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Groundwater remediation from the past to the future: A bibliometric analysis

Shu Zhang [a], Guozhu Mao [b,*], John Crittenden [c], Xi Liu [b], Huibin Du [b]

[a] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA, 90095, USA
[b] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[c] Brook Byers Institute for Sustainable Systems, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA

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A B S T R A C T

Groundwater is an important component of terrestrial ecosystems and plays a role in geochemical cycling. Groundwater is also used for agricultural irrigation and for the domestic supply of drinking water in most nations. However, groundwater contamination has led to many research efforts on groundwater remediation technologies and strategies. This study evaluated a total of 5486 groundwater remediation-related publications from 1995 to 2015 using bibliometric technology and social network analysis, to provide a quantitative analysis and a global view on the current research trend and future research directions. Our results underline a strong research interest and an urgent need to remediate groundwater pollution due to the increasing number of both groundwater contamination and remediation publications. In the past two decades, the United States (U.S.) published 41.1% of the papers and it was the core country of the international collaboration network, cooperating with the other 19 most productive countries. Besides the active international collaboration, the funding agencies also played positive roles to foster the science and technology publications. With respect to the analysis of the distribution of funding agencies, the National Science Foundation of China sponsored most of the groundwater remediation research. We also identified the most productive journals, *Environmental Science and Technology* and *Journal of Contaminant Hydrology*, which published 334 and 259 scientific articles (including research articles and reviews) over the past 20 years, respectively. In addition to journal publications, a patent analysis was performed to show the impact of intellectual property protection on journal publications. Three major remediation technologies, including chemical oxidation, biodegradation and adsorption, have received increasing interest in both journal publication and patent development. Our results provide a valuable reference and global overview to identify the potential obstacles and opportunities for researchers who currently work on groundwater contamination, remediation and related topics.

1. Introduction

Globally, groundwater is an important resource for agricultural irrigation and the domestic supply of drinking water in most nations (Einarson and Mackay, 2001; NGA, 2013; Niu et al., 2014; Squillace et al., 2002). However, long-term use, the inappropriate storage of chemicals and the continuous discharge of industrial waste have resulted in numerous contaminated groundwater sites (Hadley and Newell, 2012; Mackay and Cherry, 1989). To ensure the safety and sustainability of groundwater resources, remediation technologies have been developed to remove pollutants from groundwater (Leeson et al., 2013). There are several challenges for designing remediation strategies and selecting appropriate approaches, including complex geo-physical-chemical conditions, contaminant mixtures and economic considerations (Hadley and Newell, 2012; Stroo et al., 2012). In addition, the rapid growth of innovative technologies and the future need for multidisciplinary research are not aligned. To better understand the groundwater remediation research landscape, a quantitative analysis that provides usable and relevant information is required for scientific guidelines.

Bibliometric analysis is a computer tool that can quantitatively measure and assess the research impact of a subject of interest (SOI) (Du et al., 2014). Generally, bibliographic analysis focuses on

* Corresponding author.
E-mail address: maoguozhu@tju.edu.cn (G. Mao).

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identifying research strengths and weaknesses, assessing country contributions, and recognizing the impact of journals and top scholars (Ho, 2008). Recently, a bibliometric analysis was applied to characterize the author's affiliation, citation habits, and research collaborations (Du et al., 2015; Mao et al., 2016). In summary, bibliometric analysis can be used to summarize global research trends of groundwater remediation to provide a potential guide for current and future studies.

Patent analysis is the other common quantitative approach to analyzing the technology trends in certain research fields. Because of increasing entrepreneurial activity, in particular the collaboration between academia and industry, patents are favored by companies in collaboration with researchers (Abraham and Moitra, 2001; Van Looy et al., 2006). The combination of patent and article publication analysis will enhance technology forecasting and development planning (Daim et al., 2006) for scientific researchers and industrial practitioners because both partners are allowed to deliver research output.

The aim of this study is to quantitatively and qualitatively evaluate publications on groundwater remediation from the period 1995–2015. The assessment of general patterns of publication outputs, impact on journals, national and institutional research distribution and important keywords in groundwater remediation research are evaluated. Importantly, the findings will be valuable for research landscape mapping and technology forecasting.

