Environmental Sciences Europe

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The global progress on the non-point source pollution research from 2012 to 2021: a bibliometric analysis

Zi-jian Xie[1], Chun Ye[1*], Chun-hua Li[1*], Xiao-gang Shi[2], Ying Shao[3] and Wei Qi[4]

Abstract

Background: With effective control of point source pollution, non-point source (NPS) pollution has been widely concerned as the primary reason for the improvement of global water environmental quality. Some bibliometric analysis related to NPS pollution has been carried out before the mid-2010s. Analyzing the research status and hot issues of NPS pollution in the past decade is important for guiding the control and management of NPS pollution in the future.

Results: A bibliometric analysis was conducted based on 3407 publications retrieved from the Web of Science during 2012–2021. China, USA and UK were the most productive countries. *Sci. Total Environ, Environ. Sci. Pollut. Res, and Water were* the most productive journals. The NPS pollutant, pollution types, driving forces, technology and the research object were retrieved from the keywords analysis. The common NPS pollutants of nitrogen, phosphorus, and heavy metals grabbed the highest attention, while the emerging contaminants have attracted increased attention. The migration and transformation of agricultural NPS pollution and urban NPS pollution driven by climate change and land use change were hot issues related to NPS pollution studies. Technologies related to the combination of 3S technology (RS, GIS, and GPS) and NPS pollution models, the sustainable control technologies, the technology of accurate traceability and automatic monitoring, and the comprehensive management plan were the important research areas related to NPS pollution. Although the research locations were mostly concentrated in the surface water and groundwater, the ocean and drinking water have great potential for future research.

Conclusions: This study illustrates the global focuses related to NPS pollution during 2012–2021 according to analyzing the publication outputs, source journals, source country, author, institution and the high-frequency keywords. Results demonstrated that the migration and transformation mechanism and ecological risk assessment for heavy metals and emerging pollutants, accurate traceability techniques, sustainable ecological restoration control techniques, and marine pollution have attracted rising attention. Additionally, developing countries will have a higher interest in NPS pollution in the future, because developed countries have already made great progress in controlling NPS pollution.

Keywords: Non-point source pollution, Web of Science, Bibliometrics, Cooperation analysis

Background

Historically, most research has focused on point source (PS) pollution because it was considered as one of the main causes contributing to the water pollution problem [80, 59]. With the effectively control on the PS pollution in recent years, the NPS pollution was reported as one of the most important sources threatening the security of water resources, and even contributed to the

*Correspondence: yechbj@163.com; 297535203@qq.com

[1] National Engineering Laboratory for Lake Pollution Control and Ecological Restoration, State Environmental Protection Key Laboratory for Lake Pollution Control, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
Full list of author information is available at the end of the article

outbreak of water blooms [43, 80]. Compared with PS pollution, non-point source (NPS) pollution has some distinguished characteristics of dispersive sources, diversified types, great randomness and abruptness [42, 59].

The progress in NPS pollution control differs considerably from country to country. At the end of the twentieth century, some developed countries found that the NPS pollution transformed to the primary pollution source in many waters (US [39, 40, 72]. For example, USA has accounted that 60% of water pollution originated from NPS pollution (US [72],94% of the nitrogen load and 52% of the phosphorus load in 270 Denmark rivers were caused by NPS pollution [39, 40]. Then, developed countries have made great effort against NPS pollution. The implementation of the Clean Water Act (CWA) of USA, Watershed Protection Approach (WPA) of USA, EU Drinking Water Directive (DWD), and EU Water Framework Directive (WFD) have pointed out specific measures for controlling NPS pollution. Developing countries pay less attention to NPS pollution than developed countries due to the limited pollution control techniques and funds. Among all developing countries, China paid the highest attention to NPS pollution [42, 83]. The research on NPS pollution in China sprouted in the mid-1980s, which was approximately 20 years behind the USA and EU [42, 83]. Although Chinese government has issued many laws on NPS pollution, such as the Environmental Protection Law (EPL), Water Pollution Control Law (WPCL), and Yangtze River Protection Law (YRPL), NPS pollution is still the bottleneck restricting the improvement of water quality in China [65, 68]. In terms of the first and second longest rivers in China, almost 50% of nitrogen and phosphorus pollution in the Yangtze River basin resulted from the agricultural NPS (Zhang F, 2020), and more than 60% of total phosphorus emissions in the nine provinces of the Yellow River basin was caused by the NPS pollution [69]. Therefore, analyzing the research status and hot issues of NPS pollution is of great guidance for the NPS pollution controlling around the world, especially for developing countries.

Bibliometrics is an interdisciplinary science which utilizes mathematical and statistical methods to quantitatively evaluate the research output of various disciplines and fields [42, 55]. Bibliometrics analysis is beneficial to summarize the research status and hot topics of the searched field. Additionally, it is of great significance to grasp the latest progress and innovative issues, and enhance the efficiency of scientific research [55, 83]. Although bibliometric analysis has been carried out on NPS pollution in river basins, most research were completed before the mid-2010s [42, 74, 83].

This study aimed to analyze the global trend and hot issues of NPS pollution in the past decade from the bibliometrics perspective. The research not only analyzes the document type, language, annual publication outputs, source journals, source country, author and institution, but also illustrates the high-frequency keywords and the co-occurrence of keywords. The results are beneficial to comprehend the hot issues of NPS pollution, and providing important guidance for future research.

Materials and methods

Data collection

Due to the popular use of Web of Science (WoS) [Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI)] in the academic world, WoS was selected as the key database for this research. 'Non-point source pollution', 'diffuse pollution' were chosen as the keywords to search publications published during 2012–2021. The keyword retrieval object was title, abstract, author keywords and keywords plus. The date of retrieval of the database was January 2nd, 2022.

Totally, 3576 publications were found, including research articles (95.48%), review papers (3.77%), proceeding papers (2.10%), and other publications. In terms of publication language, English is the most frequently used (98.76%), followed by Portuguese (0.40%), Spanish (0.23%), etc. Only 3407 English publications of journal articles and reviews were used for further analysis.

Data analysis

This paper makes a bibliometric analysis of the literature related to NPS pollution in the past decade according to the publication year, regional distribution, author, institution and keywords. The processing software includes Microsoft office 2013, Bibexcel v2016.02.20, Vosviewer and Scimago Graphica. Microsoft office 2013 used to analyze the annual publications and total citations, the top 20 productive authors and source journals. Bibexcel v2016.02.20 used to consolidate and extract the plain data downloaded from the WoS. Vosviewer and Scimago Graphica used to draw the collaboration network of institutions and the co-occurrence map of keywords.

Results and discussion

Performance of publication output

A total of 3407 articles related to NPS pollution were published in the SCI-EXPANDED and SSCI between 2012 and 2021. As shown in Fig. 1, the publications related to NPS pollution increased from 257 in 2012 to 519 in 2021, and the annual publication was 341. Compared with the period of 1992–2001 (49 articles per year) and 2002–2011 (165 articles per year), the related articles increased obviously during 2012–2021, indicating that

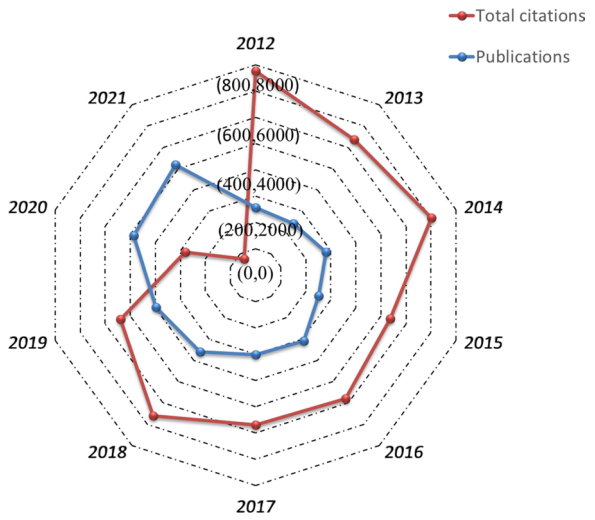

Fig. 1 The publications and total citations on NPS pollution research from 2012–2021

NPS pollution has attracted expanding attention around the world. The annual citations of articles from 2012 to 2019 were higher than 5000 times, and the total citations from 2020 to 2021 were relatively lower (Fig. 1), which was connected to the short publication time of articles.

