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Review

Global Trends and Prospects of Nepheloid Layers: A Comprehensive Bibliometric Review

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Abstract: Nepheloid layers are widely distributed in the marine environment, and their formation and evolution pose many challenges to the current understanding of ocean dynamics and marine sedimentology. In sediment transport processes, nepheloid layers significantly contribute to the exchange of sediment between the continental shelf and the slope. In this paper, we summarize the global research trends on nepheloid layers. In total, 689 publications from 1990 to 2022 were collected from the Web of Science and analyzed using bibliographic software, including Bibliometrix, VOSviewer, CiteSpace, and CorText. Based on these publications, past and present popular research on nepheloid layers is examined and evaluated. The trends in nepheloid layer research are summarized by analyzing keywords, article references, countries, institutions, and authors. Finally, prospects and several key questions related to nepheloid layers are concluded, which can potentially guide future studies. The bibliographic analysis can provide new insights into the history of nepheloid layers. The results also provide valuable information for other researchers and programs investigating geological, geophysical, and biogeochemical processes.

Keywords: nepheloid layer; global trends; prospects; bibliometric; VOSviewer; CiteSpace; CorText

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1. Introduction

The nepheloid layer is a turbid water mass that contains a high suspended particulate matter (SPM) concentration in contrast to the surrounding clear water [1–3]. As far as we know, the work of Kalle [4] was the first to state the presence of turbid water layers (nepheloid layers) near the seafloor using optical scattering measurements. Ewing and Thorndike [5] were the first to call these turbid water layers "nepheloid layers" and declared that the nepheloid layer is a ubiquitous phenomenon and a remarkable feature in the marine environment. Biscaye and Eittreim [6] first converted the measurements of optical scattering data into a SPM concentration and divided the nepheloid layers into surface nepheloid layers (SNL) and bottom nepheloid layers (BNL) according to the vertical profile of the SPM concentration. Although the nepheloid layers were first discovered on the deep ocean bottom, they have also been found to appear in a variety of marine environments, including submarine canyons [7–10], continental shelves and slopes [11,12], and coastal zones [13,14]. The depths across all these locations vary substantially and, consequently, so do the intensity and dimension of nepheloid layers. In source-to-sink transport processes, nepheloid layers are considered to be the products of a sediment-diffused effect and they play a key role in the lateral transport of sediments and organic matter [2,15,16]. Understanding this connection is of interest in terms of source-to-sink transport processes of particulate matter, which may influence the sedimentology and stratigraphy [17–19], the biogeochemical cycle [20–22], and the geological cycle [23] in the marine environment.

Nepheloid layer distribution and its properties are frequently described as a spatial–temporal variation in SPM. Most in situ SPM observation data of the nepheloid layer are mainly collected by optical observation instruments, such as nephelometers, transmissometers, and light scattering sensors. The diameter of SPM particles in the nepheloid layers generally ranges from 3 to 10 μm [24], and the settling rate of SPM varies depending on the particle size [25]. The thickness of nepheloid layers is influenced by the movement of the water mass and the strength of the bottom shear stress. The SPM concentration in the nepheloid layers varies in different ocean areas; it is mostly in the range of 0.1~3.0 mg/L, but it is higher in the near-shore area, especially when close to an estuary, and it seems to be at least a factor of ten higher than that [2]. Based on observational data, nepheloid layers are typically divided into the SNL, BNL, and intermediate nepheloid layer (INL) [26]. Usually, the SPM concentration in BNLs is lower than that in SNLs and INLs, and the concentration in the BNL at the continental margin is higher than that in a deep-sea environment.

SNLs comprise a wide range of upper layers in the marine environment [27,28]. In general, SNLs are supposed to be associated with the biological activity of the surface mixed layer [12,29,30]. In situ observations and satellite imagery indicate that SNLs in the coastal zone are typically associated with river plumes [31]. Furthermore, SPM related to biological activity, also known as marine snow, is the main component in the SNLs [6]. These suspended biological particles sink at a high rate and are thought to be the main means by which organic carbon is transported to the ocean bottom [12,32]. In addition, biogeochemical rates over the surrounding water are elevated, and organisms swimming freely outside the SNLs can take advantage of the food source [33]. The properties of SNLs make them an important player in the marine food web structure and global biogeochemical cycles [13].

BNLs are a phenomenon that can be found in many deep regions of the world's oceans (see Figure 1), and they were first observed by Kalle [4]. BNLs originate from SPM in the ocean bottom mixed layer and are maintained by turbulent mixing induced by a strong bottom current [2,34,35]. The in situ observation indicates that the BNL thickness is typically between 500 and 1500 m, and has the potential to reach a 2000 m thickness in exceptional cases. The BNLs at the highest SPM concentrations are commonly found in deep regions of up to a 3000 m water depth where strong bottom currents seem to be a major factor [36–38]. Gardner and Sullivan [39] described these deep BNL events as "benthic storms". The energy associated with internal waves is an important mechanism in the periodic resuspension of bottom sediments, and also plays a part in forming nepheloid layers on the deep-sea bottom [40]. When propagating to a certain depth, internal waves may induce sufficient shear stress to resuspend bottom sediment and create BNLs and INLs [2,10,40,41]. Moreover, several studies have recognized deep-sea trawling [16,33,42] and mining [43] as significant driving forces of sediment resuspension that can overcome natural processes as an important mechanism for BNL formation. Additionally, several studies indicated that the concentrations of BNLs found in the southern Indian and Atlantic oceans are very similar to the broad Antarctic bottom water (AABW) patterns, possibly implying the contribution of SPM carried by ocean circulation to BNL formation [6,36]. At the continental margins, contour currents run parallel to the slopes. Their counterparts, i.e., turbidity currents, which are usually caused by a submarine landslide (or mass movement), follow perpendicular paths to the outer-shelf margins. Both currents visibly contribute to BNL formation at continental margins [44].