2. Methods

2.1. Data collection

The Web of Science Core Collection (2016a) annually collects thousands of journals to provide various records for each publication, including author information, journals, citation and institutional affiliation, from multiple disciplines for bibliometric analysis. This study used two keywords “groundwater contamination” and “groundwater remediation”—to search and collect 11,037 and 5486 publications (1995–2015), respectively. The search for “groundwater contamination” was used to identify the major problems and contaminants, while “groundwater remediation” was used to reflect the research focusing on technologies and solutions to address groundwater contamination issues. The present study focused on the analysis of 5486 publications with “groundwater remediation” as keywords. In addition, the OmniViz (BioWisdom Ltd) was applied to extract the keywords from “groundwater remediation” publications. OmniViz is developed to analyze large data source via different clustering methods, provides the clusters and associated terms for a field, and eventually makes a special visualization of the network relationships. It is used in identifying the technology landscape in the study of technology intelligence and open innovation (Veugelers et al., 2010). In our analysis, we use OmniViz to address the important topics and the relationships among research areas. By using the K-Means Clustering method, we define the similarity metric by magnitude and shape to measure the similarity of two records within a high-dimensional space. To visualize results, we employ the Galaxy and Thememap for plots. The Galaxy provides relationships among the large numbers of records and the Thememap identifies the most important themes in the field. Nature Index records was used to compare and analyze the distribution of countries and academic performance.

2.2. Impact factors

The impact factor (IF) is a useful tool to quantify the importance of citation frequencies and to rank, evaluate and compare scientific journals. The IF of a journal is calculated by dividing the citation count of the current year by the number of published articles in the journal during the previous two years (2016b, Garfield, 2006). The IF has often been used in various research fields to measure the performance of journals (Du et al., 2015; Mao et al., 2015). This study employed the impact factors in 2015 from InCites™ Journal Citation Reports® (Thomson Reuters, Philadelphia, PA). The journal publication year was collected from National Center for Biotechnology Information and the journals' home pages.

2.3. Social network analysis and data visualization

Social network is a set of people or groups in which they are connected to others. And collaboration is a common social interaction in the social network. The social network analysis (SNA) is a method that illustrates the social interaction between people or groups on a particular issue (McLinden, 2013), such as computer science, energy efficiency, corporate governance system and disease etc.(Otte and Rousseau, 2002; Prem Sankar et al., 2015; Saldanha et al., 2016; Xu et al., 2012). It aims to quantify the network's structure features and the dynamics interactions among network vertices (Chen and Chang, 2015). By using varieties of measurement metrics like degree centrality, closest centrality etc., it indicates the relational properties of social networks such as who occupies different roles and positions in a network (Makagon et al., 2012).

To analyze the social network among countries and institutions, we employ the bibexcel software for data processing and Pajek for data visualization that are commonly used in previous studies (Ye et al., 2011; Zhang et al., 2016a). Briefly, we manually retrieved and optimize download records to resolve random errors such as missing content. We standardize each record with same formatting to extract the information of county and institution. The collaboration between countries and institutions by calculating their co-occurrence frequencies using bibexcel. A symmetric proximity matrix for their co-occurrence was established, and the number in each cell represented counts of two countries or institutions cooperation (Wang et al., 2015). Furthermore, this matrix could be used to generate net-file in bibexcel, which could be directly input to the mapping software Pajek to visualize their cooperation patterns (Leydesdorff and Vaughan, 2006).

3. Results and discussion

3.1. Groundwater contamination

3.1.1. Remediation versus contamination

As previous bibliometric research has described, “groundwater” and “contamination” were two frequently used keywords from 1993 to 2012 (Niu et al., 2014). Our study focuses on the groundwater contamination and remediation topics to further the understanding of recent contamination problems and remediation technology developments. We also include the discussion of various remediation as the consideration of contamination cleanup strategies. In the present study, the search for “groundwater contamination” resulted in higher numbers of publications and a rapid growth rate (Fig. 1). In addition to environmental science and water resources, the subjects within this search included multidisciplinary geosciences, engineering, soil science, public health, environmental health and toxicology. However, “groundwater remediation” was the subject of only approximately 50% of the publications with the subject “groundwater contamination”. A slight increasing trend can be observed during the past 20 years. The bibliometric analysis and patent analysis of groundwater remediation technology will be discussed in the following sections.

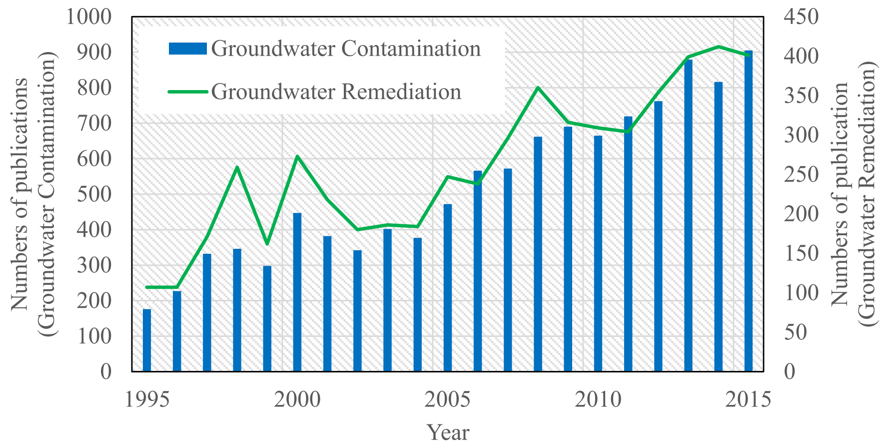

Fig. 1. The number of groundwater contaminations and groundwater remediation publications from 1995 to 2015.