Performance of countries/territories

During 2012 to 2021, a total of 110 countries/territories participated in the study of NPS pollution, and 54 countries/territories published more than 10 articles. This demonstrates that nearly half of the countries/territories did not conduct in-depth study on NPS pollution with only a few publications. As shown in Fig. 2, China, USA, and UK were the most productive countries, with 1287, 560 and 358 articles, respectively. In terms of the international collaborative research, China and the USA had the highest cooperation intensity. Meanwhile, as the country with the largest number of publications in the past decade, China, USA and EU maintains the closet cooperation (Fig. 2).

The research on NPS pollution in the USA, UK and other developed countries was 20 years earlier than that in China, the USA and UK was the most productive country, and had the strongest cooperative network in the global collaboration before the 2010s [42, 83]. China accounts for approximately 20% of the world's population and 7% of the world's arable land. Over 50% of the nitrogen and phosphorus pollution in the Yangtze River basin and phosphorus pollution in the Yellow River basin caused by the NPS pollution (Zhang F, 2020,[69]. Compared with developed countries, China has suffered more from NPS pollution over the last decade. Inversely, developed countries have achieved considerable achievements in controlling NPS pollution due to the implementation of numerous effective programs.

In the USA, the major programs related to NPS pollution include the Great Lakes Restoration Initiative (GLRI), Clean Water State Revolving Fund (CWSRF), and National Water Quality Program (NWQP), etc. As the largest investment in the Great Lakes over the latest 20 years, the GLRI has focused on the excessive nutrient

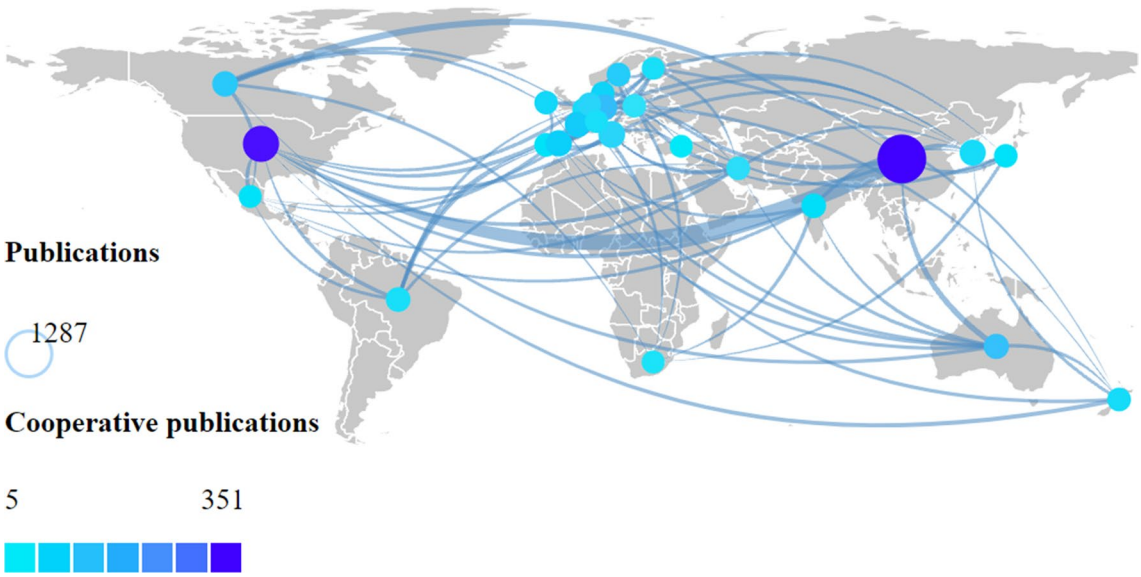

Fig. 2 The geographical distribution and cooperation network of the top 29 productive countries/territories during 2012–2021

loading, agricultural and stormwater runoff, industrial pollution, wildlife waste, that could degrade region water quality (Tyner et al., 2020; [29]. The CWSRF effectively supported the implementation of the CWA, it has provided low-cost financial assistance for stormwater mitigation, non-point source pollution control, estuary management project, etc. [6, 15]. The NWQP has provided research, education, and extension activities on eight key "themes" identifying agricultural and rural NPS pollution, and effectively improved the quality of water resources throughout the USA and its territories, particularly in agriculturally managed watersheds.

Similarly, EU has also funded many projects related to NPS pollution, such as SOLUTIONS, MODELKEY, WISER, etc. SOLUTIONS is a large integrated project, funded by the European Commission under the WFD. This project has proposed new and improved tools, models, and methods to support decisions in environmental and water policies, particularly for present and future emerging pollutants in the River Danube and River Rhine [14, 56]. MODELKEY is dedicated to the use of models to assess and predict the effect of environmental key pollutants on marine and freshwater ecosystems and biodiversity, the research was mainly focused on the River Elbe, River Schelde, and River Llobregat [30]. Similarly, WISER has developed methods for assessing and restoring aquatic ecosystems, and addressed the assessment and management of rivers, lakes, transitional and coastal waters in EU [11, 12].

In China, the major projects related to NPS pollution include the Major Science and Technology Program for Water Pollution Control and Treatment (Water Major Project), the National Water Pollution Prevention and Control Reserve Project, the Key Project for the Comprehensive Treatment of Major Rivers, such as the Yangtze and Yellow rivers, for Water Resources and Environment, etc. The Water Major Project was the largest investment in water pollution control technology project in China. This project has developed a number of technologies for China's key scientific issues in water pollution treatment and management, and effectively improved the water quality in some typical demonstration water shed. The National Water Pollution Prevention and Control Reserve Project effectively supported the implementation of the Action Plan for Prevention and Control of Water Pollution by identifying the major pollution problems in the surface water, groundwater and drinking water of key river basins in China, and effectively improved the ecological environment quality of target river basins through the implementation of engineering measures. Additionally, the Key Project for the Comprehensive Treatment of Major Rivers, such as the Yangtze and Yellow rivers, for Water Resources and Environment, aims to solve scientific and technical bottlenecks in the integrated management of water resources, water environment and water ecology in China's key river basins.

Performance of authors and institutions

A total of 11773 authors retrieved during 2012–2021 from the processing 3407 articles. Nearly 11430 authors (97%) published less than 3 articles, while 58 people published articles were higher than 10, with a total of 1033 articles. As shown in Fig. 3, Wei Ouyang from Beijing Normal University took the highest number of articles (55) and H-index (19). His main research interest is the simulation and control of NPS pollution in watersheds [54]. The top 20 most productive authors were mainly come from China, USA and UK (Fig. 3). The previous analysis showed that Raghavan Srinivasan from the United States Department of Agricultural Research Service contributed the most articles and the North America and Europe accounted for 10 and 6 of the top 20 productive authors during 1991–2015 [42]. Although scientists from North America and Europe still have a high influence on long time series, Chinese researchers have gained increasing academic and personal influence in the last decade.

Meanwhile, a total of 3313 institutions were retrieved from the WoS database between 2012 and 2021. 3120 institutions (94%) published less than 10 articles, while 193 institutions published articles were higher than 10 (6%). According to the analysis of top 21 productive institutions (≥ 25 articles) and their cooperation intensity, Chinese Academy of Sciences published the highest number of articles (304), and has close links with other institutions, followed by Beijing Normal University (162) (Fig. 4). Among these 21 institutions 15 come from China (71%) and 6 come from the UK (29%). In the past decade, these research institutions have actively conducted research on NPS pollution, which indicates that they have strong scientific research strength and competitiveness.