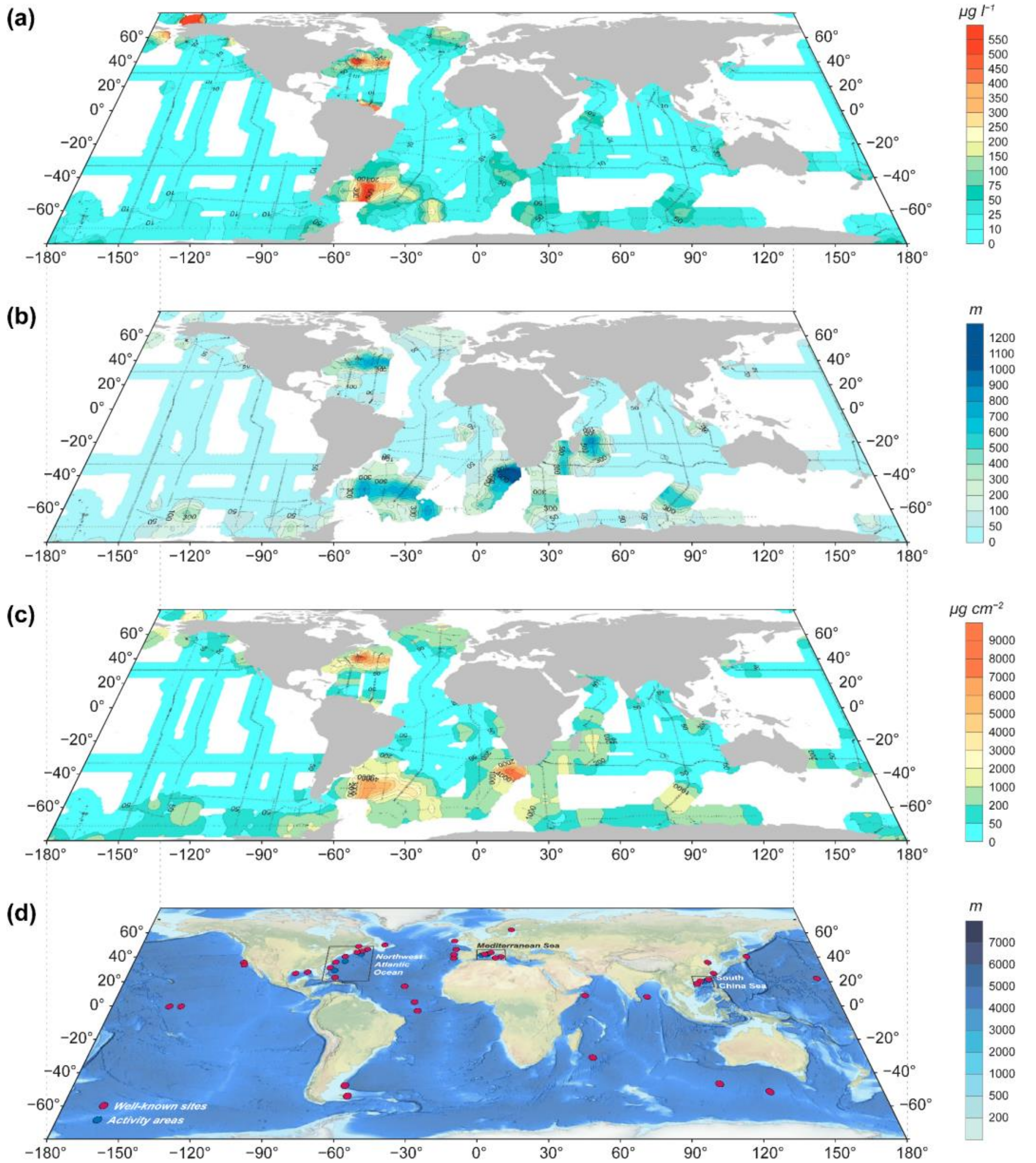


Figure 1. Global assessment and comparison of nepheloid layers based on vertical profiles of beam attenuation c_p data measurements from transmissometers. (**a**) Average SPM concentration in the bottom 10 m of each profile. (**b**) The strong nepheloid layer (>20 μg L^{-1}) thickness; scale changes at 100 m thickness. (**c**) SPM load in the strong nepheloid layers (>20 μg L^{-1}); scale changes between 0 and 1000 μg cm^{-2}. (**d**) The observed global nepheloid layers (1953–2019) and the map of global bathymetry. The well-known sites are those where nepheloid layers have been identified before and where their properties have been thoroughly described. The activity areas are places where nepheloid layer activity has been noted; however, the features are unknown. To show more precise information, scales are not linear. Panels (**a**–**c**) are adapted from Gardner, et al. [45] with permission from Elsevier, and panel (**d**) is adapted from Tian, et al. [46].

The INLs are typically found to be associated with a strong density front near the continental shelf, upper slope, or deep continental margin, where strong BNLs exist [27]. The majority of INLs are created from BNL detachment and lateral spreading near the shelf break. Particles move laterally over great distances in these processes from the shelf to the slope and deep basin [47] and effectively transport SPM laterally to the deep-sea basin [2,3,28,29,48]. INLs settle over a wide area, resulting in sediment being deposited far from its source [3,40,48–50]. There is evidence that the lateral transport of INLs on continental shelves and slopes has a greater impact on the abyssal sediment compared to the direct vertical settling of SPM from the upper layer [51,52]. The composition of the material in the nepheloid layers can determine its origin, transport pathways, and geochemical changes [49].

Since 1937, in situ observations and theoretical research related to nepheloid layers have been developed along with new technologies, and there have been many studies involving different research areas such as physical oceanography, marine geology, ocean chemistry, etc. Recently, numerous studies have reviewed the findings on nepheloid layers [46,53], but comprehensive reviews of the global evolutionary trends in this research field are lacking. One of the most useful tools for quantitative and qualitative evaluations of academic publications is a bibliometric analysis [54], which combines statistical and mathematical methodologies to track the developing states of research fields [55,56]. By analyzing the influence or value of research achievements, bibliometric analysis provides academics with the chance to identify fresh issues and paths for a scientific inquiry [57,58]. In order to undertake a comprehensive evaluation of the research field and comprehend the progress, frontiers, and trends of the research on nepheloid layers, a bibliometric analysis was conducted in this study. Additional understandings of current research interests and potential prospects for future study were also gleaned from these findings. The remaining sections of this bibliometric analysis are structured as follows: In Section 2, we briefly describes the bibliometric tools and the analysis methods used in this paper. In Section 3, we describe the statistical analysis of the data gathered, as well as the network and evolution analyses. Finally, we summarize the conclusions and provide potential future research directions in Section 4.

2. Material and Methods

2.1. Data Source and Bibliometric Tools

The Web of Science Core Collection database, one of the most extensively used databases, covers a significant number of papers published from 1990 to the present and provides scientific output data for bibliometric analysis [59]. The software employed in this study for bibliometric analysis and science mapping of obtained data included Bibliometrix (R language, version 4.2.2 and R studio, version 2022.12), VOSviewer (version 1.6.19), CiteSpace (version 6.1.R6), and CorText. Specifically, Bibliometrix was mainly used for collaboration analysis; VOSviewer was used for keyword analysis, cited document analysis, author co-citation analysis, and co-occurrence analysis; CiteSpace was used for analysis of the keywords with the strongest citation bursts; and CorText was used for keyword, research area, and journal analysis.

2.2. Data Collection and Search Criteria

We retrieved data for this study on 7 February 2023 using the search function of Web of Science set from 1990 to 2022. The search options were selected before using the search function: database—"Web of Science Core Collection"; topics—("nepheloid*") OR ("nepheloid layer*") OR (("turbid layer*" OR "cloudy layer*") AND ("marine" OR "ocean" OR "river")). The publications unrelated to nepheloid layers were then removed using a manual filter based on article content. A total of 689 publications were determined for analysis, including "articles," "reviews," and "proceeding papers" (Figure 2).

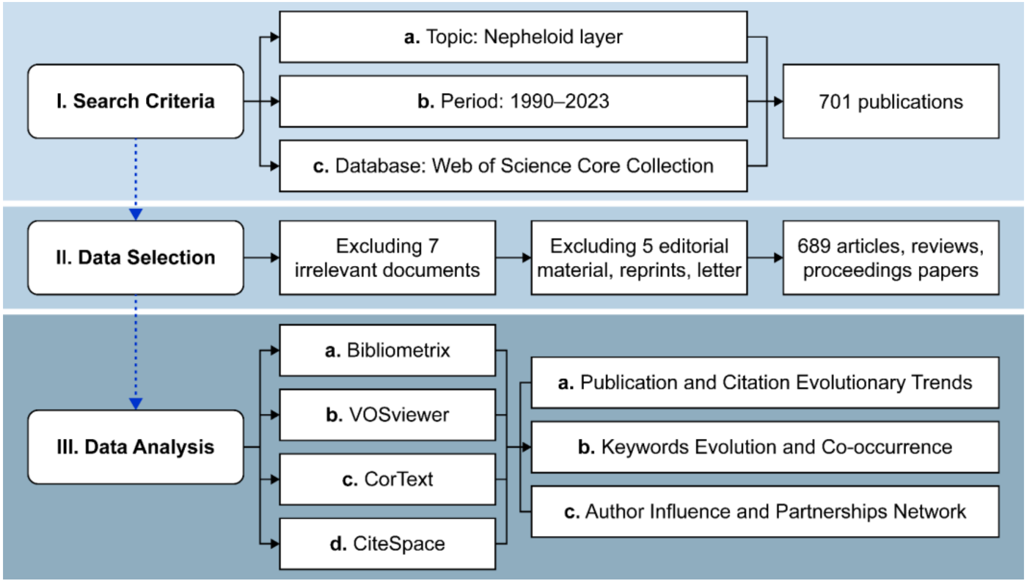


Figure 2. Paper selection process and flow chart framework for the bibliometric analysis using Web of Science.

2.3. Data Analysis and Evaluation Metrics

Keyword analysis was selected to identify keywords of nepheloid layer research in this study. VOSviewer was used to extract keyword data from titles, abstracts, and author keywords of publications, and to create the data files needed for the keyword analysis. With the use of the impact factor (IF), H-index, number of citations, and number of publication indexes, the academic impact of nepheloid layer research was assessed. The IF is a global academic index used to rank journals [60]. The H-index was chosen to evaluate the academic impact of nepheloid layer research in terms of journals, countries, institutions, and authors. This is defined as the number of articles co-authored by the researcher with at least H citations each [61]. The number of citations was used in this study to evaluate the significance of highly cited articles.

