evaluation of environmental change, particularly the degree of heavy metal pollution in lakes. Common metal elements include lead (Pb), iron (Fe), copper (Cu), zinc (Zn), chromium (Cr), aluminum (Al), cadmium (Cd), and mercury (Hg). By calculating the enrichment factor [57], which involves

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comparing the concentration ratio of pollutant elements to reference elements, the extent to which elements such as heavy metals in sediments are influenced by human activities can be evaluated. Watershed-scale hydrological models will be needed to simulate the transport of nutrients and heavy metals across watersheds. Additionally, integrating different long-term scale lake sediment records can reveal the influence of socio-economic conditions on lake environments in the watershed. The study on lake environmental change contributes to the understanding of environmental issues such as heavy metal pollution and eutrophication. By assessing the quality and health status of lake environments, potential human health risks can be prevented.

4. Concluding Remarks

In recent years, lake sediment research which includes international collaboration in China has shown a rapid increase and attracted widespread attention both domestically and internationally; this is likely related to the growing prominence of global climate change and environmental issues. Lake sediment research provides an important scientific basis for understanding and addressing these problems. There are differences in the distribution of lake sediment research in different geographical regions: the studies in the QTP, MXP, and YGP are relatively numerous, because these regions have rich lake resources, diverse landforms, and are significantly affected by climate change. The dating scale of lake sediment mainly focuses on two time-intervals: 100–200 years and 500–30,000 years. Additionally, lake sediment dating is increasingly being integrated with various methods and techniques to investigate the influence of climate events on lake environments and regional climate evolution. The focus of lake sediment research not only includes hot topics such as paleoenvironmental change and lake ecosystem evolution but also emerging issues such as lake environmental pollution. This indicates that lake sediment research is evolving in a more comprehensive and integrated direction.

In the past decades, extensive studies have focused on local paleoenvironmental reconstruction using lake sediment proxies, resulting in significant data on Holocene sediment, vegetation, and climate evolution. This data will help geoscientists further explore the spatiotemporal distribution characteristics of lake sediment and its driving factors (e.g., climate and environmental change). Additionally, the development of information processing technologies (e.g., artificial intelligence and big data analysis) provides technical support for integrating lake sediment data in the Holocene, analyzing surface process, and coupling Earth's climate, thereby constructing a sediment knowledge diagram that integrates 'time-space-material' characteristics. The related work contributes to summarizing and forming sedimentology data-driven methods and technical systems, thus promoting research on big data in Earth system science. Currently, we are in a context where global climate change and environmental pollution impact sustainable human development. Therefore, factors such as policy support, research projects, and international collaboration in China will play an important role in promoting research on lake sediments. Lake sediment research, as an important interdisciplinary field, often requires collaboration across disciplines such as geography, geology, environmental science, and ecology to drive innovation and development.

Author Contributions: Conceptualization, M.L., G.T. and H.H.; methodology, M.L.; validation, M.L. and H.H.; formal analysis, M.L.; data curation, M.L.; writing—original draft preparation, M.L.; writing—review and editing, G.T. and H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the starting grant for introduced talents from Sun Yat-sen University (to H.H.) and the National Natural Science Foundation of China (NSFC) (no. 42171025 to G.T.).

Acknowledgments: We thank Dr. Robert J. Morley (Palynova Limited, UK) for improving an early version of this manuscript, particularly the linguistic help.

Conflicts of Interest: The authors declare no conflicts of interest.

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