Performance of publication sources and highly cited articles

The 3407 publications were collected from a wide range of 690 journals. Among these 690 journals, 631 journals (91%) published less than 10 articles related to NPS pollution, while 20 journals (3%) published more than 10 articles. Fig. 5 demonstrates the distribution of the top 20 most productive journals and their H-index during the past decade. *Sci. Total Environ* ranked the first and published 268 (7.9%) publications, which indicated that this journal paid more attention to NPS research; meanwhile, the second most productive journal was *Environ. Sci. Pollut. Res* (164 publication; 4.8%), followed by *Water*

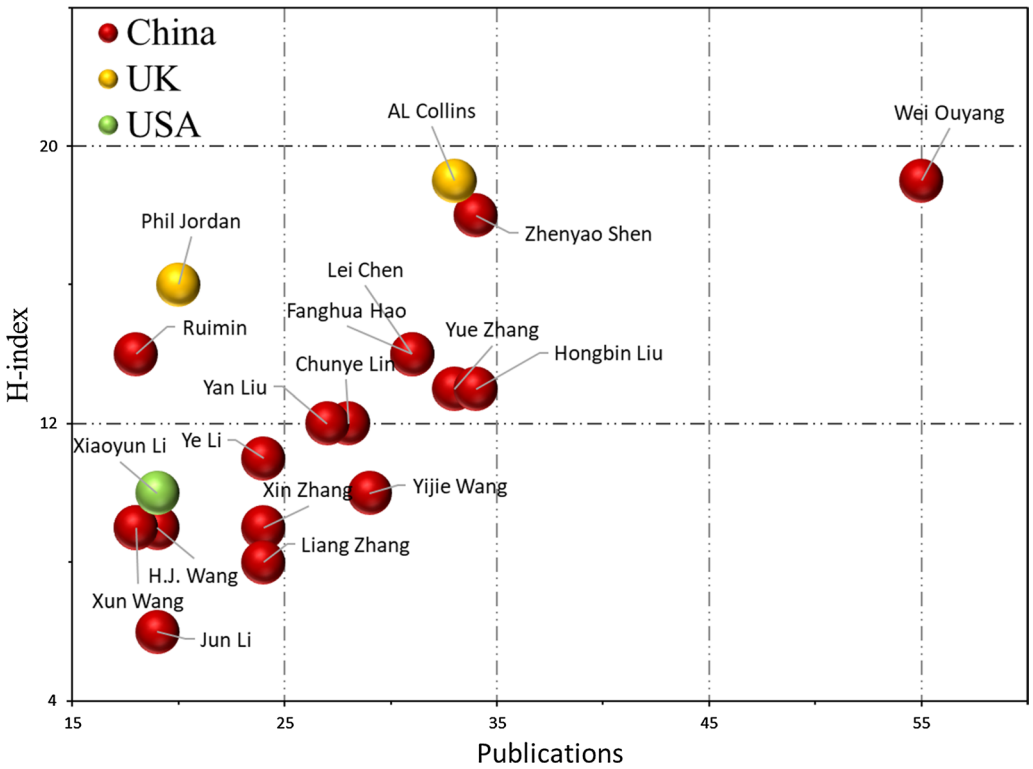

Fig. 3 The distribution of the top 20 authors with their H-index values during 2012–2021

(127 publications; 3.7%) (Fig. 5). With regard to the H-index, *Sci. Total Environ* was also ranked first (45), while *Agric. Ecosyst. Environ* (25) and *Water Res* (24) ranked second and third, respectively (Fig. 5). In terms of the 3-year impact factors (IF), the highest three journals were *Water Res* (9.427) *J. Clean Prod* (7.646) *Environ. Pollut* (6.857).

The top 20 cited articles retrieved in WoS database were total cited 5031 times, and the average citation was 252 times (Table 1). These articles were published in 14 journals. Six articles were published in *Sci. Total Environ*, and two published in *Agric. ecosyst. Environ*. The corresponding authors come from 14 countries. China and UK ranked first with three publications, followed by the USA (2) and France (2). These countries have the greatest influence on NPS pollution research. The most widely cited research was entitled "*Effectiveness of low impact development practices: Literature review and suggestions for future research*" in *Water Air and Soil Pollution* [2]. This article highlights evidence in the literature regarding the beneficial uses of low impact development (LID) practices, and suggests directions for future research opportunities.

Hot issues and development trend of NPS pollution based on the keywords analysis

Keywords analysis in scientific contributions are beneficial for identifying the hot issues and trends in a particular field [55]. Authors tend to list a number of keywords that are closely related to the article. A total of 14819 keywords appeared in all articles retrieved from WoS during 2012–2021. 1275 keywords occurred more than 5 times, and 568 keywords occurred more than 10 times.

Previously, bibliometrics mostly used 30–100 keywords to analyze the research hotspots and development trends [42, 55], which was not conducive to a comprehensive understanding of the aimed topic. In this study, 568 keywords occurred more than 10 times were taken as the target database, then reclassified it from the aspects of NPS pollutants, pollution types, driving factors, the key points of NPS pollution technology research and the research object.

The NPS pollutants were diversified

Regarding the 568 keywords with the occurrence frequency more than 10, a total of 75 keywords related to NPS pollutants, which could be divided into seven

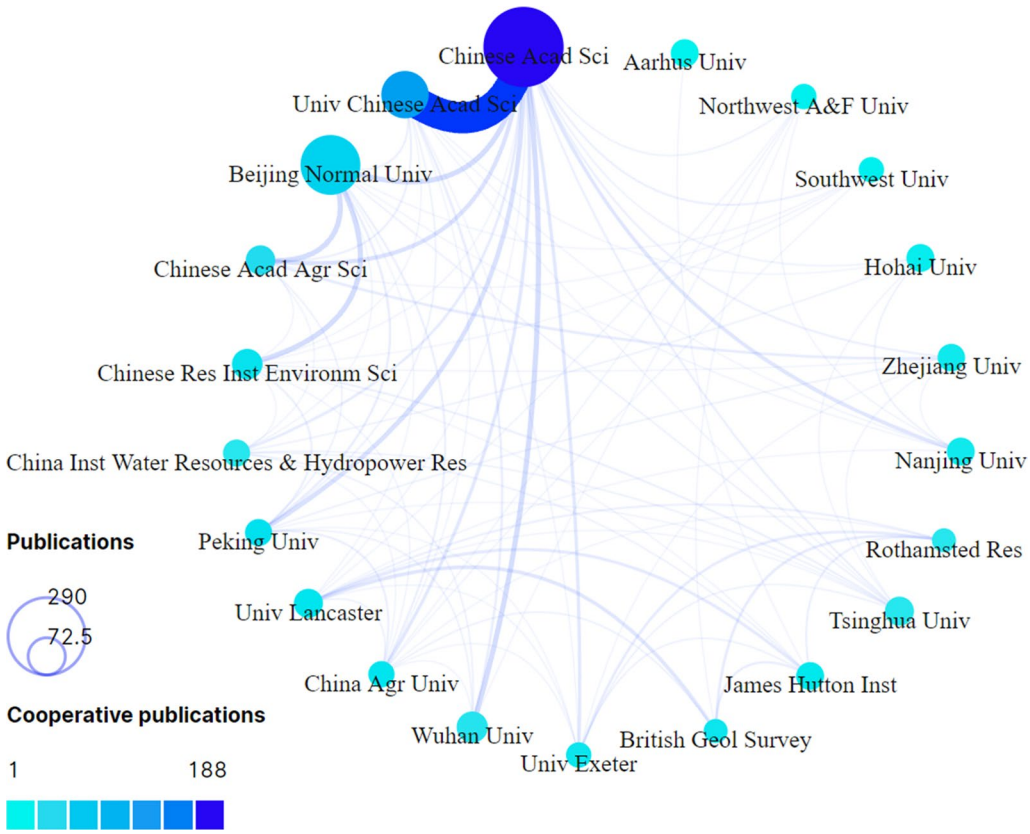

Fig. 4 The publications and cooperation network of the top 21 productive institutions from 2012–2021

categories, including nitrogen, phosphorus, heavy metals, carbon, emerging contaminants, pesticides, and microorganisms (Fig. 6).

Nitrogen and phosphorus were the main pollutants causing water eutrophication. The frequency of nitrogen and phosphorus ranked first (803 times) and second (530 times), accounting for 33.05% and 21.81%, respectively. The high-frequency keywords related to nitrogen include 'nitrate pollution', 'nitrogen loss', 'nitrogen removal', 'source nitrogen', 'ammonia volatilization', 'nitrogen use efficiency', 'nitrogen deposition', etc. The high-frequency keywords related to phosphorus constitute 'phosphorus retention', 'phosphorus loss', 'phosphorus loads', etc. The research on the migration and transformation paths of nitrogen and phosphorus and their influence on the quantification of water quality is a challenge in many watershed studies [55, 83].

Heavy-metals pollution which is caused by mining, industrial production, agricultural activities and urbanization severely endangers human health and safety [16, 17]. The frequency of heavy metals was ranked third (477 times), accounting for 19.63%. The high-frequency keywords related to heavy metals include 'cadmium', 'copper', 'plumbum', 'mercury', 'zinc', 'arsenic', etc. The migration, transformation and distribution of heavy metals in sediments of the estuary and urban runoff is the current research focus [9, 27].