The formulas for computing the H-index [61] and IF [62] have been published in earlier works. Journal Citation Reports, which is offered by the Web of Science, was used to determine the IF, number of citations, and number of publications of the journals. The Web of Science Core Collection database's document information was used to calculate the H-index for journals, countries, institutions, and scholars.

3. Results and Discussion

3.1. Publication and Citation Evolutionary Trends Analysis

3.1.1. Temporal and Spatial Distribution of Publications

The number of publications can, in part, predict future development trends. We identified 689 publications in the Web of Science Core Collection database on nepheloid layers that met our criteria, published from the year 1990 through to 2022. There has been a gradual upward trend in the annual number of publications, from 8 publications in 1990 to 25 publications in 2022 (Figure 3a), and a peak was reached in 2015 (31 publications); thus, there was a 3.62% yearly growth rate. In particular, the number of publications per year showed a significant increase from 2011 to 2015. Three distinct periods make up the evolutionary patterns of publications. The first period was from 1990 to 1996, and was a time when publications on nepheloid layers rapidly increased but also fluctuated greatly, thus reflecting the fact that nepheloid layer research was in its adolescence. The second era was from 1996 to 2011 when there was a marked increase in publications, showing that nepheloid layer research was progressing. However, after 2002, although the number of publications remained high, the overall trend began to decline until 2011. The third period was from 2011 to 2022, during which the number of publications showed a significant increase again. In particular, 2015 witnessed 35 publications, the highest of any year in 1990–2022, thus indicating that the research on nepheloid layers was in a rapidly growing stage during this period. There have been 144 articles published in the last five years, accounting for 20.90% of all publications on nepheloid layers, which points to the topic as a thriving research trend.

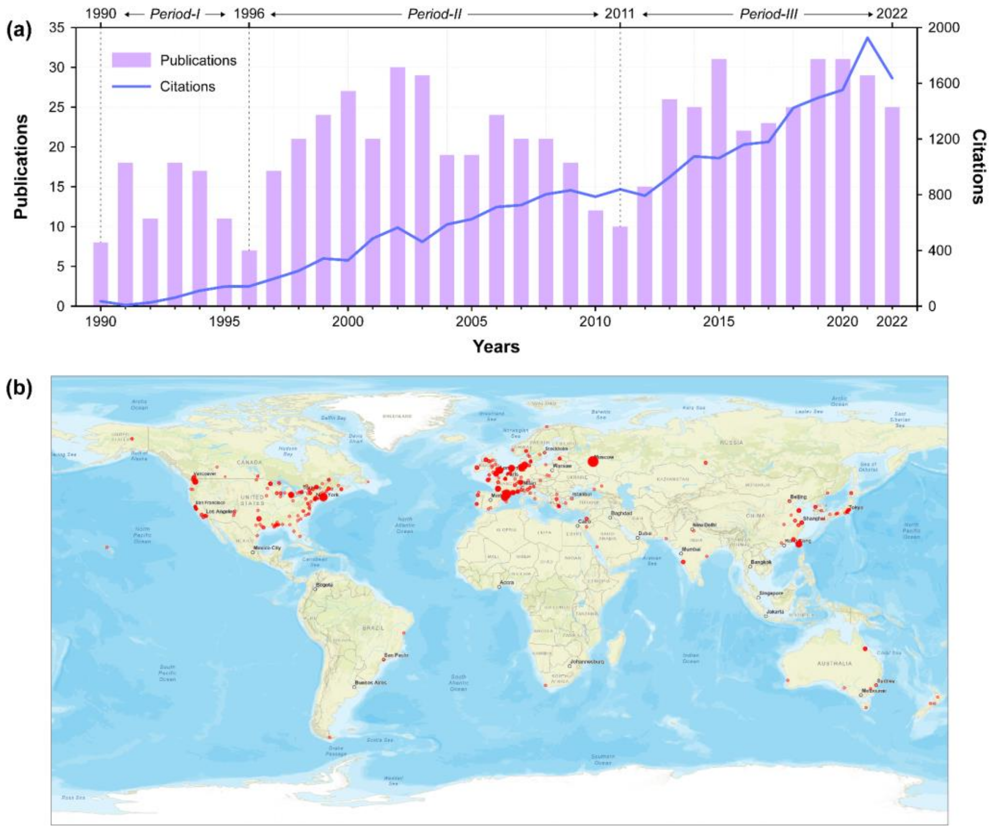


Figure 3. Spatiotemporal distribution of nepheloid layer research from 1990 to 2022. (**a**) Temporal trends of the annual number of publications and citations found in Web of Science Core Collection. (**b**) Geographical distributions of all institutions contributing to publications related to nepheloid layers. The size of the red circles reflects how many publications each institution has produced.

Bibliometrix was used (Figure 3a) to show the annual citations of publications. The most citations were made in 2021. A total of 29 papers were published in 2021, with each paper receiving an average of 66.41 citations. The overall trend of increasing citations in this field demonstrates that more academics have been paying attention to this topic recently.

The affiliations of the authors were extracted from the database, and the cities where the institutions are located were extracted for each affiliation to analyze the geographical distributions of the publications (Figure 3b). Nepheloid layer research has been carried out on every continent excluding Antarctica. By 2022, 708 institutions had been involved in the study of nepheloid layers. The eastern United States and Europe have higher densities of contributing institutions. The Centre National De La Recherche Scientifique (CNRS) in France produced the most publications (74 publications), followed by the UDICE-French Research Universities in France (60 publications), and the Helmholtz Association in Germany (50 publications) (shown in Table 1). Overall, the geographical spread of these institutions shows that nepheloid layer research has attracted organizations and research centers from around the globe.

Table 1. Top 10 institutions with the most publications related to nepheloid layers from 1990 to 2022.

Rank	Institution	Country	Number of Publications	Proportion of Publications (%)	H-Index
1	Centre National De La Recherche Scientifique (CNRS)	France	74	10.663	34
2	UDICE-French Research Universities	France	60	8.646	32
3	Helmholtz Association	Germany	50	7.205	27
4	University of California	United States	38	5.476	24
5	Woods Hole Oceanographic Institution	United States	38	5.476	20
6	Utrecht University	Netherlands	37	5.331	24
7	Russian Academy of Sciences	Russia	37	5.331	7
8	Netherlands Institute for Sea Research (NIOZ)	Netherlands	35	5.043	24
9	Texas A&M University	United States	35	5.043	22
10	Consejo Superior de Investigaciones Cientificas (CSIC)	Spain	34	4.899	19
11	Shirshov Institute of Oceanology (IO RAS)	Russia	33	4.755	6
12	University of Washington	United States	31	4.467	23
13	National Institute for Earth Sciences Astronomy (INSU)	France	31	4.467	21
14	National Oceanic and Atmospheric Administration (NOAA)	United States	29	4.179	16
15	Universite of Perpignan	France	28	4.035	18

3.1.2. Evolution of Research Areas and Sources of Publications

The analysis of research areas is a potent method for identifying the knowledge gaps. Nepheloid layer research has been published in 34 research areas, and the top 15 research areas are listed in Table 2. The bibliometric analysis showed that the publications are now linked to a variety of research areas, such as Oceanography (59.94%); Geosciences Multidisciplinary (25.21%); Marine Freshwater Biology (15.42%); Environmental Sciences (10.37%); and Geochemistry and Geophysics (6.34%) (Table 1). Oceanography was the most popular area, with 416 publications. With 175 and 107 publications, Geosciences Multidisciplinary and Marine Freshwater Biology took second and third place, respectively. This fact indicates that research on nepheloid layers encompasses several areas, and hence has multidisciplinary and interdisciplinary characteristics.

Table 2. Top 15 research areas from 1990 to 2022 with the most publications on nepheloid layers.

Rank	Research Areas	Number of Publications	Proportion of Publications (%) *
1	Oceanography	416	59.94
2	Geosciences Multidisciplinary	175	25.21
3	Marine Freshwater Biology	107	15.42
4	Environmental Sciences	72	10.37
5	Geochemistry and Geophysics	44	6.34
6	Limnology	44	6.34
7	Chemistry Multidisciplinary	27	3.89
8	Meteorology Atmospheric Sciences	24	3.46
9	Paleontology	24	3.46
10	Geography Physical	20	2.88
11	Multidisciplinary Sciences	20	2.88
12	Water Resources	16	2.31
13	Physics Fluids Plasmas	15	2.16
14	Mechanics	11	1.59
15	Fisheries	10	1.44

Note: * the same publication may belong to more than one research area.

