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Characteristics and development trends of ecohydrology in lakes and reservoirs: Insights from bibliometrics

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Abstract

Ecohydrology, an interdisciplinary subject connecting ecology and hydrology, has developed rapidly in recent years. Because lakes and reservoirs are responsible for the drinking water supply of billions of people and water issues are becoming increasingly severe, the importance of these water bodies is self-evident. Lake (reservoir) ecohydrology has thus attracted considerable attention. This study aimed to analyse the characteristics and development trends of ecohydrology using a bibliometric analysis based on the Science Citation Index database. A total of 21,753 papers from 1900 to 2017 on lake (reservoir) ecohydrology were published in 2,323 journals, and the large majority of them were published in the past three decades. Most research has been concentrated in Europe (40.0%) and North America (31.0%). Among these studies, a few key lakes, for example, Lake Taihu, Lake Erie, Lake Michigan, and Lake Ontario, have been analysed in detail by numerous researchers. The results of a word frequency analysis show that the topics related to ecohydrology have transformed from the microcosmic perspective to the macroscopic perspective, and major topics include *eutrophication*, *global change*, *models*, and *ecosystem management*. The results of a principal component analysis show that the scope of lake (reservoir) ecohydrology research in Europe and North America has stagnated in recent years, whereas in China, ecohydrology research has developed rapidly over the same period. The development of ecohydrology research around the world is not even, and we need to push for more research on major lakes that are outside of Europe, the United States, and China.

KEYWORDS

bibliometric analysis, current hots, development trends, lakes (reservoirs) ecohydrology

1 | INTRODUCTION

The term "ecohydrology" has recently attracted increasing attention in academic circles, although there is no widely accepted definition of ecohydrology in the scientific community (Jørgensen, 2016; Rodriguez-Iturbe, 2000; Wassen & Grootjans, 1996; William, 2002a, 2002b; Zalewski, 2000; Zalewski, 2002). However, the community agrees that ecohydrology is an interdisciplinary field combining aspects of ecology and hydrology and that it can promote better protection and management of water resources and aquatic ecology. Although the concept of ecohydrology is still new, past research may unintentionally involve aspects of ecohydrology. Therefore, even though the discipline was not given a name until recently, it has existed for a long time. In recent years, water environmental issues have included the double threats of pollution and global change (Zalewski, 2010), and ecohydrology research is becoming more prevalent.

Lakes (in the following, the term "lake" is used to represent both lakes and reservoirs) are important sources of human drinking water worldwide (Gleick, 1993) and as the major research focus of ecohydrology. The ecological service demands for lakes and reservoirs have increased continuously with the development of society and the economy. Meanwhile, human society has imposed increasing requirements on the ecological environment of lakes and reservoirs. However, in recent years, the ecological and environmental problems of lakes and reservoirs have become increasingly prominent, and independent research on lake hydrology and ecology and the use of traditional approaches cannot meet the needs of lake research. In the process of exploration, scientists have gradually integrated hydrology and ecology and promoted the formation of lake ecohydrology. As a new interdisciplinary subject formed by the integration of hydrology and ecology, lake ecohydrology is a basic research approach to the study of lakes and reservoirs. The hydrologic mechanisms associated with ecological processes and the ecological patterns affecting lakes are studied using the theory and methods of ecohydrology, that is, how the hydrological process in the basin affects lakes on different spatio-temporal scales. In short, how does the ecological pattern, the ecological process, the ecological function, and the lake ecosystem change in response to the hydrological process?

Bibliometrics is the statistical analysis of written publications. It has become an important field in the digital age (Desai, Veras, & Gosain, 2018). This type of analysis has been widely used to quantitatively and qualitatively assess the scientific output or research patterns of authors, periodicals, countries, and research institutions (Liu, Zhang, & Hong, 2011; Zhi et al., 2015). The Science Citation Index (SCI) Expanded database is the most comprehensive and commonly used data source for evaluating scientific development, research hot spots, and future research directions (Braun, Schubert, & Kostoff, 2000; Tan, Fu, & Ho, 2014; Zhang, Yao, & Qin, 2016). Among the publication information, the article's keywords and abstract represent the theme of each article and can be used for text mining to further identify the characteristics and development trends of particular disciplines.