Carbon is the major component of organic matter in soil and water. Dissolved organic matter is one of the main factors leading to the water eutrophication in lakes and reservoirs [23, 38]. Moreover, the carbon emissions are one of the main causes contributing to the global warming [45]. The keywords related to carbon occurred 212 times (8.72%). The high-frequency keywords related to carbon include 'organic-matter', 'organic-carbon', 'activated carbon', biochar, 'dissolved organic-matter', 'black carbon', etc. Since many countries hope to be carbon neutral by the middle of the twenty-first century, the carbon-related research will continue to increase in the next 30 years.

Emerging contaminants exist in various environmental media and are widely concerned because of its complex structure, easy enrichment, and high toxicity [20, 58, 60]. The frequency of emerging Organic pollutants was 164 times, accounting for 6.75%. The high-frequency keywords related to emerging contaminants constitute

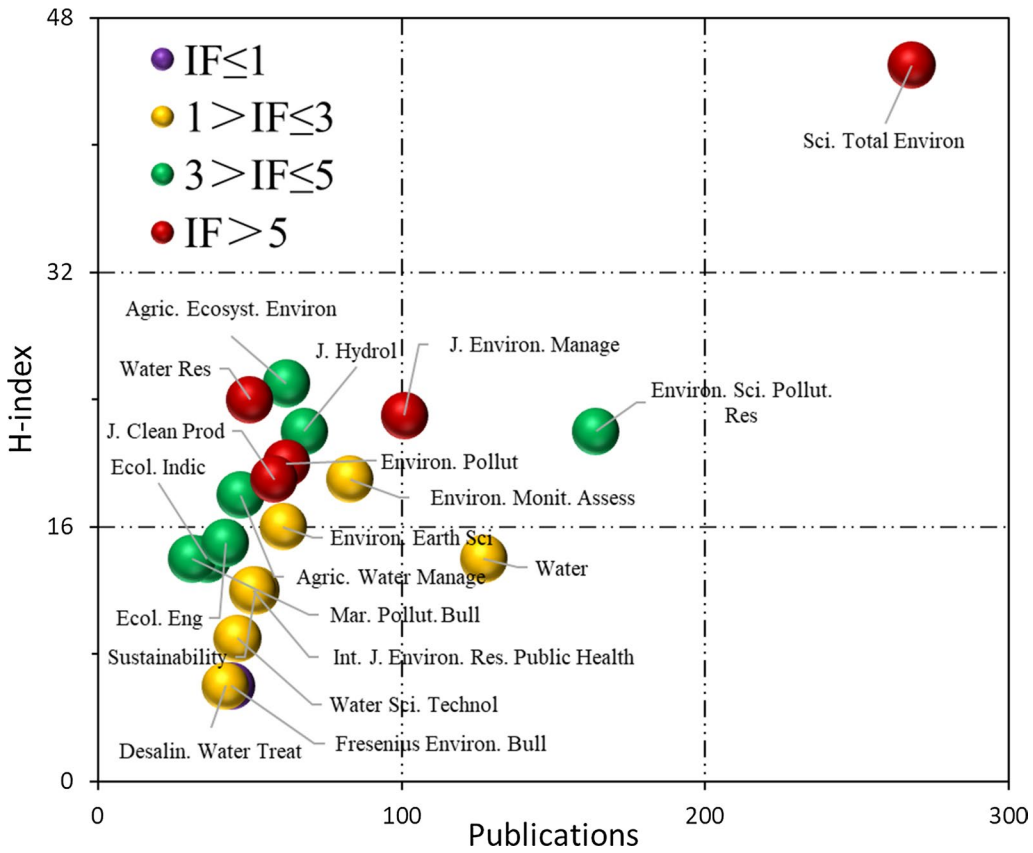

Fig. 5 The publications and H-index for the top 20 productive source journals with NPS pollution research from 2012–2021

'polycyclic aromatic-hydrocarbons', 'pharmaceuticals', 'polychlorinated-biphenyls', 'microplastics', 'antibiotics', etc. The research difficulties in emerging contaminant incorporated quantitative detection technology and influence mechanism on human health [7, 20, 32, 60].

Pesticides are derivatives of agricultural production activities and have an important impact on food security [51, 78]. The keywords related to pesticides occurred 140 times (5.76%). The common studied pesticide types include 'glyphosate', 'atrazine', 'organochlorine', etc. The promotion of organic agriculture and the development of biodegradable pesticides have alleviated pesticide pollution, but research on pesticides will continue for a long time due to the large area of arable land and the large amount of pesticide residues in arable soils, and also in estuarine areas that are conducive to pollutant accumulation [51], Masset et al., 2018; [78].

Most microorganisms in water bodies are harmless and essential to the normal functioning of the aquatic ecosystem, but there are also pathogenic microorganisms that can cause diarrhea, gastroenteritis, pneumonia, typhoid and other diseases [19, 76]. The frequency of microorganism occurred 104 times (4.28%), including 'bacteria', 'pathogens', 'escherichia-coli', etc. The research on microorganisms related to NPS pollution is mainly focused on sewage, urban reclaimed water, and drinking water [19, 76].

Regarding the top 20 most-cited articles, four publications were connected to nitrogen and phosphorus [57, 61, 62, 47], while four articles were related to microplastics, antibiotics and heavy metals [20, 32, 37, 60].

Agricultural NPS pollution and urban NPS pollution were the main pollution types

Regarding the 568 keywords with frequency more than 10, a total of 22 keywords related to NPS pollution types, which could be divided into three categories, including agricultural NPS pollution, urban NPS pollution, and natural runoff NPS pollution (Fig. 7).

Agricultural NPS pollution started earlier than urban NPS pollution [68, 80]. Compared with urban NPS pollution, the agricultural NPS pollution involved a wider source area, and its process of migration and transformation was more complicated [61, 67]. The frequency of agricultural NPS pollution was 354 times, accounting for 62.54%. The high-frequency keywords related to

Table 1 Top 20 most frequently cited articles related to NPS pollution research from 2012 to 2021

Number	Country[†]	TC[§]	Title
1	USA	462	Effectiveness of low impact development practices: Literature review and suggestions for future research [2]
2	France	361	Eutrophication: A new wine in an old bottle? [43]
3	Chile	359	Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal [20]
4	France	343	Long-term fate of nitrate fertilizer in agricultural soils [62]
5	Turkey	321	Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey) [63]
6	China	313	Agricultural non-point source pollution in China: Causes and mitigation measures [68]
7	UK	289	The impact of fine sediment on macro-invertebrates [36]
8	Czech Republic	260	The use of constructed wetlands for removal of pesticides from agricultural runoff and drainage: A review [73]
9	Wales	250	Agriculture and eutrophication: Where do we go from here? [80]
10	Netherlands	236	Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review [61]
11	Australia	223	Drought impacts on the water quality of freshwater systems; review and integration [50]
12	UK	215	The impacts of urbanization and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom [48]
13	Netherlands	204	Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water [47]
14	UK	183	Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield [57]
15	China	175	An integrated approach to assess heavy metal source apportionment in pen-urban agricultural soils [32]
16	USA	172	Pharmaceuticals, perfluoro surfactants, and other organic wastewater compounds in public drinking water wells in a shallow sand and gravel aquifer [60]
17	Japan	170	Assessment of the sources and inflow processes of microplastics in the river environments of Japan [37]
18	Sweden	168	The pollution conveyed by urban runoff: A review of sources [52]
19	UK	164	A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture [67]
20	China	163	Assessment of surface water quality via multivariate statistical techniques: A case study of the Songhua River Harbin region, China [79]

[†] Refers to the country where the corresponding author is affiliated; [§]Total citation.

agricultural NPS pollution include 'agricultural runoff', 'agricultural watersheds', 'paddy field', 'wheat', 'rice', etc. Although agricultural NPS pollution has been studied for a long time, the pollutant source area determination, load calculation and risk assessment are still the focus of current research [57, 65].

The urban NPS pollution has been widely concerned because of the rapid development of the urbanization [48, 52]. The frequency of urban NPS pollution occurred 166 times (29.33%). The high-frequency keywords related to urban NPS pollution constitute 'urban runoff', 'urbanization', 'highway runoff', etc. The utilization of urban runoff in rainy season is a difficult research item for urban NPS pollution, particularly in arid areas [48, 52].