From 1990 to 2022, 689 articles about nepheloid layers were published in 173 journals, with the top 15 journals accounting for 54.77% of all publications (Table 3). With 61 approved publications, *Marine Geology* was the most productive journal and had the highest H-index (416). *Deep-Sea Research Part II-Topical Studies in Oceanography* and *Continental Shelf Research* ranked second and third and had the same number of publications (48), but *Deep-Sea Research Part II-Topical Studies in Oceanography* had a relatively high H-index of 175. *Geochimica et Cosmochimica Acta* ranked 15th, although it had the highest IF value of 5.921.

Table 3. Top 15 publication sources related to nepheloid layers with the highest H-index from 1990 to 2022.

Rank	Publication Sources	H-Index	IF	Number of Citations	Publish Year Started	Number of Publications	Proportion of Publications (%) *
1	Mar. Geol.	416	3.627	2779	1991	61	8.79
2	Deep-Sea Res. Part II-Top. Stud. Oceanogr.	175	2.887	2217	1993	48	6.92
3	Cont. Shelf Res.	107	2.629	1963	1990	48	6.92
4	Deep-Sea Res. Part I-Oceanogr. Res. Pap.	72	3.101	1630	1994	42	6.05
5	Prog. Oceanogr.	44	4.416	1244	1992	36	5.19
6	J. Geophys. Res.-Oceans	44	3.938	918	1993	33	4.76
7	Mar. Chem.	27	3.994	567	1991	22	0.29
8	J. Mar. Syst.	24	3.010	806	1992	23	3.31
9	Limnol. Oceanogr.	24	5.019	1201	1993	15	2.16
10	Earth Planet. Sci. Lett.	20	5.785	524	1992	11	1.59
11	J. Gt. Lakes Res.	20	3.032	402	1991	22	3.17
12	Biogeosciences	16	5.092	272	2007	15	2.16
13	Paleoceanography	15	3.313	956	1993	8	1.15
14	Estuar. Coast. Shelf Sci.	11	3.229	341	1993	9	1.30
15	Geochim. Cosmochim. Acta	10	5.921	528	1991	7	1.01

Note: * that the same publication may belong to more than one research area.

Figure 4a displays specific information about the yearly growth trends in the related research areas. Between 1990 and 1996, Oceanography was in a development phase, and after 1996, its trend significantly increased. The development trends of nepheloid layer research in Geosciences Multidisciplinary and Marine Freshwater Biology have increased in recent years. At present, the research on nepheloid layers is focused on three major areas: Oceanography, Geosciences Multidisciplinary, and Marine Freshwater Biology.

The majority of the top 20 productive journals showed consistent increases in the number of publications (Figure 4b). In particular, *Marine Geology*, *Continental Shelf Research*, and *Journal of Great Lakes Research* maintained consistently high publication numbers in Period 1, while the other journals entered a stage of growth in publication numbers in Period 2 or Period 3. The publications on nepheloid layers from *Continental Shelf Research* covered all years from 1990 to 2022, whereas *Marine Geology* is currently the fastest-growing journal in terms of annual publication numbers.

3.1.3. Most Cited Publication Analysis and Co-Citation Reference

The number of citations is an important reflection of the impact and attention received by a publication thus far. The top publication was published by McCave, et al. [63], with a total of 446 citations (Table 4). Their research on fine sediment size via repeated size measurement studies was thoroughly presented in this paper. They found a boundary of sediment size at 10 μm. Fine sediment showed noncohesive behavior when their diameters were larger than 10 μm, and showed cohesive behavior when their diameters were smaller than that. The results provided a basis for establishing models of fine sediment and supported further marine investigations; thus, the paper has been increasingly cited. The top five most cited publications regarding research content included two reviews that were published ten years ago. One review [64] was written about measuring the flux of sediment using Th-230. The other [35] was a review of bio-affected resuspension and deposition, which is related to nepheloid development. Among the three research articles, particles were gathered or used for different analyses. The particle size was statistically analyzed by McCave, et al. [63]. Bruland, et al. [65] detected trace metals in the stratified central north Pacific to study the structure and composition changes of nepheloid layers. Babin, et al. [66] focused on light scattering that was affected by marine particles to describe the profile of nepheloid layers. We found that among the articles in Table 4, the proportion of publications in which authors come from different countries is four-fifths. This transnational cooperation can effectively promote communication between countries and produce high-quality publications.

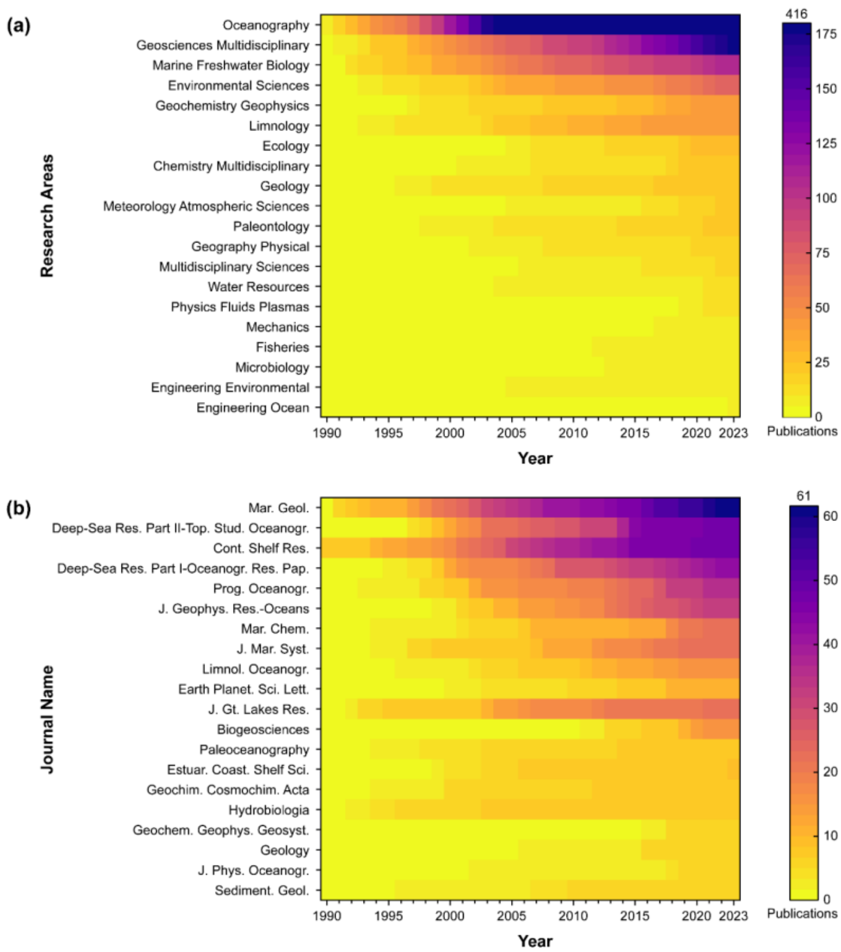


Figure 4. Research areas and sources of publication analysis of nepheloid layer research from 1990 to 2022. (**a**) The top 20 most productive research areas' annual evolutionary trends. (**b**) The top 20 most productive journals' annual evolutionary trends.

We then created a co-citation reference analysis map with VOSviewer. Figure 5a shows the three major clusters that make up the nepheloid layer research's cognitive structure. The cluster method is based on hybrid networks of co-cited articles, citing words and noun phrases from these articles. Publications concentrating on resuspension, sediment traps, and suspended particular matter are in the green cluster. Documents on bottom nepheloid layers, transmissometers, and submarine canyons are in the red cluster. Research articles dealing with internal waves, continental slope, and sedimentation are in the blue cluster. Other publications belonging to clusters about lakes, turbidity, and particles are in the yellow cluster. These four clusters are quite similar to those that the author co-citation analysis revealed. Research on nepheloid layers is always related to sediment, and particles are shown in each cluster as a key research object. The largest dot in Figure 5a, which represents the McCave [2] article published in 1986, exhibits how the article has the greatest influence and has connections to all four topical clusters.

Table 4. Top 10 highly cited publications related to nepheloid layers from 1990 to 2022.