3.1.2. Major contaminants

The total of 73 clusters was observed from OmniViz analysis and the top 30 clusters were presented in Table 1 and Fig. 1. The cluster C48 (contaminant, soil, model) has the most publications of 547, accounting for about 15.4% of all the publications with keywords. It indicates that studies related to contaminant, soil and model are popular in the groundwater remediation field, indicating the research joint of groundwater and soil studies. The cluster C43 (model, transport, simulate), C59 (soil, metal, extract), C63 (iron, zero-valent, nanoparticle) and C14 (iron, zero-valent, nanoscale) are also frequently selected as research topics. Furthermore, studies inside these clusters have high relatedness for the close location between publications points in these clusters, while these clusters are not so much related to other studies. Cluster C1, C2, C13 and C57 are closed to each other, suggesting that "biofilm, redox, reaction" are often linked to arsenic pollution, mine pollution or hydrocarbon pollution are related to studies of biofilm and redox reaction studies. Similarly, the C0, C44 and C53 are also have close relation, indicating that bioremediation studies, phytoremediation studies and metal studies are related to each other. It also shows the close relationships between DNAPL and water studies from the C19 and C49. Clusters C15, C16 and C38 present the identical major terms, "reactive, barrier, permeable", but they are resulted from different collections of publications (Fig. 2), for example, "reactive, barrier, permeable" was studied as a technology permeable reactive barrier (PRB) development and an application to remove various contaminants. This finding also suggests the cross-disciplinary research in the groundwater research area.

Further, we could observe the strong themes in the groundwater remediation field from Fig. 2. The top 3 highest peaks are about "contamination, soil, model", "iron, nanoscale, nanoparticle", "soil, metal, pollute" and "model, transport, simulate". It is consistent with the results of cluster analysis. The results also reveal that these topics are not so related to other topics for the steep slope and valley between them and their surrounding peaks as Fig. 2 shows. In general, the contaminants can be classified as two types: inorganic chemicals and organic chemicals. In organic chemicals such as arsenic, cadmium, chromium, uranium and nitrate can be found as major terms. The organic contaminates, for example chlorinated compounds, solvents and petroleum-hydrocarbons are showed in Table 1. These organic and inorganic chemicals have been as common contaminants in many nations (Kitanidis and McCarty, 2012; Parviainen et al., 2015; Zhang et al., 2016b, 2016c). For example, China has about 64.1% sites with heavy problems and 17.9% sites with volatile organic compound (Huang and Zhang, 2016). Similarly, chlorinated volatile organic compounds (CVOCs) and its stabilizer were widely manufactured and commonly used in the U.S. for many decades (Anderson et al., 2012; Mohr, 2010; Stroo et al., 2012). In addition, the organic pollutant mixtures (BETX, MTBE and VOC) (Table 1) suggests that the groundwater pollution is often found with multiple contaminants, which becomes the challenge for

Table 1
The selected clusters (recodes > 30) by OmniViz analysis.

No.	records (≥30)	Major terms	No.	records (≥30)	Major terms
C0	57	reduce, sulfate, metal	C38	58	reactive, barrier, permeable
C1	90	biofilm, redox, reaction	C39	63	attenuate, nature, bioremediation
C2	32	arsenic, adsorb, immobilize	C40	94	optimize, algorithm, genetics
C8	86	iron, reactive, barrier	C43	283	model, transport, simulate
C9	37	biodegrade, bacteria, bioaugmentation	C44	50	metal, phytoremediation, leach
C10	32	dechlorination, reductive, nanoparticle	C48	547	contaminant, soil, model
C13	51	mine, metal, drain	C49	79	water, quality, drink
C14	206	iron, zero-valent, nanoscale	C53	68	bioremediation, in-situ, bioaugmentation
C15	46	reactive, barrier, permeable	C57	48	hydrocarbon, fragrance, petroleum
C16	69	reactive, barrier, permeable	C58	55	transport, flow, mass
C19	35	source, zone, DNAPL	C59	265	soil, metal, extract
C23	34	organic, compound, volatility	C61	104	water, drink, surface
C24	30	chlorinate, solvent, dechlorination	C63	227	iron, zero-valent, nanoparticle
C32	115	oxidize, chemical, in-situ	C64	31	acid, drain, humic
C33	35	risk, land, health	C73	52	hydrocarbon, petroleum, soil

Note: C15, C16 and C38 clusters show the same major terms, but concluded from different publications.