Based on bibliometrics, this paper reviews the research characteristics and development trends of lake ecohydrology. First, we summarize the variation characteristics of the total publication output, document types, and languages of the publications, as well as the distribution of output based on subject categories and journals. Second, we use text mining to reveal the current hot spots, research object distribution, and development trends of lake ecohydrology based on abstract analysis. Finally, we compare the development characteristics of major countries or regions through principal component analysis (PCA).

2 | METHODS

2.1 | Search strategy

The SCI Expanded database, Web of Science (Thompson Reuters Corporation, USA), was used in this study. The database includes publications from 11,149 major journals that span 237 disciplines and that are published in 82 countries. Summaries have been added to each SCI publication since 1991 (Zhang et al., 2016), such as information related to headings, abstracts, and keywords (Zhi et al., 2015). To cover the general subjects of lake ecohydrology, the following search strategy was used in this study: (TS = ((ecosystem* or phytoplankton* or zooplankton* or benthos* or macroinvertebrate* or macrophytes* or microbial*) and ("water level" or hydrology* or flow* or "water quantity" or wave* or current* or "hydrologic* residence* time" or "lake residence* period*" or "suspended solid*" or "water* temperature*" or light* or transparency* or sediment*) and (lake* or reservoir*))). The publication time period covered 1900 to 2017. The search was carried out on May 1, 2018.

2.2 | Data analysis

Document information, including author, title, source (journal title), language, country/region, document type, author's keywords and address, and subject category, was downloaded for further analysis. Articles from Hong Kong and Taiwan were not grouped under the heading of China. Multivariate linear regression was used to understand the correlation between the number of articles published by different countries and the economic development and national area. Gross domestic product data were obtained for countries from 1990 to 2017 from the World Bank. The R package World Development Indicators was used to directly read these gross domestic product data and national area data from Wikipedia.

The abstract contained the main information from each publication; hence, we used the information provided by the abstracts to carry out the following analysis. The R package "tm" (Feinerer, Hornik, & Meyer, 2008) was used to generate word frequency statistics for all the abstracts of the publications and to generate super large sparse matrices. From the top 200 terms with the highest frequency, the words with practical meaning were selected, the number of occurrences was counted, and the relative importance values were ranked according to rank values. In this way, we could see the interannual variation in the popularity of the subjects. Mann–Kendall trend analyses were used to test the interannual variation trends for these terms (Salmaso, 2011). The Mann–Kendall trend analyses were carried out using "Kendall" (McLeod, 2011). According to the results of the word frequency statistics, we selected several topics that have been of high concern in recent years and identified research hot spot characteristics by calculating the correlations among words. The long-term variation trends of these words were determined using the geom_smooth function (Cleveland, 1992) in ggplot2 and marking the 95% confidence interval.

To analyse the global distribution of lakes and reservoirs, we summarized the names of the lakes and reservoirs mentioned in the abstracts. We used the R package "stringr" to find the name of the lake by looking for the words before and after the keyword "Lake" or "Reservoir" and then manually searched for lake names. Although the names of the lakes were not available for some publications (less than 4% in our study), we think the information is still representative and meaningful.

To understand the relationship between the research objects (lakes and reservoirs) and the economic development and population density, we chose the global night lighting map published by National Aeronautics and Space Administration (NASA) to measure regional economic development and population density. We combined this information with the lake name data to obtain the relationship between human activities and the subjects of lake ecohydrology. The night lighting map (2012 Colour Global Map) published by NASA was selected in this paper. Google Map was used to determine the longitude and latitude of lakes and reservoirs (URL: http://www.gpsspg.com/maps.htm). The R package "leaflet" and "leaflet.extras" were used to add the lake distribution heatmap to the NASA night lighting map (Cheng & Xie, 2015; Karambelkar, 2017).

Based on the generated sparse matrix, PCA was carried out using the R package "vegan" (Oksanen et al., 2016). Taking every article as a row vector, we retrieved keywords as column vectors (the names of the column vectors are "ecosystem," "phytoplankton," "zooplankton," "benthos," "macroinvertebrate," "macrophyte," "microbial," "water," "hydrology," "flow," "level," "wave," "current," "residual," "time," "lake," "period," "suspend," "solid," "temperature," "light," "transparency," "sediment," and "reservoir") to form a super large sparse matrix. Of the articles included, due to increasing international cooperation, many articles featured authors from multiple countries. We used the nationality of the corresponding author as the country to which the article belongs. Through PCA analysis, we can better understand the characteristics of the articles published in different countries and in different years.