Rank	Title	Authors	Year	Source	Citations
1	Sortable silt and fine sediment size/composition slicing-parameters for paleocurrent speed and paleoceanography	Mccave, I. N., Manighetti, B., Robinson, S. G.	1995	Paleoceanography	445
2	Light scattering properties of marine particles in coastal and open ocean waters as related to the particle mass concentration	Babin, M., Morel, A., Fournier-Sicre, V., et al.	2003	Limnol. Oceanogr.	435
3	Reactive trace-metals in the stratified central north pacific	Bruland, K. W., Orians, K. J., Cowen, J. P.	1994	Geochim. Cosmochim. Acta	300
4	Th-230 normalization: An essential tool for interpreting sedimentary fluxes during the late Quaternary	Francois, R., Frank, M., Van Der Loeff, M. M. R., et al.	2004	Paleoceanography	246
5	Bioresuspension and biodeposition: A review	Graf, G., Rosenberg, R.	1997	J. Mar. Syst.	233
6	Sediment trap fluxes and benthic recycling of organic-carbon, polycyclic aromatic-hydrocarbons, and polychlorobiphenyl congeners in lake-superior	Baker, J. E., Eisenreich, S. J., Eadie, B. J.	1991	Environ. Sci. Technol.	224
7	The oxygen minimum zone in the Arabian Sea during 1995	Morrison, J. M., Codispoti, L. A., Smith, S. L., et al.	1999	Deep-Sea Res. Part II-Top. Stud. Oceanogr.	212
8	Hydrodynamic controls on cold-water coral growth and carbonate-mound development at the SW and SE Rockall Trough Margin, Ne Atlantic Ocean	Mienis, F., De Stigter, H. C., White, M., et al.	2007	Deep-Sea Res. Part I-Oceanogr. Res. Pap.	195
9	Internal waves, an under-explored source of turbulence events in the sedimentary record	Pomar, L., Morsilli, M., Hallock, P., et al.	2012	Earth-Sci. Rev.	186
10	The distribution of Fe in the Antarctic Circumpolar Current	Loscher, B. M., Debaar, H. J. W., Dejong, J. T. M., et al.	1997	Deep-Sea Res. Part II-Top. Stud. Oceanogr.	175

The author co-citation map is composed of six coherent and separate but related groups (Figure 5b). The blue and green groups are the most effective clusters on the map. Academics that have concentrated their research on McCave [50,63], Hollister [67,68], Richardson [69,70], and Ewing [5], make up the blue cluster. Research associated with this cluster paid attention to benthic storms, benthic nepheloid layers, and the southwest Pacific. Academics who have studied organic carbon, benthic nepheloid layers, and particulate matter make up the green cluster. The core authors of this group mainly include Gardner [39,41], Thomsen [71], Berger [72], and Baker [73,74].

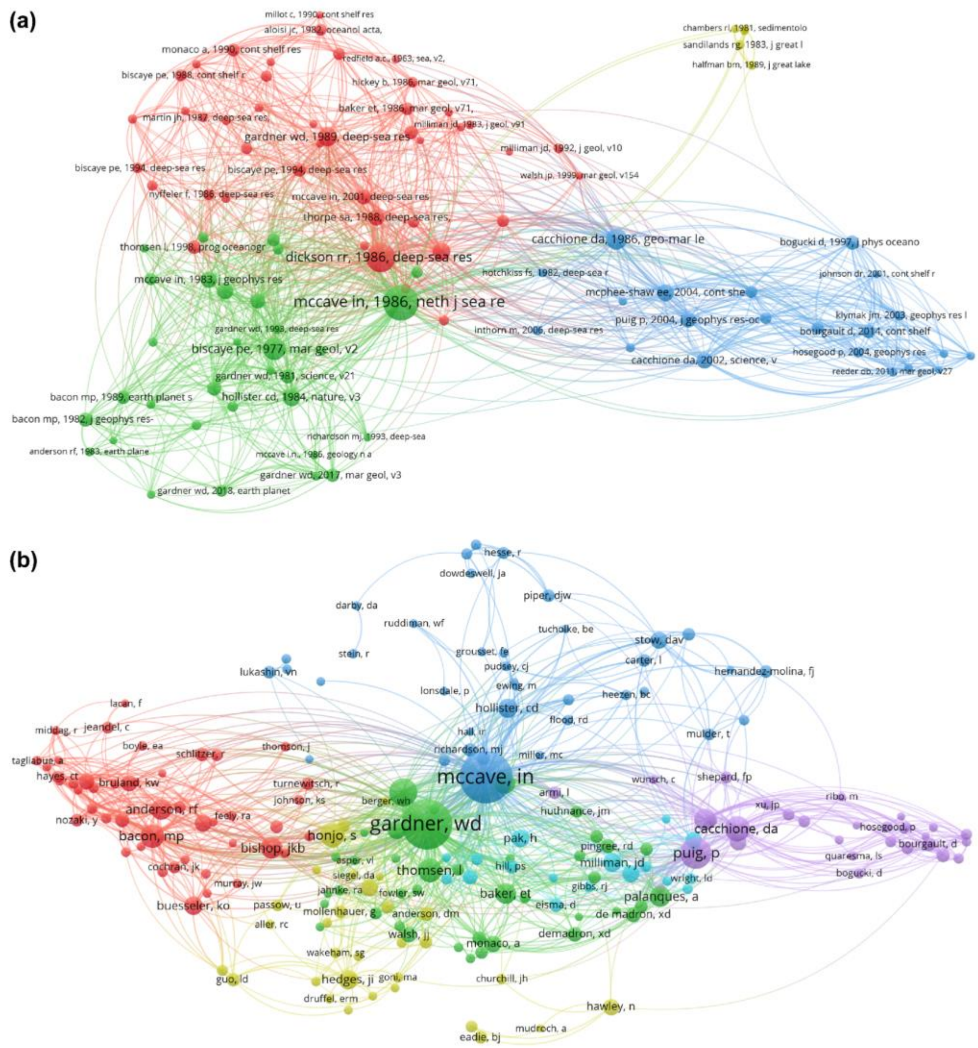


Figure 5. Co-citation reference analysis of the publications related to nepheloid layers from 1990 to 2022. (**a**) Publication co-citation analysis (threshold 15 co-citations, 27,062 cited references in the network; here, 101 publications with the strongest connection displayed). (**b**) Author co-citation analysis (threshold 25 co-citations, 2199 cited authors in the network; here, 204 authors with the strongest connection displayed).

3.2. Keywords Evolution and Co-Occurrence Analysis

3.2.1. Keyword Timeline Evolution Analysis

Figure 6 depicts the bump graph (a variant of a line graph showing the rank of keyword occurrence) of the combined 689 nepheloid layer publications. The keyword nepheloid layers almost occupies the most important position in all periods. Sediment transport became the most-used keyword from 1996 to 1998, and still maintains a high occurrence frequency in other periods, which is similar to the keyword resuspension. Only introduced in 2010, the keyword geotrace has rapidly increased in use since then. Organic matter has been intensively investigated since 1992, but from 2013 to 2022, its use in studies gradually increased after a decline in 2001. It should be mentioned that the popularity of submarine canyons suddenly increased from 2008 to 2012. Studies on this keyword have been maintained from 2012 to 2022.

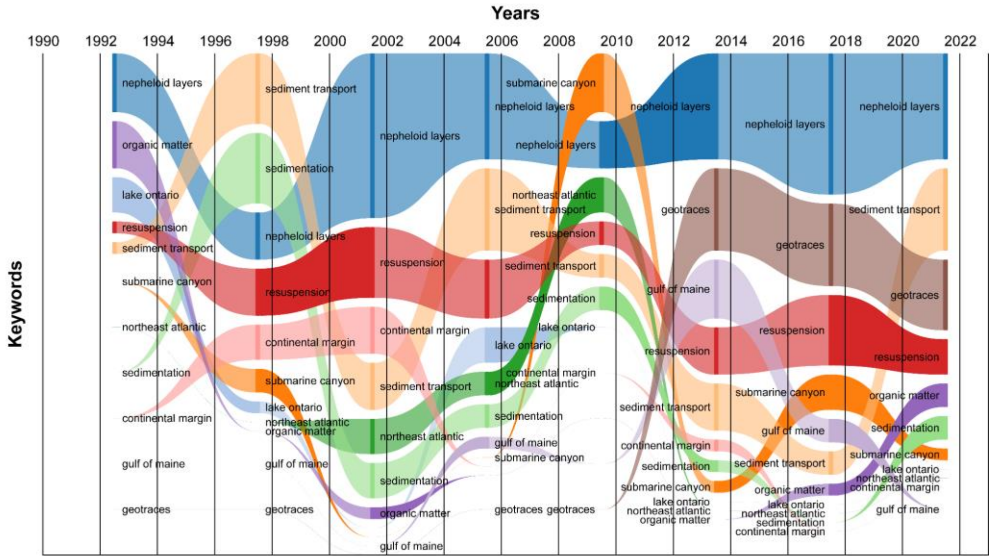


Figure 6. Top three keywords for every two years, tracking dramatic changes from 1990 to 2022. A bump graph shows the keyword's evolution of frequency and ranking through time. The tube width depicts the average frequency of the keywords in the abstract, title, and paper.