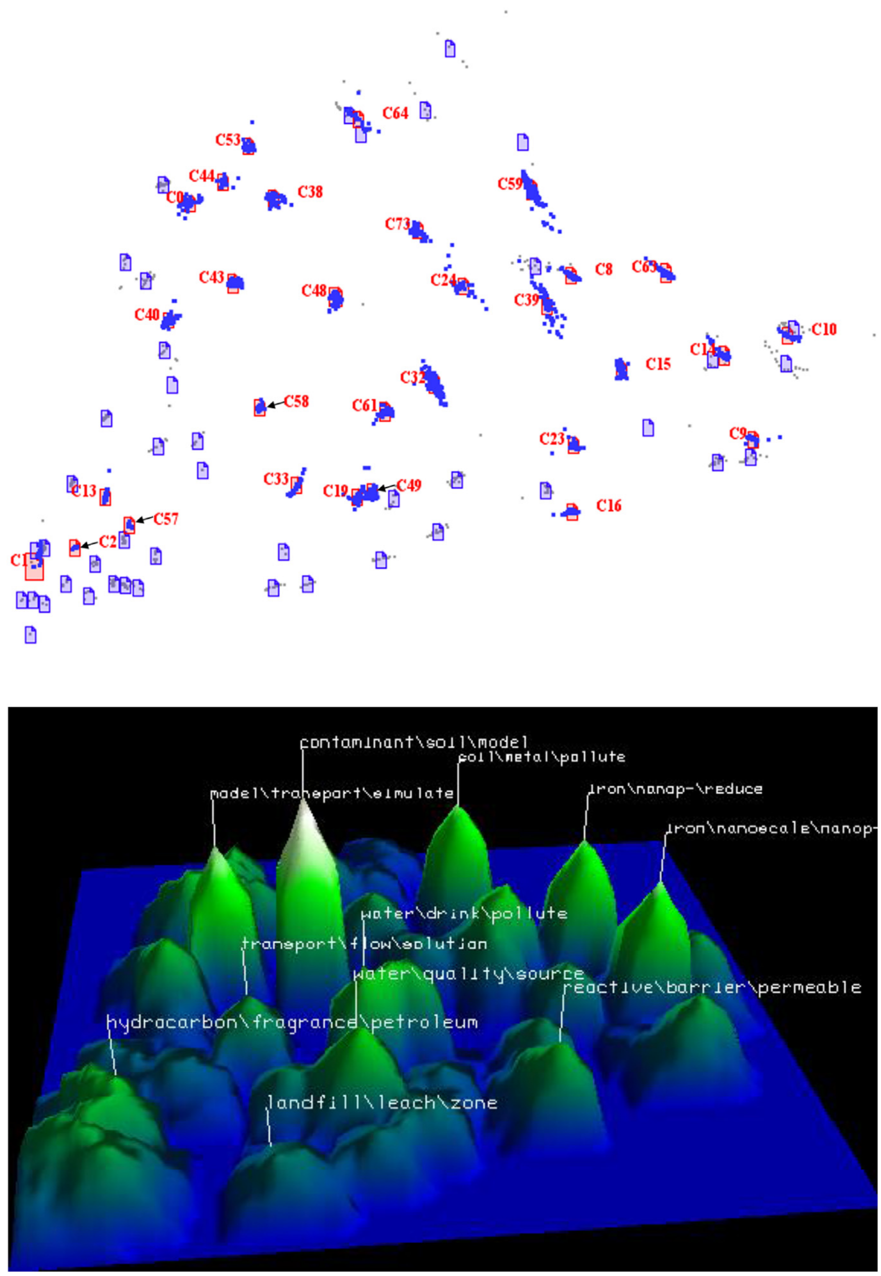

Fig. 2. Keywords- Galaxy (top) and Thememap (bottom) with its main peaks and terms. (note: “nanop-” is short for nanoparticle).

remediation. These organic and/or inorganic mixtures often require different removal technologies due to their different chemical and physical priorities. For example, the presence of BTEX inhibit the degradation of MTBE via impeding the microbial consortia activities (Wang and Deshusses, 2007). While many sites have undergone active remediation for decades, there is an urgent demand for cost-effective and sustainable technologies that allow treatments to simultaneously or sequentially remove mixed contaminants (contaminants with different solubility, vapor pressure, and degradation potential) under various redox regimes and geological conditions.

Furthermore, new chemicals that are continuously invented and manufactured; exist compounds that displayed new environmental transportation pathways; and exist compounds that have increased potential to threaten the human health will become potential emerging contaminants, as well as contaminant of emerging concern (CEC) (Lapworth et al., 2012; Leeson et al., 2013; Suthersan et al., 2016). For example, 1,4-dioxane, perfluorooctanoic acid (PFOA) and related perfluorinated compounds, and N-nitrosodimethylamine (NDMA) were addressed as emerging contaminants (Leeson et al., 2013). Recently, Strategic Environmental Research and Development Program (U.S.) released the proposal calls - Improved Strategies for Remediating Mixed Contaminants in Groundwater in 2015 and Improved Understanding of Per- and Polyfluoroalkyl Substance Source Zones in 2016 (SERDP, 2015, 2016). The 12th Five - Year Plan for the Development of the National Natural Science Fund released by Chinese government, underscored the importance of soil and water contamination control and management (National Natural Science Foundation of China, 2012). This finding suggests there are research needs and opportunities for future emerging contaminant remediation studies.