Compared with agricultural NPS pollution and urban NPS pollution, the natural runoff NPS pollution received less attention. The frequency of natural runoff NPS pollution was 46 times, accounting for 8.13%. The high-frequency keywords related to natural runoff NPS pollution constitute 'grassland', 'pasture', 'forest', etc. Regarding the top 20 most-cited articles, eight publications were related to the agricultural NPS pollution, and three paper was related to urban NPS pollution (Table 1).

Land use change, rainfall and irrigation were the main driving factors of NPS pollution

Regarding the 568 keywords with frequency more than 10, a total of 16 keywords related to the main driving factors of NPS pollution, which could be divided into three categories, including land use change, climate change, and irrigation (Fig. 8).

Land use changes caused by agricultural reclamation and urbanization accelerate the formation of NPS pollution [68, 48]. The frequency related to land use change occurred 451 times, accounting for 51.13%. According to the World Bank database, the global

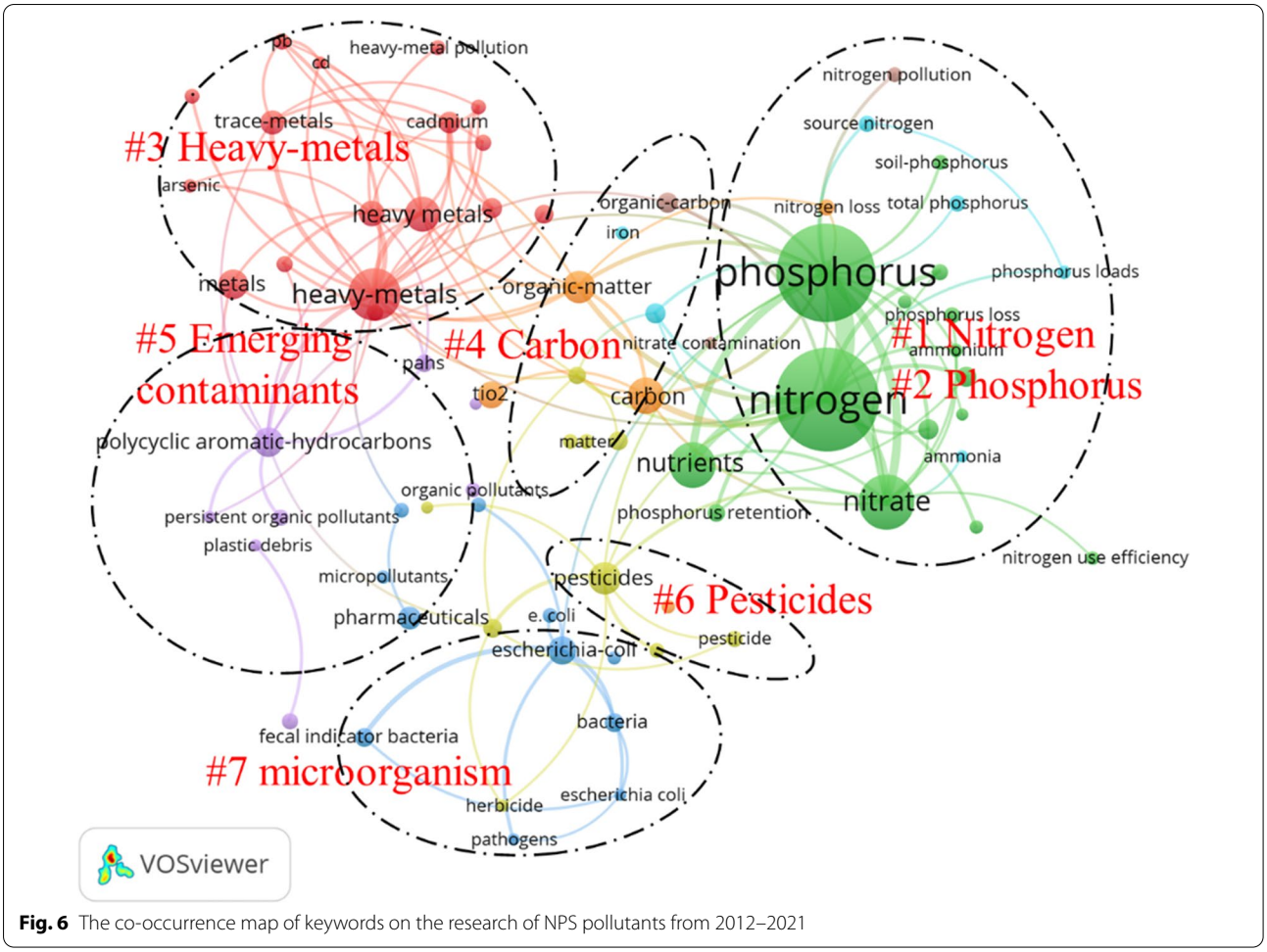

Fig. 6 The co-occurrence map of keywords on the research of NPS pollutants from 2012–2021

population, arable land, urbanization rate raised from 30.3×10^8 to 73.4×10^8, 1.28×10^9 hm^2 to 1.73×10^9 hm^2, and 33–51%, respectively, during 1960–2015. The population growth increases the demand for agricultural land and urban land. Agricultural reclamation will enhance soil fertility and soil erosion risk, thus increasing the risk of NPS pollution [68, 80]. Urbanization, on the one hand, will improve the surface impervious area and thus increase the runoff volumes and peak flow; on the other hand, the growth of human activities will increase the pollutant emissions [48, 52].

Climate change, especially rainfall and snowmelt, is the main carriers of NPS pollutants. The first flush is the main source of urban NPS pollution [50, 48]. Climate warming is an important global environmental problem. The frequency of climate change was 386 times, accounting for 43.76%. The high-frequency keywords related to climate change include 'rainfall-runoff', '1st flush', 'rainfall intensity', 'stormwater runoff', etc. The global land temperature increased at a rate of 0.32 °C per decade from 1981 to 2019 [64]. The global warming may cause extreme rainfall, which will produce more NPS pollution load and increase the control difficulty of NPS pollution [48, 45].

Irrigation is the key factor formatting agricultural NPS pollution. The frequency of irrigation was 45 times, accounting for 5.10%. Although the application of water-saving irrigation equipment alleviates NPS pollution caused by irrigation, it is still a difficult problem to effectively control NPS pollution caused by the recession of paddy field [22, 53].

Load calculation and integrated management were the key points of NPS pollution technology research

In terms of the 568 keywords with frequency ≥ 10 times, a total of 69 keywords related to the key points of NPS pollution technology research, which could be divided into five categories, including monitoring and identification, load calculation, risk assessment, control technology and integrated management (Fig. 9).

Monitoring and identification of NPS pollutants is the basis for the control and management of NPS pollution.