3.2.2. Keyword Burst Detection Analysis

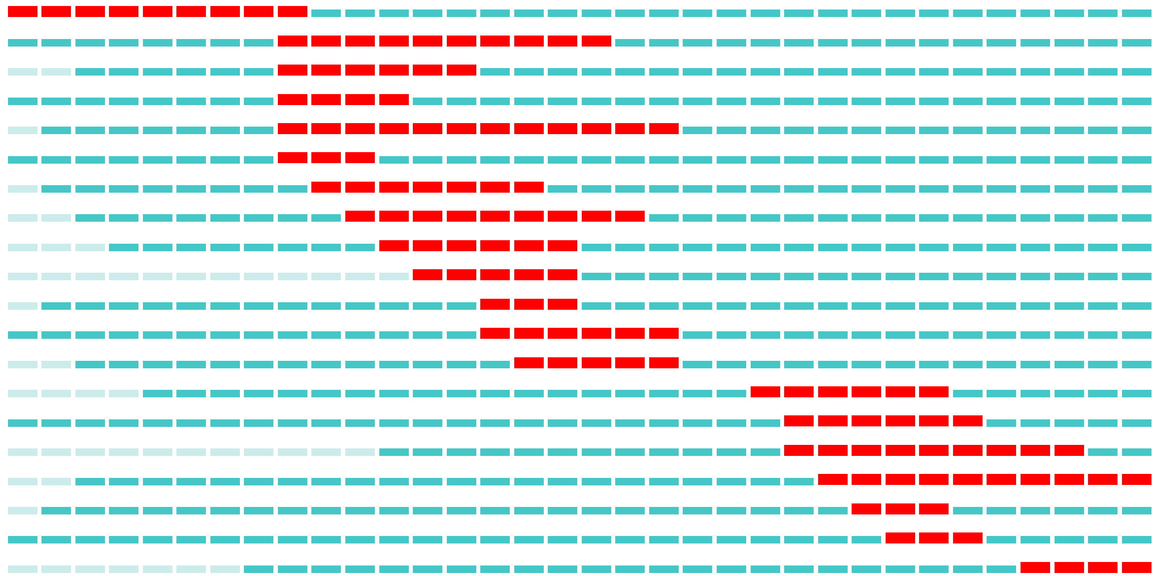
The 20 burst keywords were found by constructing a keyword co-occurrence network for nepheloid layer research from 1990 to 2022 (Table 5). This network was completed with the CiteSpace software. In total, 689 publications were divided into two-year time slices. The software extracted the top 15 keywords with the highest occurrence frequency from every slice. For example, "continental margin" was popularly studied from 1998 to 2007, with more than six times the occurrence of other words. The first term cited was "particle" (3.58), which was targeted over 8 years (1990–1998) based on chronological order. There were five keywords after it: "sediment" (1998–2007), "continental margin" (1998–2003), "ocean" (1998–2001), "transport" (1998–2009), and "shelf" (1998–2000). The terms "sediment resuspension" and "benthic nepheloid layer" have received attention recently as the studies in this field have become more in-depth.

3.2.3. Keyword Co-Occurrence Analysis

Figure 7a shows a cluster visualization map of the keywords, with the current investigation revealing five clusters. According to cluster 1, the core keyword with the highest occurrence was nepheloid layers. Sediment resuspension and suspended particles indicate the main research direction. Benthic and bottom boundary layers, deep sea, and ocean-indicated studies in cluster 1 focused on sediment activities near the seabed in the deep sea. The main research regions included the Aegean Sea, Baltic Sea, Gulf of Lions, Gulf of Mexico, and the Mediterranean Sea. Cluster 2 mainly focused on the observation of nepheloid layers in areas of submarine canyons and continental slopes. Observation content included contourites, sediment dynamics, turbidite, and water masses in the north Atlantic, Bay of Biscay, Barents Sea, and northern South China Sea. Cluster 3 was the classification for organic carbon-related keywords. Marine snow, diatoms, and cysts indicated that the cluster contained more studies than other clusters related to biology and chemistry. Cluster 4, which concentrated on sediment resuspension, was closely related to the carbon cycle. Cluster 5 included studies on continental shelves and margins. Relative keywords included intermediate nepheloid, particle size, salinity, river plume, internal tides, transmissometer, and POC.

Table 5. Top 20 keywords with the strongest citation bursts. The strength reflects how many times the keyword occurs more frequently than other words. The colored line reflects the data on the left. The red bar marks the beginning and end year of a burst keyword. The pale turquoise bar reflects the period in which the keyword had not been used or focused. The dark turquoise bar means the keyword was not burst in that period.

Keywords	Year	Strength	Begin	End	1990–2022
particle	1990	3.58	1990	1998	
sediment	1990	10.76	1998	2007	
continental margin	1992	8.38	1998	2003	
ocean	1990	7.05	1998	2001	
transport	1991	6.41	1998	2009	
shelf	1990	4.65	1998	2000	
carbon	1991	4.99	1999	2005	
benthic boundary layer	1992	4.97	2000	2008	
suspended sediment	1993	4.56	2001	2006	
lateral transport	2002	3.72	2002	2006	
resuspension	1991	3.95	2004	2006	
suspended particulate matter	1990	3.57	2004	2009	
variability	1992	4.66	2005	2009	
current	1994	4.1	2012	2017	
submarine canyon	1990	8.19	2013	2018	
internal wave	2001	5.33	2013	2021	
sediment resuspension	1992	9.24	2014	2022	
organic matter	1991	4.77	2015	2017	
organic carbon	1990	3.93	2016	2018	
benthic nepheloid layer	1997	3.96	2020	2022	