3.2. Groundwater remediation technology

The gradually increasing number of article citations from 1995 to 2015 is associated with the appearance of new journals (e.g., Chemical Engineering Journal, which has been publishing since 1996, and Environmental Earth Science, which has been publishing since 2009). A total of 5486 publications include 72.9% that are refereed journal articles, 21.7% that are proceedings papers, 3.6% that are reviews and 1.7% that are other document types. We explored the contribution of country, international collaboration, distribution of funding agencies and journal productivity to the groundwater remediation field.

3.2.1. Contributions of countries

The top 5 productive countries in publishing journal articles are the United States (2332 publications), China (784 publications), Germany (456 publications), Canada (426 publications) and the United Kingdom (318 publications) (Fig. 3). In addition, the United States has absolute advantage in the total number of published articles (2332) for groundwater remediation during 1995–2015. We also identified the growing of publications of China associated with the increasing budget form National Science Foundation of China since 2000 (Yang, 2016a,b) and published 117 articles in 2015 which has reached the same productivity as the U.S. (Fig. 4). The U.S. Environmental Protection Agency (EPA) was formed in 1970 and was finally given authority in 1980 to clean up hazardous waste sites with the enactment of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund). To achieve the regulatory advisory guidelines for many types of chemicals, a wide range of studies on effective cleanup technologies have been gradually reported in the past two decades. Similarly in China, Nature Index revealed that China's research output (reported as weighted fractional count, a metric that apportions credit for each article according to the affiliations of the contributing authors) grew by 16% from 2013 to 2014 (May and Brody, 2015; Nature, 2015). This finding suggests the potential of China to lead this research area in future.

The distribution of patent registrations showed that the United States (3275 patents), China (3050 patents), and Japan (1748 patents) are the top 3 countries that produce groundwater remediation-related intellectual property (Fig. 3). The number of patents (11,420) is much larger than the number of publications (5486), which indicates the reporting of inventions and new technologies occurs primarily as patents rather than journal articles. Government agencies also play an important role in encouraging and stimulating knowledge-generating institutions such as university research laboratories, industrial research and research and development centers and national laboratories (Van Looy et al., 2006). The timeline of registration and the potential profitability are also considered controlling factors (Geuna and Nesta, 2006). The varying contributions of patent and scientific article publications are also heterogeneous across countries and disciplines. For example, the United States and China are highly productive in both areas, but Japan has a primary focus on intellectual property rights (IPR) protection, which may affect their scientific and technical publications (David and Hall, 2006).

3.2.2. Pattern of international collaboration

We applied SNA to analyze the international collaboration among the 20 most productive countries during the period 1995–2015 (Fig. 4). Each node represents a different country, and the size of the node indicates the number of publications. Similarly, the lines connecting the countries represent their cooperation and the line thickness indicates the degree of collaboration. As previous described, the countries were ranked by the total number of publications in the present study. Collaboration was determined by the affiliations of coauthors and all countries or institutes can benefit if one publication is a collaborative study (Bozeman et al., 2013; Chen et al., 2005). These 20 productive countries worked closely with each other, particularly the U.S., China, Canada and South Korea. The U.S. was the center of this collaboration network and the leader of groundwater remediation research in cooperation with the other 19 productive countries. The U.S. and China had the closest collaboration, followed by the U.S.-Canada, U.S.-South Korea, China-Canada and U.S.-UK. Interestingly, our results are in agreement with the Nature Index record that displays international collaboration among all of the research areas in the past year. For example, the U.S. is also the center of the network and closely collaborates with China, the UK, Germany, Canada and France (Grayson and Pincock, 2015; Nature, 2016). The research subjects cover the physical, life, and environmental sciences as well as chemistry. These findings indicate that the collaboration on groundwater remediation research plays an important role in the overall international cooperation. In addition, the international collaborations may promote the individual productivity of cooperative countries. For instance, China, Canada, the UK and Germany have a close collaboration with the U.S., and these countries are also ranked as the top five productive countries (Figs. 4 and 5).