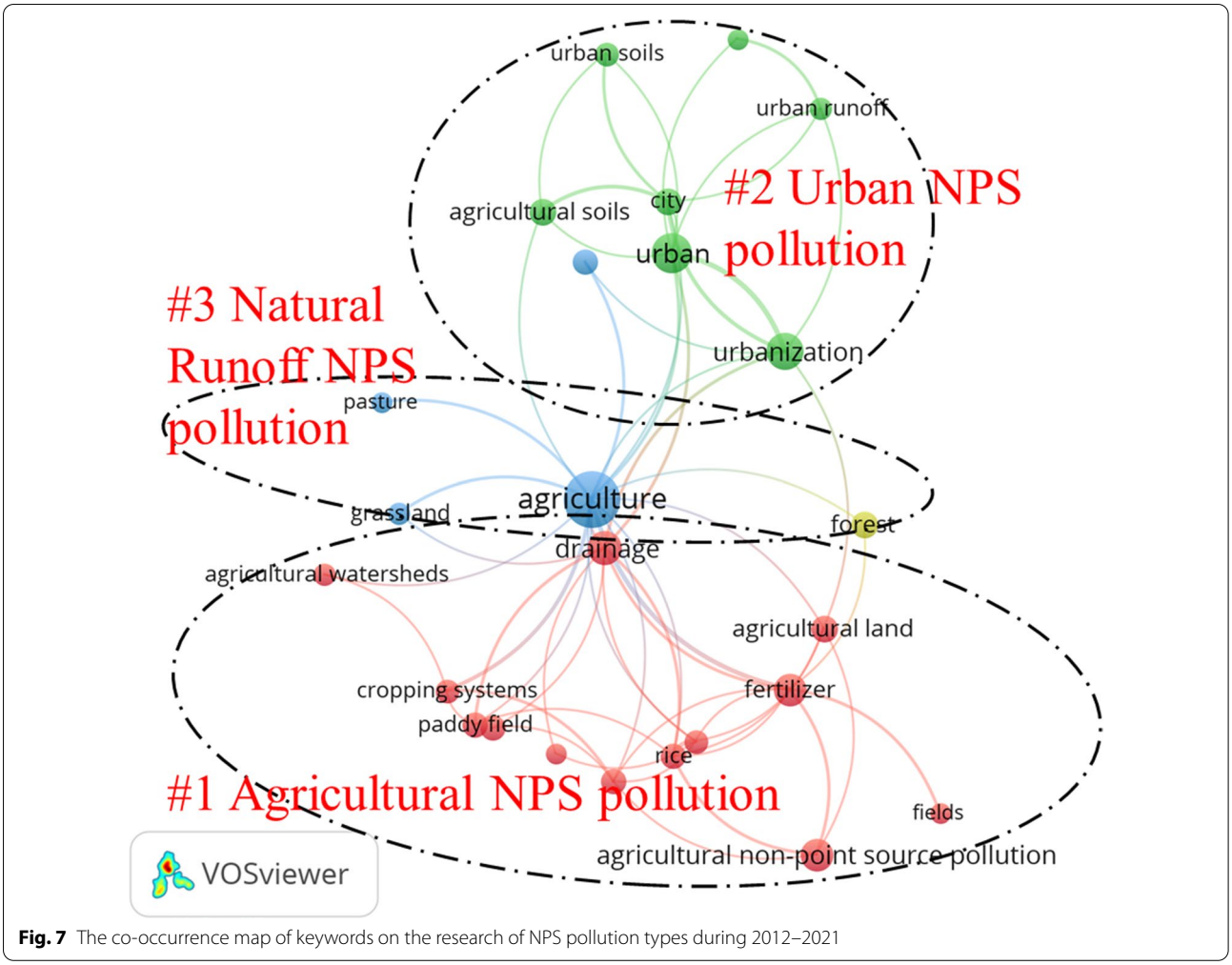

Fig. 7 The co-occurrence map of keywords on the research of NPS pollution types during 2012–2021

The frequency of keywords related to monitoring and identification was 361 times, accounting for 15.30%. The high-frequency keywords constitute 'monitoring', 'identification', 'stable isotopes', 'source apportionment', 'microbial source tracking', 'indicator bacteria', etc. The water quality and quantity obtained based on the automatic monitoring platform can be directly used to calculate the NPS pollution load in the catchment units, it is the most direct method to characterize NPS pollution. However, the high cost of simultaneously monitoring water quality and quantity hinders the development of the automatic monitoring system [77]. Additionally, the rapid identification of priority contaminants among mixed pollutants, particularly for emerging pollutants, is also a focus for future water contamination monitoring [4, 5]. The source identification technology based on the isotopic of nitrogen and oxygen, the three-dimensional fluorescence spectrum, and indicator bacteria is helpful for quantitative analysis of NPS pollution. How to correct the influence of nitrification and denitrification on isotopic abundance and the overlap and scattering of spectral peak, and isolating the highly identifiable fecal indicator bacteria are key for the traceability accuracy improvement [34, 41, 59].

Load calculation can provide important data support for the control and management of watershed water quality. The frequency of keywords related to load calculation occurred 769 times (32.58%). The high-frequency keywords include 'SWAT', 'AGNPS', 'export coefficient model', 'SWMM', 'remote sensing', 'GIS', etc. USA is the pioneer in developing the load calculation model of NPS pollution, the export coefficient model, SWAT (Soil and Water Assessment Tool), AGNPS (Agricultural Non-Point Source), and SWMM (Storm Water Management Model) were all developed by USDA ARS and US EPA [1, 83, 87]. The export coefficient model is easy to operate, but it cannot describe the pollutant migration process [26]. SWAT, AGNPS, and SWMM can be used for the mechanism simulation at watershed scale and often combined with 3S technology 'RS、GIS、GPS' [1, 87].

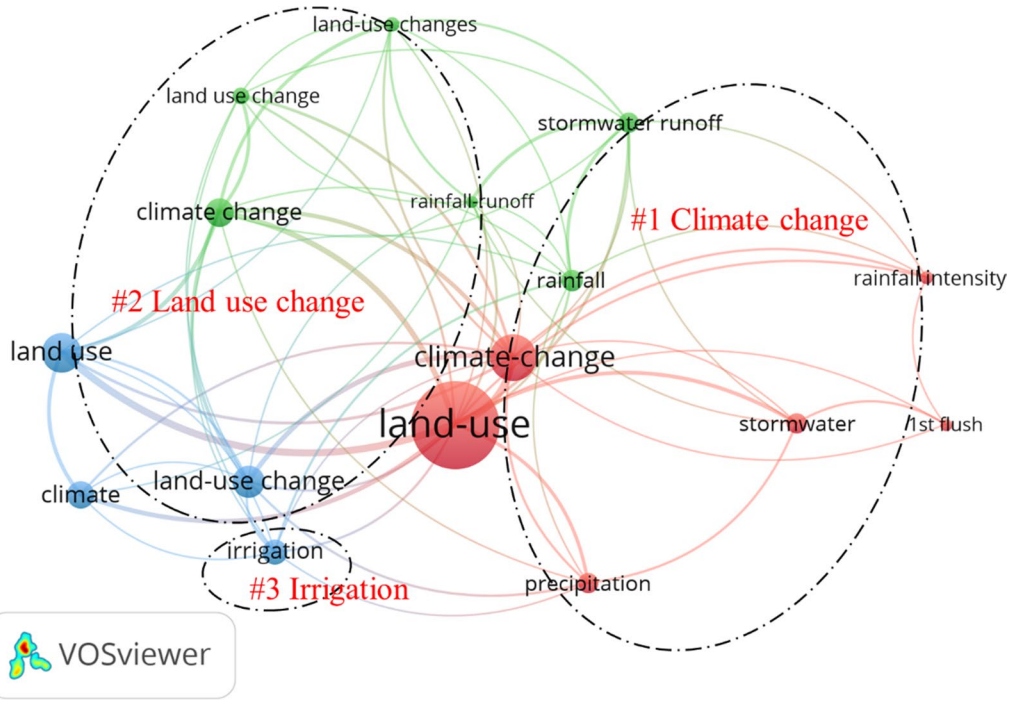

Fig. 8 The co-occurrence map of keywords on the driving factors of NPS pollution research from 2012–2021

SWAT model is used to simulate the long-term effects of soil, land use and management practices on runoff, sediment load, and agricultural chemical transport in a large-scale watershed [1, 87]. AGNPS model is used to analyze the impact of agricultural management practices, soil and water conservation methods, land use and tillage practices on agricultural NPS pollution [1, 83]. SWMM model is used to simulate the process of urban rainfall, runoff and pollutant movement [1, 83]. These models have abundant application cases in the USA, while in other countries, how to localize the model parameters is the key to upgrade model simulation accuracy [1, 83, 87].

Risk assessment is an important tool for assessing the severity of NPS pollution. The frequency of keywords related to risk assessment was 207 times, accounting for 8.77%. The high-frequency keywords constitute 'environmental risk', 'health-risk', 'quality assessment', 'soil and water assessment tool', 'water assessment-tool', etc. Load calculation model, Source identification technology, and water quality index assessment method were the most common assessment tools for NPS pollution [1, 41, 85]. Most risk assessment methods were focused on the single pollutant of soil and water, the integration of a comprehensive assessment method for multiple chemical and biological contaminants, and the impact of NPS pollutants on human health risk is a future research focus [5, 41]. It is worth noting that the construction for ecological thresholds of toxicological concern is conducive to the environmental hazard assessment and the selection of pollutant control technology [10].