Figures were drawn using the R package "ggplot2" (Wickham, 2009), and network visualization was carried out with "igraph" (Csardi & Nepusz, 2006).

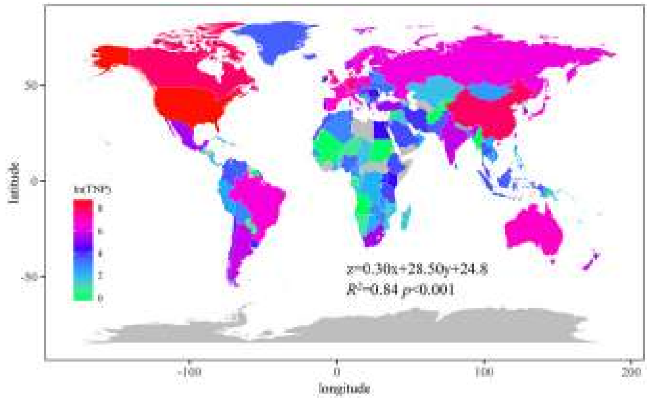

FIGURE 1 Global geographic distribution by country/territory. (Grey represents areas that did not publish an article included in this study. The formula expresses the linear relationship between the number of articles published, the average GDP, and the area of a country. In this equation, z represents the number of articles published by each country, x represents the average GDP [billion dollars] from 1990 to 2017, and y represents the area [million km^2]). TNP: total number of publications; GDP: gross domestic product

TABLE 1 The exponential fitting coefficient, correlation coefficient (adjusted r^2), and P value

Country/region	Fitting coefficient	r^2	P value
Total	1.094	0.86	0.000
USA	1.087	0.78	0.000
Europe	1.092	0.83	0.000
Canada	1.086	0.68	0.000
China	1.284	0.96	0.000

3 | RESULTS AND DISCUSSION

3.1 | Variation characteristics of total publication number

A total of 21,753 publications were retrieved through the search strategy mentioned above. Among them, 6,750 papers were published in the United States, 2,671 in China, 2,626 in Canada, and 8,720 in Europe (Figure 1). In general, we can conclude from the linear regression results that the number of published articles is positively correlated with the degree of development and the size of each country. The first article appeared in 1972, but before 1990, the number of publications per year was less than or equal to 10; hence, we focus on the changes from 1990 to 2017 in the following analysis. In recent years, according to the exponential fitting equation (Table 1), the annual exponential increase rate has been approximately 9.4% (Figure 2). Compared with the development of research on lake ecohydrology in different countries/continents, research on lake ecohydrology in Europe and the United States developed quickly from 1990 to 2017 and has maintained an exponential growth rate of approximately 8%. Although research in Canada started earlier than that in China, Canada has a lower total number of publications and a lower growth rate than the United States and China. The most obvious change occurred in China: In the 1990s, the number of publications was very small, but it increased rapidly from 2000 through 2017, when the number of published articles nearly reached that of the United States. The exponential increase ratio of the total number of publications for China was 0.284 from 1990 to 2017, which is approximately three times that of other countries/continents, for example, Canada, the United States, and Europe. This dramatic increase corresponds to the rapid development of China in recent years and to the more prominent environmental problems of lakes and reservoirs in China than in developed countries.

3.2 | Document types and languages

Among the publications, 14 types of documents were identified. The most common article type was peer-reviewed journal articles (19,680; 90.88% of all publications), followed by proceedings papers (2,238; 10.335%) and reviews (930; 4.295%). Other document types included editorial material (69), notes (36), book chapters (26), meeting abstracts (nine), letters (six), corrections (five), data papers (four), reprints (two), retracted publications (two), correction additions (one),