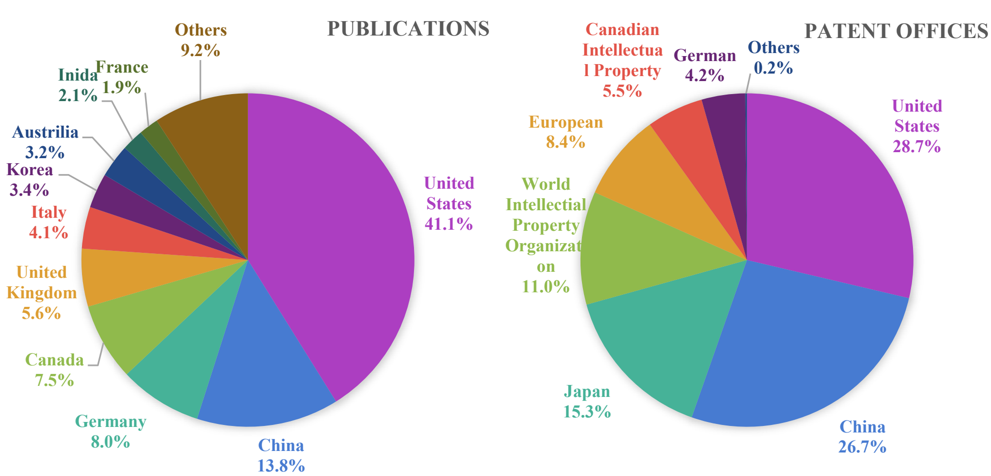

Fig. 3. Distribution of publications and patent offices during 1995–2015.

Year	USA	China	Germany	Canada	UK	Italy	South Korea	Australia	India	France
1995	52	0	19	11	8	1	0	0	0	1
1996	78	1	1	11	3	1	1	2	1	0
1997	123	2	8	12	8	3	0	7	1	0
1998	143	6	34	16	20	3	0	4	2	1
1999	112	3	7	17	4	1	2	5	0	3
2000	172	5	20	19	10	3	3	3	2	2
2001	136	7	8	20	12	5	6	1	4	2
2002	92	7	14	18	12	4	5	13	4	4
2003	99	11	16	15	9	10	6	5	3	3
2004	75	14	25	16	8	3	8	8	2	4
2005	110	25	18	16	24	8	14	7	9	2
2006	110	25	21	30	23	9	10	5	9	4
2007	145	32	20	30	21	12	25	8	13	3
2008	117	42	47	30	26	28	12	14	21	7
2009	115	56	27	31	9	16	21	10	17	5
2010	93	58	33	25	22	18	13	8	17	9
2011	94	61	26	11	22	11	10	19	16	10
2012	114	102	32	27	11	17	10	9	19	7
2013	119	96	25	24	24	23	20	21	10	15
2014	114	114	24	30	25	23	17	15	14	11
2015	120	117	31	17	18	32	8	19	8	15

Fig. 4. The annual productivity of the top 10 most productive countries from 1995 to 2015. The color bars represent the number of publications and the numbers are also reported.

The institutional collaboration among the 20 most productive organizations from 1995 to 2015 was also analyzed using SNA (Fig. 6). As previously described, each node represents a different organization and the size of the node indicates the number of publications. The linkage lines represent their cooperation, and the line thickness indicates the degree of collaboration. Ten of the organizations are from the U.S., which suggests that these highly productive organizations contribute to the overall leadership of the U.S., as shown in Fig. 4. These 20 productive organizations worked closely with their geological neighbor organizations. In other words, these institutes favorably collaborate with others from the same country, for example, the University of Regina and the University of Waterloo in Canada, Oak Ridge National Laboratory and Stanford University in the U.S. and UFZ Helmholtz Center for Environmental Research (UFZ Helmholtz Ctr Environ Res) and the University of Tubingen in Germany.

3.2.3. Distribution of funding agencies

Research subjects and directions can be influenced by research funding agencies (Nature, 2015). In general, most financial support is from national science foundations and governments, which engage in knowledge-transfer strategies and decision making (Lavis et al., 2003). The diverse distribution of funding agencies in the groundwater remediation research field can be observed in the present study. From 1995 to 2015, the top 20 productive funding agencies, which account for 9.3% of publications, were from China, the United States and Europe, as shown in Table 2. This result is in agreement with the distribution of country performance described above (Fig. 3). Moreover, China has many specific grant programs (e.g. Program for new century excellent talents in university of China and China Postdoctoral Science Foundation) to support research in universities, but the United States and European Union also provide specific funding opportunities to other institutes and private companies, for example the National Institute of Health Academic–Industry Partnership Program and the Danish National Advanced Technology Foundation (Chai and Shih, 2016). These academic-industry partnerships not only drive the increasing scientific publications, but also the development of innovative technologies (Chai and Shih, 2016). For example, several environmental consulting companies and chemical manufacturers, such as