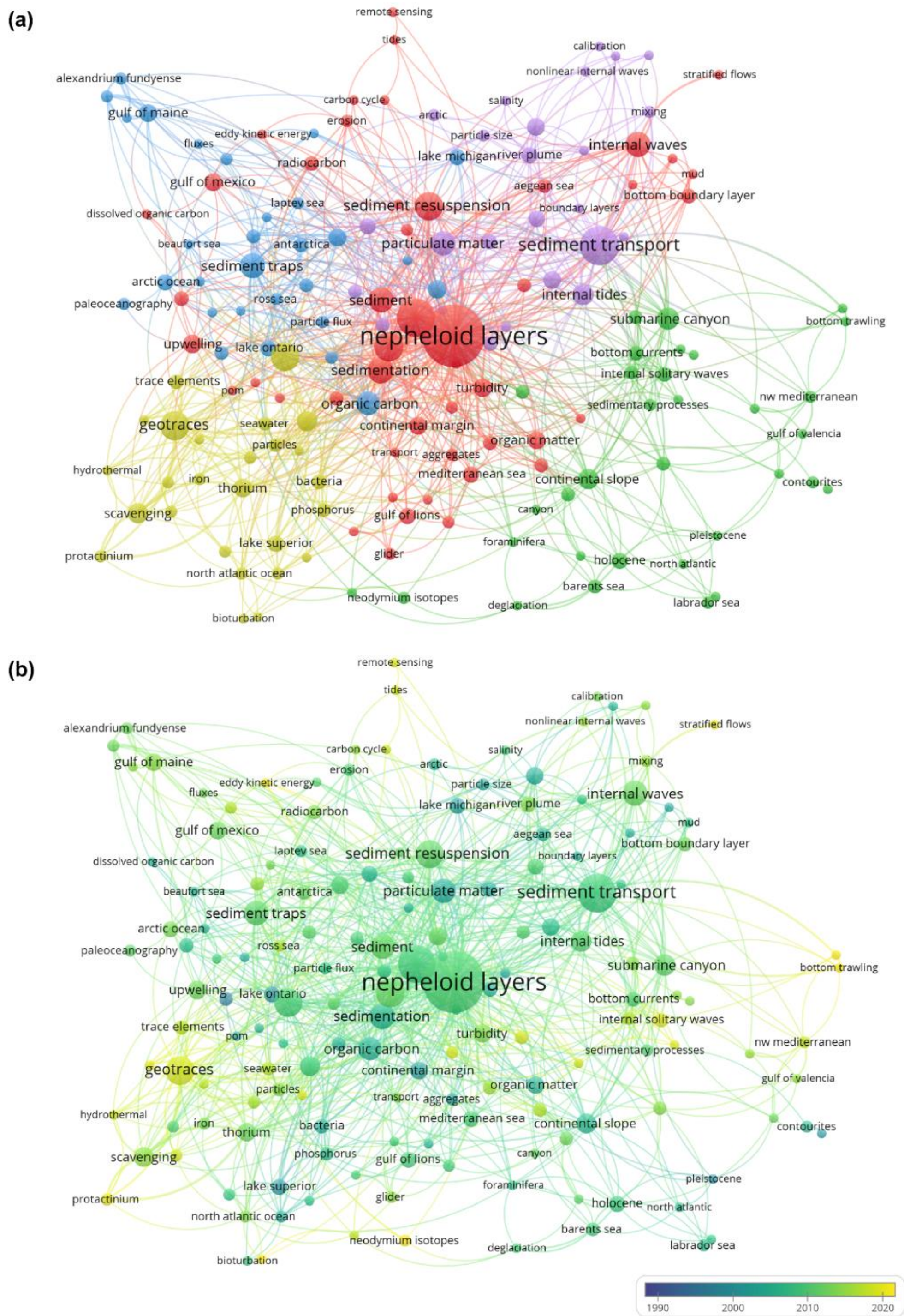


Figure 7. Keyword co-occurrence analysis for nepheloid layer research from 1990 to 2022. (**a**) Co-occurrence network of keywords. Different clusters can be identified by their nodes' colors. (**b**) Time distribution of keyword co-occurrence network. The brighter yellow color on a node indicates a later keyword appearance, while the darker purple color on a node suggests an earlier keyword appearance. The size of the node represents the frequency of keywords.

The VOSviewer was used to illustrate the time distribution of keyword co-occurrence from 1990 to 2022, as shown in Figure 7b. During this period, scholars mainly focused on exploring sediment transport and resuspension. The research on the observation of in situ nepheloid layers has gradually evolved into more practical subjects, providing sustainable development for sediment transport and marine geology in the future. Currently, researchers are working on approaches to explore geotraces and internal solitary waves.

The keyword nepheloid layers, which is in the middle of the map, had the highest density of the keywords (Figure 8). Sediment, turbidity, and sediment trap are all closely related to it. Additionally, several developing keywords with high densities and centers that were close to nepheloid layers were sediment movement, geotrace, and internal waves. Geology and oceanology keywords, such as seawater and particle, had a higher density than those of chemistry and biology, such as cysts and bioturbation. There were many keywords related to sea and ocean regions, revealing that research on marine nepheloid layers is being carried out all over the world.

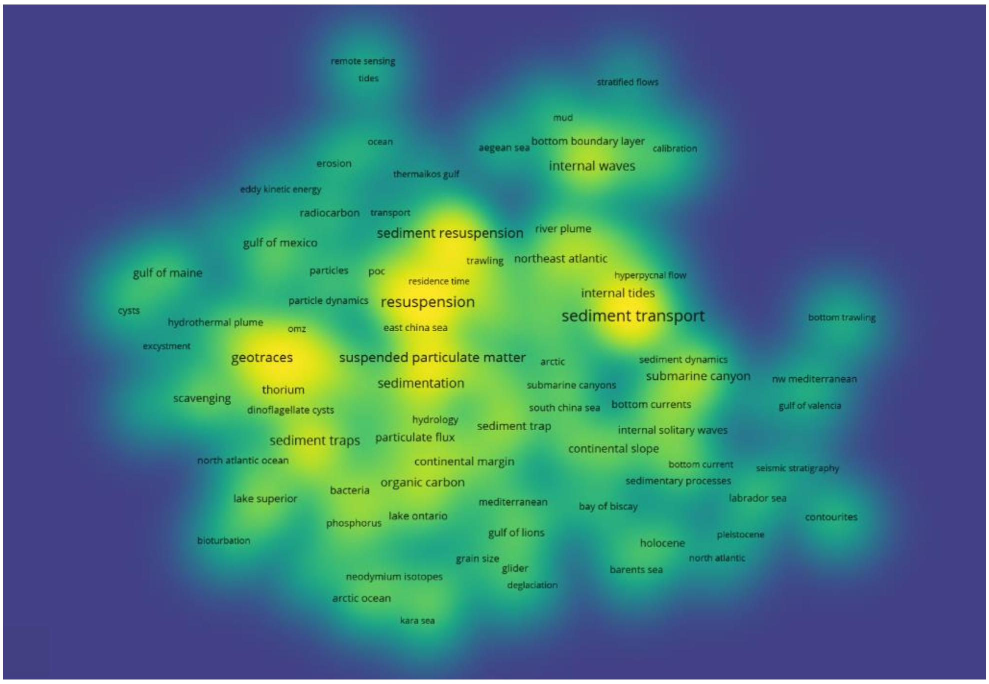


Figure 8. Keyword co-occurrence density map from 1990 to 2022 for research on nepheloid layers. A node's color indicates the number and weight of nearby items. The closer the color of the point comes to being a brighter yellow, the more items there are around a node with higher weights. The text size denotes the number and weight of adjacent items.

3.3. Author Influence and Partnerships Network Analysis

3.3.1. Author Network and Most Productive Authors

The formation of 21 clusters can be seen in this network visualization of 1062 authors in the same set (Figure 9a). Any two of the authors can be connected together by links and nodes. The three largest clusters are as follows: (i) red, which is the largest with 82 authors; (ii) green, with 77 authors; and (iii) blue, with 69 authors. The most cited authors in each cluster are Puig (760 citations in cluster 1), Liu (202 citations in cluster 2), and Eglinton (286 citations in cluster 3). The most relevant paper from the three larger clusters is discussed in the paragraphs that follow, considering the Web of Science's relevance indicator. Additionally, the dominant problem in each cluster is displayed based on the author's keywords. The article [10] published by Puig, Palanques, Guillen et al. was mainly written about the formation of nepheloid layers caused by internal waves. By analyzing observation data from CTD and a transmissometer, the composition of SNLs, INLs, and BNLs was discussed. The article [75] written by Liu and Du discussed particle dynamics during the summer monsoon and typhoon winds. It revealed the formation and development of SNLs, INLs, and BNLs. In article [76] written by Eglinton, Inthorn, Mollenhauer et al., compound-specific radiocarbon dating was used to demonstrate the features of organic matter on the continental shelf, which were related to the lateral sediment transportation caused by nepheloid layers.