Control technology is the key to controlling NPS pollution. The frequency of keywords related to control technology was 388 times, accounting for 16.44%. The high-frequency keywords constitute 'best management practice', 'constructed wetland', 'buffer strips', 'riparian buffer', 'vegetative filter strips', 'nanoparticles', etc. Nanomaterials have potential applications in NPS pollution control due to its high adsorption properties [3]. The best management practices (BMPs) constructed by Wright Water Engineers of USA played an effective role in the control of NPS pollution, including more than 300 NPS pollution control measures for engineering and non-engineering [88]. Constructed wetland, buffer strips, riparian buffer, and vegetative filter strips are commonly used engineering measures in BMPs, focusing on the interception of NPS pollution transmission process and the treatment of received soil and water [73, 44, 81]. In Europe, more than 30 countries launched the Costaction 869 program in 2005, establishing a cost–benefit assessment database for surface water and groundwater nutrients, including nutrient management, farmland management, fertilizer application management, etc. (Panagopoulos et al., 2011). Similarly, [84] proposed the Reduce–Retain–Reuse–Restore (4R) Theory and

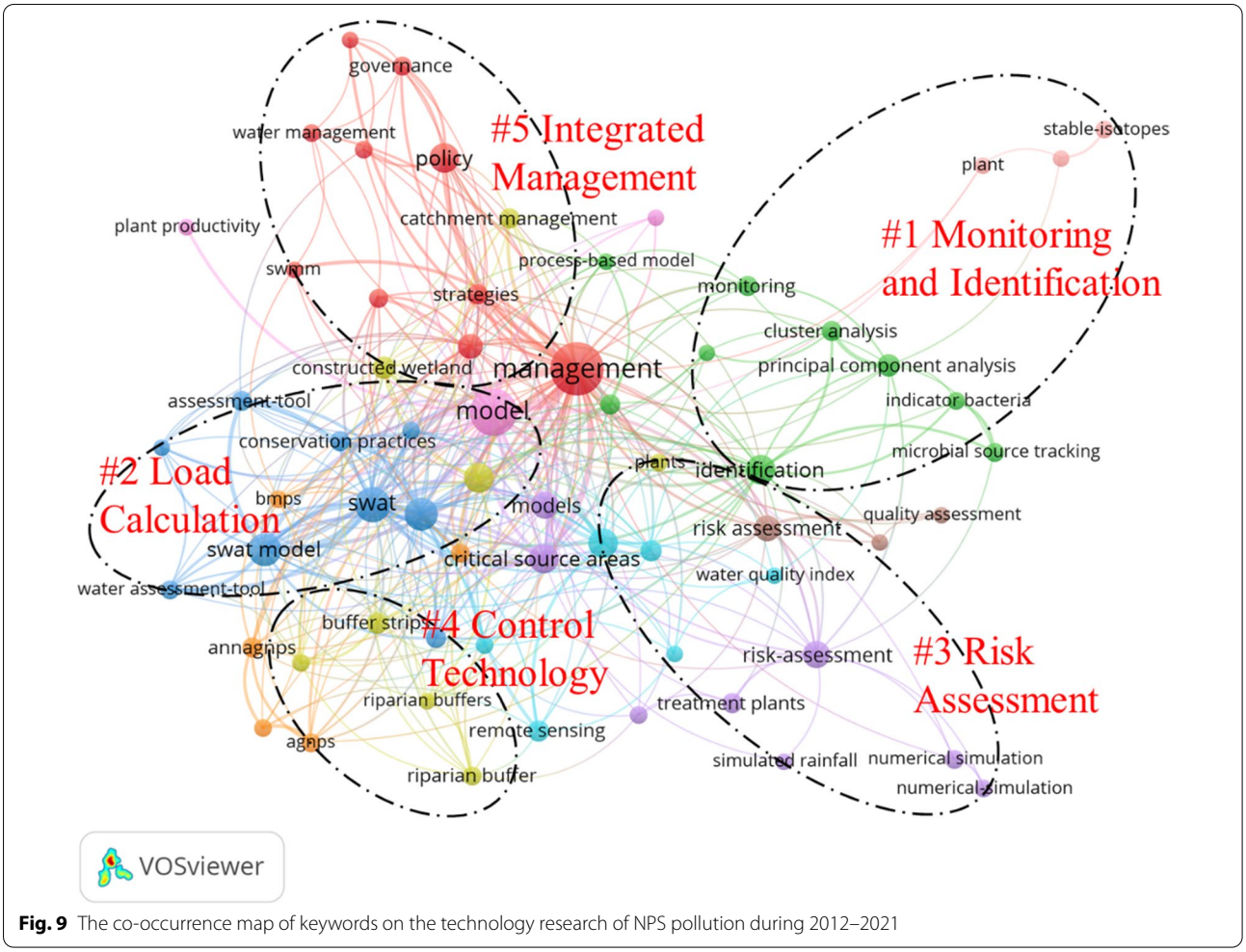

Fig. 9 The co-occurrence map of keywords on the technology research of NPS pollution during 2012–2021

Technology, which has clarified the overall idea and integrated application framework of technology for agricultural NPS pollution control, and achieved good practice in China. The LID practices have been widely used in urban rain and flood integrated management, that aims to integrate storm water management into urban green infrastructure system [31]. To sum up, sustainable control technologies based on ecological restoration measures is a hotspot in the research of NPS pollution control technology.

Integrated management is not only an important driving force to solve the NPS pollution, but also an important guarantee for the research on monitoring, source identification, and control technology [14, 67]. The frequency of keywords related to integrated management occurred 635 times (26.91%). The high-frequency keywords include 'catchment management', 'governance', 'nutrient management', 'policy', 'water governance', 'water management', etc. The USA and EU have abundant practices in national management of NPS pollution. The USA formulated the first NPS pollution control law in 1936, which made clear provisions for the improvement of rural environmental quality. The CWA (1972) is an important guidance and guarantee for the control of NPS pollution in the USA. The CWA set the ground rules for controlling sewage discharges in the USA, and raised the Rural Clean Water Program by implementing BMPs to control soil erosion and reduce agricultural NPS pollution. The Water Quality Act of 1987 officially defined the agricultural NPS pollution, and systematically divided various types of agricultural NPS pollution. The Environmental Quality Incentives Program (EQIP) was established in the 'Federal Agriculture Promotion and Reform Act' of 1996. This program aims to achieve the dual goals of improving agricultural production and environmental quality by providing financial and technical support for producers. Meanwhile, the WPA, National Irrigation Water Quality Program, and Total Maximum Daily Load (TMDL) have made great contributions to controlling NPS pollution in the USA. In the EU, the DWD (1980), Nitrate Directive (1991), and WFD (2000) have promoted the control of regional NPS pollution. China has carried out the most

research on NPS pollution in the past decade. China has issued many laws, regulations, and guidelines for controlling NPS pollution, including the EPL (1989), Agricultural Law (2002), WPCL (2008), and YRPL (2020), etc. The utilization rate of chemical fertilizer and pesticides in China was 40.2% and 40.6% for the major crops of rice, wheat and corn, increasing 5 and 4 percent from 2015 to 2020 (MOA [49]. The control of NPS pollution in China is nearly 20 years behind developed countries. It is likely to be a hot issue in the next decade as the pollution situation is still serious. Currently, how to evaluate the impact of policy implementation on the local government and improve farmers' awareness of pollution control is a challenge for the management of NPS pollution in China.

The research locations were mainly concentrated in surface water and groundwater, but the ocean and drinking water might be the future research focuses

As for the 568 keywords with frequency ≥ 10, a total of 34 keywords connected to NPS pollution research objects, which could be divided into five categories: surface water, groundwater, drinking water, wastewater and seawater (Fig. 10).

Surface water and groundwater in land areas are the main receiving waters of NPS pollution, which are most affected by agricultural production, human activities, mining, etc. [47, 68]. The frequency of keywords related to the surface water and groundwater were 627 and 190 times, accounting for 50.61% and 15.33%, respectively. The high-frequency keywords include 'agricultural runoff', 'highway runoff', 'subsurface drainage', 'shallow groundwater', etc. The pollutants with high attention in agricultural surface water includes nitrogen, phosphorus, organic matter, and pesticides, while in urban surface water, it constitutes heavy metals and emerging contaminants [16, 68, 17, 75]. Additionally, nitrate is the high-concern pollutant in the shallow groundwater of agricultural areas, and heavy metals is the main pollutant in mining area [57, 17].

Wastewater has a high concentration of contaminants. The frequency of keywords related to wastewater was 194 times (15.66%). Wastewater is usually discussed as PS pollution and easily controlled. It is worth mentioning that the overflow of wastewater during rainstorms is a research focus of NPS pollution [35].