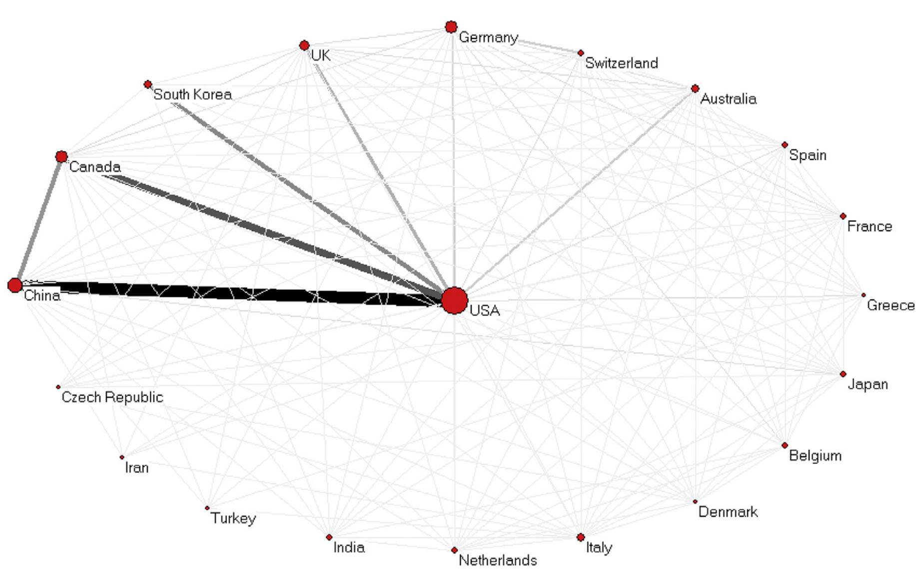

Fig. 5. International collaboration according to social network analysis.

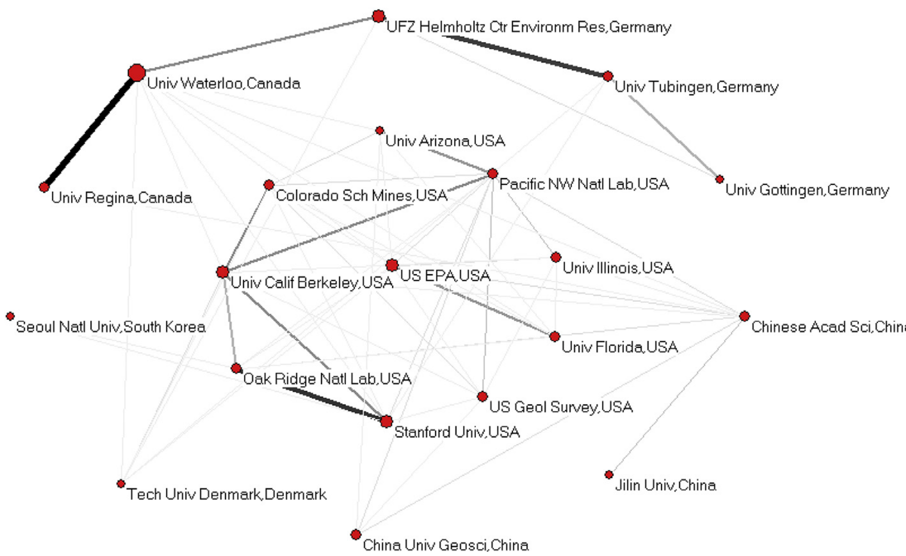

Fig. 6. Institutional collaboration according to social network analysis. The "Univ" abbreviation represents university.

AECOM, ERM and DuPont (not listed in the table) provide grants for fundamental scientific research to meet clients' needs. In 2015, Nature Index reported a global overview of research publications in a select group of scientific journals (May and Brody, 2015), which indicated that the U.S. was ranked 10th in the world for research and development funding as a percentage of gross domestic product (GDP) (Nature, 2015).

3.2.4. Characterization of research areas and publication sources

The top 20 most productive journals, which account for approximately 38.4% of the total publications, are listed in Table 3. Environmental Science and Technology and Journal of Contaminant Hydrology are the most productive journals, with 334 and 259 articles, respectively. Water Research and Environmental Science and Technology have the highest IFs, at 5.5991 and 5.393, respectively. The increasing IF of Water Research (increased from 2010 to 2015 from 4.546 to 5.991) and Environmental Science and Technology (increased from 2010 to 2014 from 4.827 to 5.393) in the past five years can be explained by their wide scope of environmental disciplines and broad audience, which includes chemical engineers, chemists, civil engineers, environmental engineers, biologists and microbiologists. Moreover, environment pollution as a global issue is widely recognized and the rapid growth of environment-related research subjects reflects this awareness and the importance of this issue. The impact of the journal is not the significant indicator to reflect the influence in the field of "groundwater remediation". Therefore, we included the average cited amount to better reflect the performance and influence of groundwater remediation-related papers published in one journal. We applied the calculation of total citation divided by the number of published "groundwater remediation" articles. The results indicated that publications in Environmental Science and Technology had the largest average cited amount (56.85), followed by Chemosphere, Journal of Hazardous Materials and Water Research.

3.2.5. Groundwater remediation technology

The slow growth rate of groundwater remediation publications and the gap between the problems (groundwater contamination)

Table 2
The top 20 productive funding agencies.