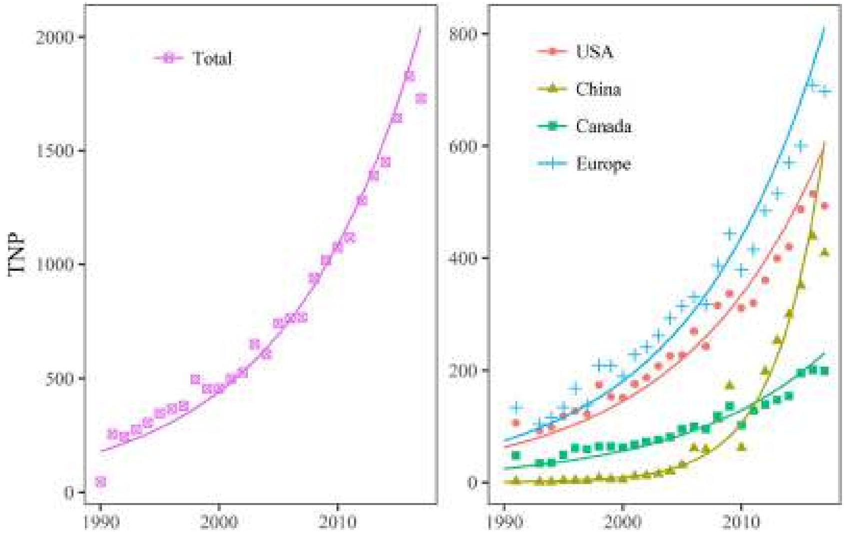

FIGURE 2 The number of articles published each year and the exponential fitting curves. TNP: total number of publications

and news items (one). The numbers in parentheses represent the number of publications corresponding to each document type.

These publications were published in 19 languages, including 21,492 in English (98.956%), which was the dominant language, followed by French (61; 0.282%), Spanish (930; 0.226%), Portuguese (24, 0.111%), and Polish (22, 0.102%). Other languages included Russian, Chinese, German, Japanese, Turkish, Czech, Romanian, Catalan, Croatian, Danish, and Latvian, but all of these accounted for less than 0.1%.

3.3 | Characteristics of the research objects

From the top 200 terms, 63 words with practical meaning were selected (Figure S1). The trend and significance of changes in these words are shown in Table S1. The three words "lake," "water," and "sediment" were deleted because they were the most common words and did not change during the period of 1990 to 2017. Next, the research characteristics of lake ecohydrology in the last 27 years (1990–2017) will be discussed from the two aspects of research, timescale, and research objects in the following sections.

Assessment of the research timescale was based on five keywords and their frequency of occurrence over our study period, and these keywords exhibited the following order: year > summer > spring > winter > autumn. Attention to spring, summer, and winter has decreased, especially since 2000. The interannual variation (the word "year") first increased and then decreased, according to the smooth curve (Figure S1), and the inflection point occurred in approximately 2005. In general, the downward trend of the frequency of "year" since 2005 is not as intense as those of the four seasons, and its relative importance is higher. The possible cause of this change is that the researchers may mention "year" in a study of seasonal changes, resulting in a greater frequency of the word "year." The declining trend after 2000 is less marked than those of "summer," "spring," and "winter," indicating that researchers are more concerned with interannual variability than seasonal changes, especially in recent years. On the basis of the relative importance of the word frequency of the four seasons, researchers were more concerned about summer changes than changes in other seasons, which may be related to issues during the summer growing season. For example, the problem of cyanobacteria blooms around the world occurs in the summer. The word "day" represents short-term studies, and the frequency of this term showed a decreasing trend. The results also indicated that researchers are paying increasing attention to long-term changes, which was implied by four seasons.

In terms of research objects, most of the words describe ecosystems (including ecology and hydrology) and their changes can help us to better understand the trends and characteristics of lake ecohydrology. The most obvious change is the shift from research topics on the "micro" scale to ones on the "macro" scale. For example, words that describe the biological elements of an ecosystem (algal, plankton, phytoplankton, zooplankton, benthic, chlorophyll, macrophyte, fish, etc.) and words that describe the chemical–physical elements of an ecosystem (pH, oxygen, acid, light, etc.) declined significantly (Figure S1). In contrast, words describing the macroscopic ecosystem (aquatic, community, ecology, ecosystem, freshwater, structure, etc.) increased significantly. The cause for the microrelated research decline may be due to the wider field of research, the increasing diversity of research objects, and the decreasing occurrence of popular research objects (phytoplankton, zooplankton, etc.) in recent years. A possible explanation for the increase in macrorelated words is that researchers are paying increasing attention to changes in ecosystems and are studying problems from a macroscopic perspective. Even in specific case studies, researchers are increasingly likely to study problems from a macroscopic perspective.