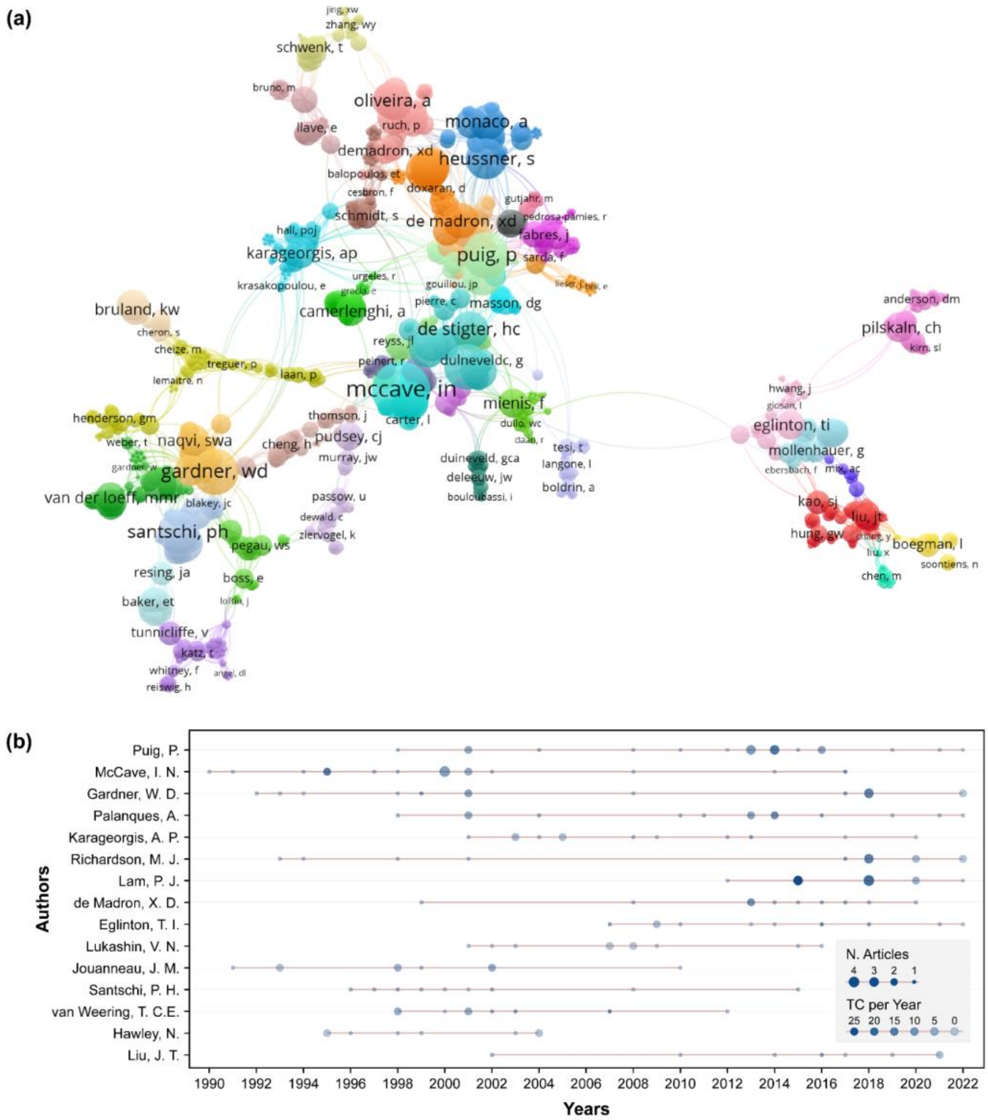


Figure 9. Bibliometric analysis of author influence from 1990 to 2022 [1–3,7,8,10,12,20,21,28–31,38,39,41,45,50,63,67,69,70,76–78]. (**a**) The author co-occurrence analysis network of 1062 most expressive authors. The size of the circles, which denotes its significance, is indicated as the number of citations for each author. (**b**) Temporal trends of an annual number of publications from the top 15 most productive authors. The number of publications (No. of articles) is shown by the size of the circles, and the overall number of citations every year is represented by the color of the circles (TC per year).

Figure 9b shows the results of the top 15 authors from 1990 to 2022. Puig is shown to be the most productive author from 1990 to 2022, and their publications from these years received the most citations in 2014. Lam was the most productive author in 2018 overall (4 publications in 2018, and 11 publications in total). Compared to the other authors, Eglinton's publications from 2007 continue to accumulate more citations each year. Lam still holds the record for the most citations in 2015 (77.33 citations/publication).

3.3.2. Country/Region Collaboration Network

Visually, the country/region networks clearly illustrate the distribution of production and collaborations among countries/regions (Figure 10). The publications are distributed among 47 countries/regions. The United States, France, and China have the most publications. Figure 10 illustrates how close collaboration exists between countries, particularly those that produce the most publications, which are the United States, France, Germany, and the United Kingdom. The collaboration frequency between Germany and the United Kingdom is 21, which is the same as the frequency between the United States and Germany, and ranks first. The United States had more publications and collaborations each year (544 and 183, respectively) than any other country. In total, 31 countries collaborated with the United States while only 13 collaborated with China.

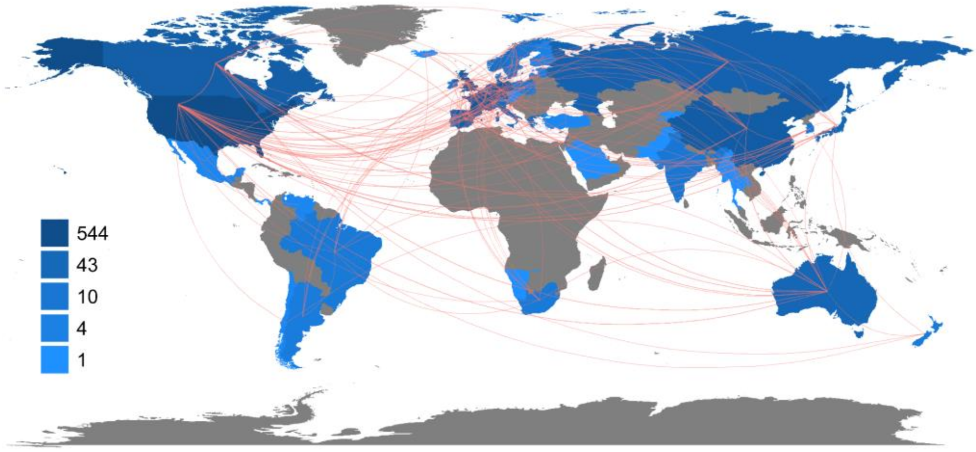


Figure 10. Bibliometric analysis of country/region collaboration from 1990 to 2022. More publications from the countries or areas are represented by a darker color. The red lines depict the cooperation relationships among the countries/regions.

4. Conclusions and Future Perspectives

Over the past 30 years, hydrological studies have provided abundant information about the fate and impact of nepheloid layers in the marine environment. This paper collected 689 articles related to nepheloid layers from the Web of Science Core Collection (1990–2022) and conducted a comprehensive analysis with Bibliometrix, VOSviewer, CiteSpace, and CorText. This is the first time that a bibliometric analysis has been used in nepheloid layer research.

This paper focused on analyzing some evolutionary trends of publications related to spatial–temporal distribution, research areas, publication sources, and a co-citation reference analysis. We can draw the conclusion that Oceanography, Geosciences Multidisciplinary, and Marine Freshwater Biology have attracted much interest, and that cooperation between Germany and the United States and between Germany and the United Kingdom is rather close. The keyword timeline evolution map of publications and keyword co-occurrence networks were then created, and the keyword burst detection of publications was examined. The results show that sediment resuspension and the benthic nepheloid layer will become research hotspots for a period of time in the future. Sediment particle transport in the deep sea will continue to be a focus. Further, the mechanism of formation and the development of nepheloid layers will be demonstrated. The timeline view analysis shows that 11 keywords were examined, with the current concentration of research being in the fields of sediment transport, geotraces, and the resuspension of nepheloid layers. Then, the author networks and the country/region collaboration networks were constructed, and the most productive authors were analyzed. The results show that the study of nepheloid layers mainly focuses on Oceanography, Geosciences Multidisciplinary, and Marine Freshwater Biology. More than half the publications are related to Oceanology and nearly one-fourth are on Geosciences Multidisciplinary. *Marine Geology* is the most published and cited journal on nepheloid layer research. The top three countries for nepheloid layer research are the United States, France, and Germany. The top three institutions are the Centre National De La Recherche Scientifique (CNRS) in France, the UDICE-French

Research Universities in France, and the Helmholtz Association in Germany. The top three authors are Pere Puig, I.N. McCave, and W.D. Gardner.

Detailed research over the past 30 years about nepheloid layers has yielded enormous insights, but some questions still remain [46,77]. For example, the major influencing factor for the formation of giant BNLs (>1000 m) is the towering seabed topography [2,77]. How does the near-bottom flow interact with the significant topographical changes in the bottom boundary layer to influence giant BNL formation [1,79]? Could eddy diffusion gradually mix suspended particles that high [2,70,77]? How can these links between giant BNL structure formation and rapidly changing strong currents be explained [78]? As a widespread marine phenomenon, nepheloid layers challenge many of our current understandings regarding the ocean dynamic linkage with marine sedimentology. Further studies are needed to address these key outstanding questions.

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