Considering most surface water and groundwater will eventually flow into the ocean, the seawater, especially the coastal waters and bay area, was the key area for the control of NPS pollution [25, 33]. The frequency of keywords related to the seawater was 126 times (10.17%).

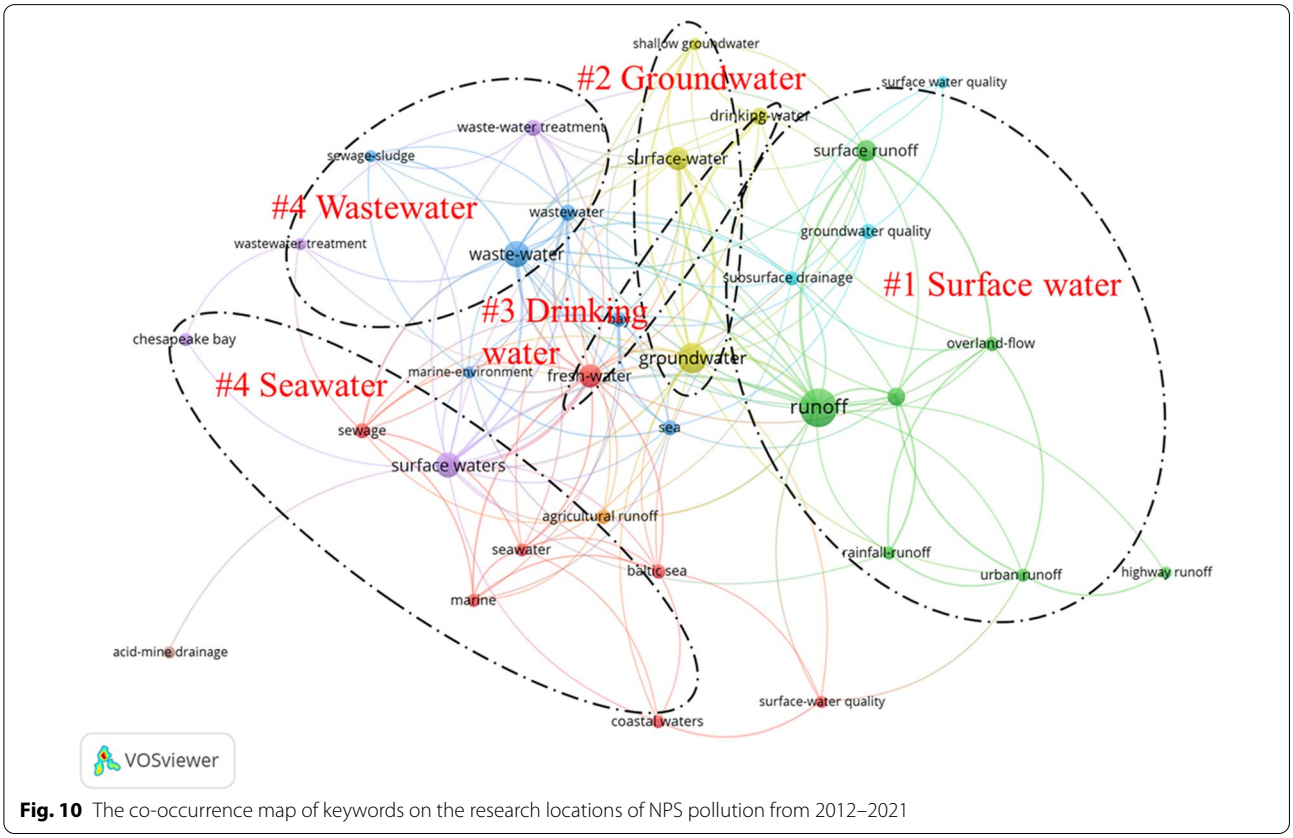

Fig. 10 The co-occurrence map of keywords on the research locations of NPS pollution from 2012–2021

The high-frequency keywords constitute 'Baltic Sea', 'Chesapeake Bay', 'coastal waters', 'bay', etc. Ocean plastic waste is listed as a global urgent problem. It is estimated that 4.8- 12.7 million tons of plastic waste enters the ocean from coastal areas around the world each year [33]. The plastic waste is difficultly degraded in the ocean, then causing serious impact on the health and safety of Marine life and human beings [33].

Drinking water was also a key area as it is closely related to humane health [8]. The frequency of keywords related to drinking water was 102 times, accounting for 10.17%. The high-concern contaminants in drinking water include nitrate, *Helicobacter pylori*, chlorinated disinfection by-products, additionally, microplastics have received wide attention in recent years [21, 66]. Most urban areas have a complete drinking water security system, while rural areas have higher drinking water safety risks due to their primitive technology and remote location, particularly in the poor areas of developing countries [21, 66].

Conclusion

3407 articles related to NPS pollution were published in SCI-EXPANDED and SSCI between 2012 and 2021. Professor Wei Ouyang from Beijing Normal University took the highest number of articles (55) and H-index (19). Chinese Academy of Sciences published the highest number of articles (304). *Sci. Total Environ*, *Environ. Sci. Pollut. Res* and *Water* were the most productive journals.

According to the keywords analysis of the NPS pollutant, the pollution types, the main driving forces, the research technology and the research object. The traditional NPS pollutants of nitrogen, phosphorus, and heavy metals took the highest concern; emerging contaminants have attracted rising attention in the past ten years. Research on NPS pollution types and the main driving forces are closely related, the migration and transformation of agricultural NPS pollution and urban NPS pollution driven by irrigation and land use change were the research hot issues. Regarding the research technology, load calculation and integrated management were the hotspots related to NPS pollution technology research. The combination of 3S technology (RS, GIS, and GPS) and NPS pollution models, the sustainable control technologies, the technology of accurate traceability and automatic monitoring, and the comprehensive management plan were the key points of NPS pollution technology research in the past decade. In addition, the research objects were mainly focused on the surface water and groundwater, while the ocean and drinking water were also a key area related to NPS pollution.

It is worth noting that developing countries, including China, have been severely affected by NPS pollution over the past decade. While in developed countries, most of them have made great progress in controlling NPS pollution. They have comprehensive pollutant monitoring network, strict law enforcement system, mature technology library for controlling NPS pollution, and operational economic compensation measures to improve farmers' enthusiasm in preventing NPS pollution. Considering that developing countries will be the major areas for controlling NPS pollution, these experiences can provide important guidance for controlling NPS pollution in developing countries.

Abbreviations

NPS: Non-point source; PS: Point source; WoS: Web of Science; SCI-EXPANDED: Science Citation Index Expanded; SSCI: Social Sciences Citation Index; CWA: Clean Water Act; WPA: Watershed protection approach; DWD: Drinking Water Directive; WFD: Water Framework Directive; EPL: Environmental Protection Law; WPCL: Water Pollution Control Law; YRPL: Yangtze River Protection Law; GLRI: Great Lakes Restoration Initiative; CWSRF: Clean Water State Revolving Fund; NWQP: National Water Quality Program; Water Major Project: Major Science and Technology Program for Water Pollution Control; SWAT: Soil and Water Assessment Tool; AGNPS: Agricultural non-point source; SWMM: Storm Water Management Model; BMPs: Best management practices; 4R: Reduce–Retain–Reuse–Restore; LID: Low impact development.

Acknowledgements

Not applicable

Author contributions

ZJX: conceptualization, methodology, investigation, formal analysis, writing—original draft; CY: validation, resources, writing—review and editing, supervision; CHL: validation, resources, writing—review and editing, supervision; XGS: conceptualization, writing—review and editing; YS: writing—review and editing; WQ: investigation, formal analysis. All authors read and approved the final manuscript.

Funding

This project was funded by the National Key Research and Development Project of China (Watershed non-point source pollution prevention and control technology and application demonstration, 2021YFC3201502).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]National Engineering Laboratory for Lake Pollution Control and Ecological Restoration, State Environmental Protection Key Laboratory for Lake Pollution Control, Chinese Research Academy of Environmental Sciences, Beijing 100012, China. [2]School of Interdisciplinary Studies, University of Glasgow, Dumfries DG1 4ZL, Scotland, UK. [3]Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, College of Environment and Ecology, Chongqing University, Chongqing 400030, China. [4]Erdos Bureau of Ecology and Environment, Erdos 017010, China.

Received: 25 February 2022 Accepted: 26 November 2022
Published online: 24 December 2022

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