In addition, these commonly used words have also provided us with considerable information on lake ecohydrology. For example, phosphorus research was popular before 1999, and since then, attention to this topic has been decreasing. Meanwhile, research on nitrogen has remained stable. This change is thought provoking; on the one hand, the phosphorus cycle in the lake is a sedimentary cycle (Filippelli, 2002), and the corresponding scientific problems should be less concerning than those related to the nitrogen cycling involved in atmospheric circulation. However, because of the prevalence of the phosphorus limitation theory in lake eutrophication (Schindler et al., 2008), research on phosphorus is always more intense than that on nitrogen. More recently, a series of studies have shown that nitrogen limitation also occurs occasionally (Xu, Paerl, Qin, Zhu, & Gaoa, 2010; Xu et al., 2015), and more attention is being paid to nitrogen at present (Schindler & Hecky, 2009). This could explain why nitrogen research has been relatively stable in recent years. In addition, the increase in words such as “management,” “assess,” and “monitor” indicates that researchers are increasingly concerned with ecosystem management and ecosystem assessment. This increase also indicates that the final purpose of lake ecohydrology research involves practical applications. According to the current development trend, future popular research terms will include global change (“climate”), isotope techniques (“isotope”), biodiversity (“diversity”), and reservoir (“reservoir”) research. These words have been used frequently in recent years and are in line with people's understanding of lake ecohydrology.

From a macroscopic view, we selected four major topics of high interest, namely, eutrophication, climate warming, lake modelling, and ecosystem management, and analysed the characteristics of the research through the correlation between words. When calculating the correlation between words, we deleted some words with no practical significance and then selected the words with a correlation coefficient greater than 0.08 to ensure that the number of selected words was less than 30. Eutrophication is a major problem plaguing countries and threatening the safety of human drinking water and the health of ecosystems (Only, 1998; Paerl, Fulton, Graneli, & Turner, 2006; Qin et al., 2010). Our results show that China seems to be the most vulnerable country (Figure 3). Because algal blooms are caused by eutrophication, researchers have focused mainly on nutrients (especially phosphorus), followed by words such as “shallow,” “internal,” “macrophyte,” and “control,” which can also provide us with useful information. On the one hand, eutrophication problems mostly occur in shallow lakes, and the internal release of phosphorous from the sediment makes eutrophication treatment difficult. On the other hand, eutrophic lake control measures must also involve macrophyte restoration. In the study of climate change, the timescale has become very notable, including analyses of the present, climate change patterns in the past, and prediction of the ecological effects of climate change in the future. Additionally, there is a large amount of other related information. For example, diatoms may play the most important role in palaeoclimate reconstructions. Climate change is a common problem faced by ecosystems, and it is therefore important to study the responses of lakes and surrounding areas (including forests and catchments) to climate change. Regarding the model topic, in addition to focusing on accurate prediction, the final product should be applicable to the management of the ecosystem, so the words “management,” “ecosystem,” and “applicate” are relevant to the model topic. In the

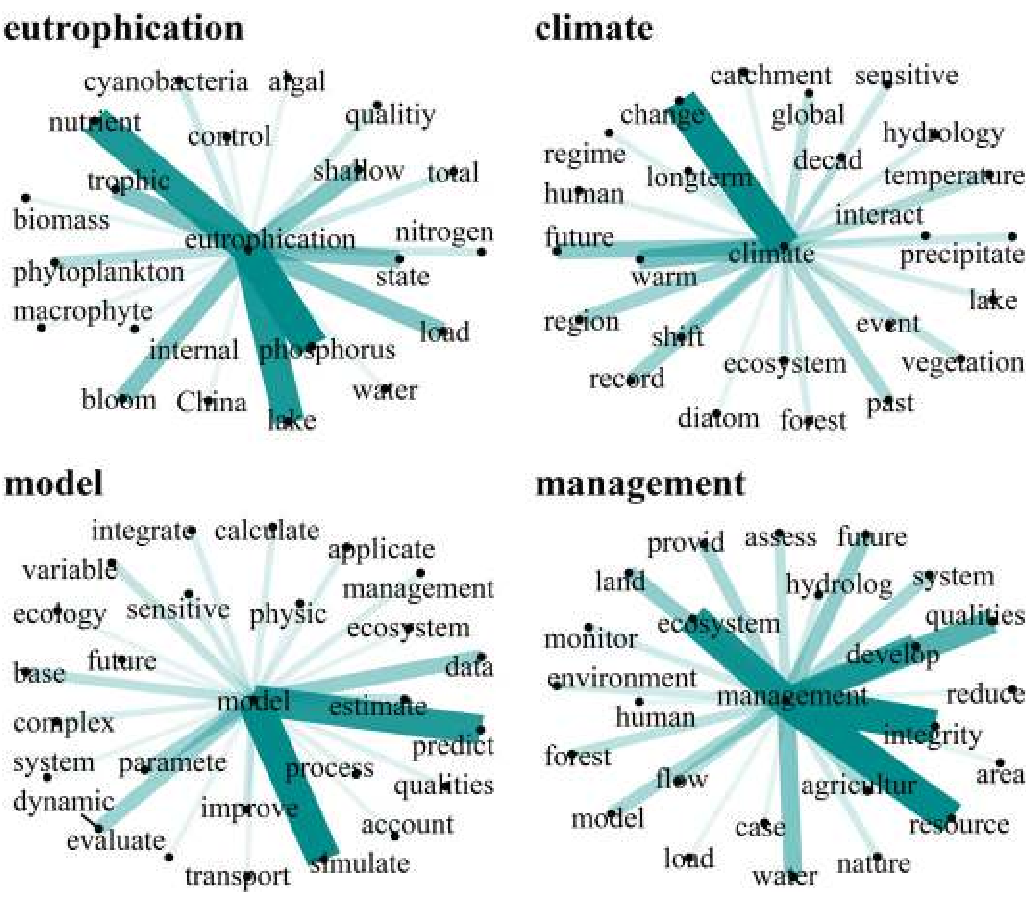

FIGURE 3 Network diagrams for words that are highly relevant to four high interest topics. (The depth of the colour and the thickness of the lines represent the strength of the correlation)

network of relations with the word "management," we can infer the following conclusions: Management of the ecosystem is associated with monitoring and assessment, ecosystem integrity is essential to ecosystem management, and the ultimate purpose of ecosystem management is to provide better services for human beings.

3.4 | Regional distribution and its characteristics

In all the publications, the abstracts of 8,010 publications mentioned lake names 9,497 times (if one lake was mentioned in the same abstract several times, it was only counted once). A total of 2,182 lake names and 332 reservoir names were mentioned. The longitude and latitude of a small percentage (approximately 10%) of the lakes were not found. In general, the studied lakes were not evenly distributed around the world (Figure 4). However, within the United States, the study objects were spread across most of the country. The comparison with the light map on the right side reveals that most of the major research areas in Europe, the United States, China, and Canada are near areas with high light intensities. On the one hand, the areas with high light intensities have high population densities, and the corresponding ecological environment problems may be more severe. On the other hand, the areas with high light intensities are also subject to more frequent human activities and are more convenient to study. The distribution of the hot spots and their relationship with human activities can be seen by combining the data on the light intensity and the number of times that the lakes were studied (Figure 4). The most studied lakes (more than 100 times) were Lake Taihu, Lake Erie, Lake Michigan, Lake Ontario, Lake Superior, Lake Baikal, Lake Kinneret, Lake Huron, and Lake Victoria. The light intensity map shows that the research hot spots are mainly distributed in the Great Lakes region between the United States and Canada and in northern Europe, Central Europe, and the downstream delta of the Yangtze River in China.

Compared with lakes, the number of reservoirs studied is relatively small, but their distribution is fundamentally similar to that of the lakes. The largest difference occurred in China. Although the quantity and frequency of lake research in China are much lower than those in Europe and North America, the quantity and frequency of reservoir research are not less than those in Europe and North America. Furthermore, because it is the world's largest dam, the Three Gorges Dam has attracted considerable attention (Wu et al., 2004), and the Three Gorges reservoir is the only reservoir discussed in more than 100 publications.

3.5 | Characteristics of lake ecohydrology in different countries/continents over time

After removing a few articles that lacked abstracts and articles published before 1990, a total of 20,987 papers were used for the PCA analysis. According to the nationality of the corresponding authors, there were 5,212 articles from the United States, 2,287 articles from China, 1,839 articles from Canada, and 6,526 articles from Europe.

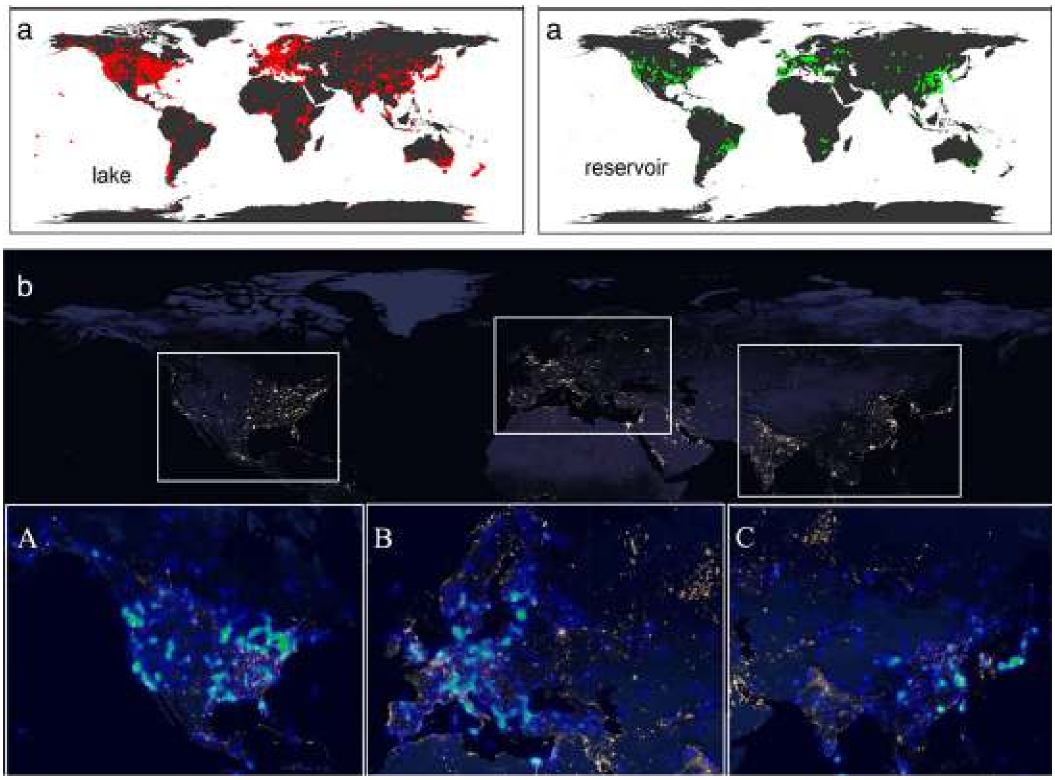

FIGURE 4 The distribution of studied lakes/reservoirs in lake ecohydrology. ([a] The distribution of lakes and reservoirs. [b] Studied lake distribution heatmap added to the night map to clearly show the relationships in North America [A], most of Europe [B], and China [C])

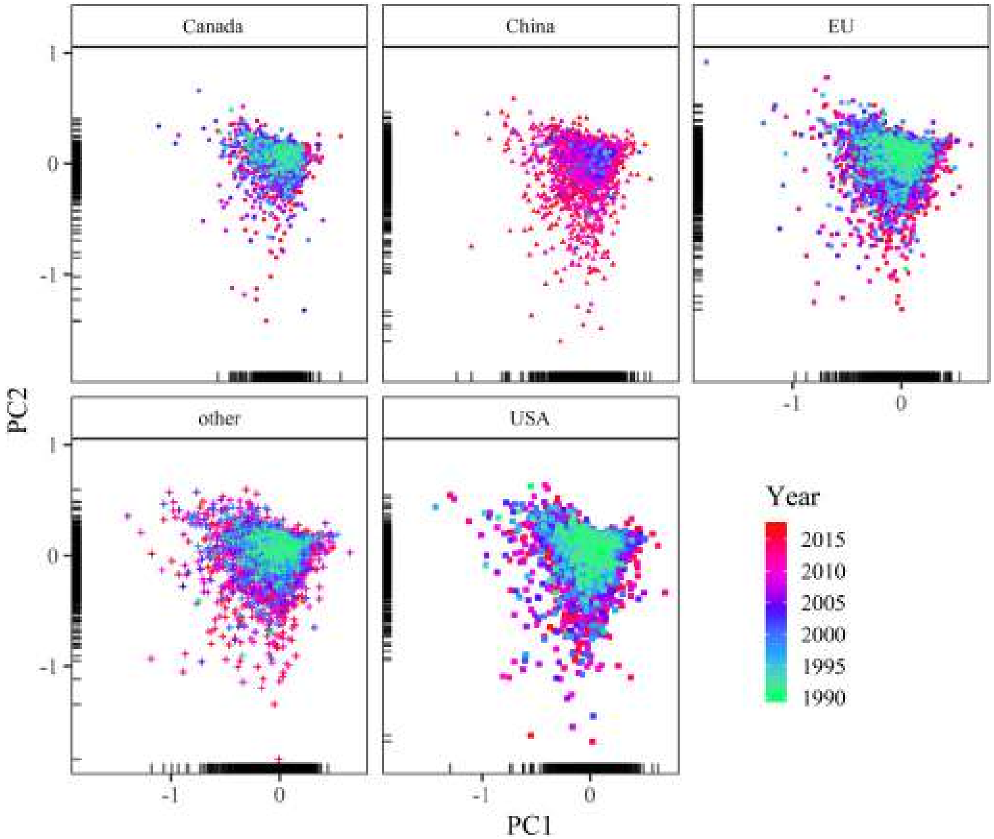

FIGURE 5 PCA scores for each country/region. The points in different years are stacked up according to the order of 2017–1990 to clearly illustrate the change over the years. The ticks on the coordinate axis represent the one-dimensional distribution of density in the last 3 years (2015–2017). PCA: principal component analysis

In the PCA analysis, the first two axes explained a total of 12.8% of the variations. The PCA score of countries/continents with more articles is illustrated (Figure 5). In the PCA analysis, each point represents an article, so we can consider the area of the PCA point distribution to be the research scope of lake ecohydrology; different colours represent the development of lake ecohydrology with time. From the PCA results, research from both the United States and Europe began in the 1990s, and the research fields are similar. Although Canada started earlier, it has been more limited in its publications than the previous two countries, and the scope of its studies is not wide. In the past few years, the field of lake ecohydrology has developed rapidly in China. In particular, in the last 3 years, its research field has become similar to that of developed countries in Europe and North America. Generally, the development of lake ecohydrology is directly related to the number of published articles. With the development of lake ecohydrology, the research field has begun to expand. Moreover, this development trajectory has no obvious difference between countries/continents. In addition to China's late start, lake ecohydrology has been expanding rapidly in the past years from 1990 to 2010 (represented by the colour change with the year in Figure 5). The red dots, which represent recent years, do not expand outwards, which indicates that the research area of lake ecohydrology has not expanded significantly in recent years. The possible reason for this phenomenon is that the research area of lake ecohydrology has been basically determined, transforming from the rapid development stage to the stable development stage. As mentioned above, although there is no recognized definition of ecohydrology, researchers have been involved in it unconsciously and are currently deeply involved in it. Lake ecohydrology research in developed countries developed earlier, and the research field of lake ecohydrology has covered all aspects before and after 2010. As a developing country, China is still experiencing the expansion of the research field of ecohydrology in recent years.

4 | CONCLUSION

Through bibliometric analysis, this paper discusses the characteristics of articles published on lake ecohydrology and the distribution characteristics of research objects (lakes and reservoirs). Text mining is used to analyse the research hot spots and trends, and the development characteristics between countries/continents are determined through PCA analysis. Our research indicates that lake ecohydrology research started in Europe, North America, and other developed countries in the 1990s and then developed rapidly. China started developing this field in the 2000s with a rapid increase in the number of articles published at a growth rate that was until recently far above the average. Lake ecohydrology studies are not evenly distributed around the world, and the distribution of research objects is strongly correlated with global night light intensity. Due to the large number of reservoirs and the high degree of attention, the number of studies on reservoirs in China is greater than that in other countries, and China contains the reservoir that has attracted the most attention, the Three Gorges reservoir. Lake ecohydrology has developed in response to global problems associated with the ecological environment and water security. Research has focused on related problems, such as eutrophication, climate change, ecosystem management, and biodiversity. With the expansion of the research scope, lake ecohydrology has gradually shifted from a microcosmic scale to a more macroscopic scale, and the temporal scale has gradually shifted from short term to long term. We also selected four major topics and discussed their research characteristics. The results of the final PCA analysis revealed that the research scope of lake ecohydrology in developed countries began to stabilize after 2010. However, the research field in China, similar to developed countries, has covered all aspects of the current development of lake ecohydrology in recent years.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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