Funding Agencies	Records
National Science Foundation of China	205
US National Science Foundation	72
National Science and Engineering Research Council of China	55
Fundamental Research Funds for the Central Universities-China	51
Strategic Environmental Research and Development Program (SERDP)-U.S.	33
European Union	24
U.S. Department of Energy	24
National Environmental Protection Public Welfare Science and Technology Research Program of China	19
China Postdoctoral Science Foundation	19
National science council of Taiwan	19
US EPA	18
Program for new century excellent talents in university of China	18
Shanghai National science funds	15
US department of defense	13
European commission	12
National institute of environmental health science (NIEHS)-U.S.	11
Engineering and Physical Sciences Research Council (EPSRC)-UK	11
Chinese academy of sciences	10
Natural Environment Research Council-UK	9
National high technology research and development program of China (863 program)	9

Table 3
The top 20 most productive publication source.

Journal Titles	Records	IF(2015)	Publication year	Average cited amount
Environmental Science and Technology	334	5.393	1967	56.85
Journal of Contaminant Hydrology	259	2.063	1986	23.28
Journal of Hazardous Materials	207	4.836	1975	33.81
Chemosphere	130	3.698	1972	36.37
Water Research	127	5.991	1967	32.45
Water Resources Research	120	3.792	1965	27.87
Bioremediation Series (Book Series)	105	N/A	1997	N/A
Water, Air, & Soil Pollution	82	1.551	1972	13.48
Science of the Total Environment	78	3.976	1972	30.26
IAHS publications	78	1.549	1982	N/A
Groundwater Monitoring & Remediation	71	0.848	1981	7.9
Environmental Science and Pollution Research	67	2.76	1994	9.75
Chemical Engineering Journal	65	5.31	1996	14.42
Water Science and Technology	64	1.064	1981	7.58
Journal of Hydrology	59	3.043	1963	18.09
Journal of Environmental Engineering	59	1.125	1983	12.82
Groundwater	52	1.947	1963	0.84
Applied Geochemistry	52	2.468	1986	25.14
Environmental Earth Sciences	50	1.765*	2009	3.31
Journal of Environmental Science and Health, Part A Toxic/Hazardous Substances and Environmental Engineering	48	1.276	1998	10.98

(* 2014 IF).

and solutions (groundwater remediation) (Fig. 1) suggest that there is another route of the transmission of research results in addition to academic publications. Therefore, we also collected the number of groundwater remediation-related patents using Google Patent Search. A total of 11,420 patents were found using the keyword “groundwater remediation” for the period 1995 to 2015. Chemical oxidation, adsorption and biodegradation are the three major patented technologies (Fig. 5).

The data extraction from Google Patent Search is not robust as the analysis on the Web of Science. To further understand the percentage of patent that were through academic and industrial collaboration, we conduct the data collection and analysis using patent information through Web of Science by keywords “groundwater contamination” and “groundwater remediation”. We collected 217 patents from 1995 to 2016 and the result indicates that the ratio of patent owners of academic and industrial is nearly 2:1. In addition, individual and some non-profit organization also published many patents. In addition, R&D in industries is still the major driving force as previously described (K and D, 2016, Yang, 2016a,b; Sun and Cao, 2014).

3.2.5.1. Pump and treat. To clean up contaminated groundwater, pump and treat was one of the earliest groundwater and soil remediation strategies widely applied. However, the treatable pollutants, cost considerations, cleanup efficiency and secondary contamination became limitations to successfully remediate the contaminated sites (Mackay and Cherry, 1989; Travis and Doty, 1990). Therefore, from 1980s, researchers began seeking more remediation options. Our analysis also indicated the decreasing number of pump-and-treat-related publications (Fig. 8). However, the rebound in recent years suggests the combination of pump and treat with other alternatives have been studies, such as advanced oxidation processes (Boal et al., 2015) and bioremediation (Thornton et al., 2014), to enhance the removal performance and lower the cost (Suthersan et al., 2015). Furthermore, the concept of *in situ* remediation has been applied to clean up contamination and reduce or eliminate transportation costs (Kitanidis and McCarty, 2012).

3.2.5.2. Biodegradation. Biodegradation is a proven *in situ* technology and can destroy harmful and toxic contaminants via microbial activities (Singleton, 1994). Because biodegradation is cost effective with less secondary contamination and long-term sustainability advantages, it has been widely studied and developed (Adamson et al., 2011). Fig. 8 depicts that the number of biodegradation-related publications has been increasing during the past 20 years, which suggests the importance of academic research and application. The successful biodegradation is usually succeeded under optimal conditions, such as aerobic and anaerobic condition and the presence of electron donor/acceptor. (Fritsche and Hofrichter, 2005; Lendvay et al., 2003; McGuire et al., 2016; Zhang et al. 2013, 2016c). Furthermore, the complex geochemistry underground, a lack of nutrients and the presence of inhibitors can also limit microbial activities to biodegrade and biotransfer contaminants. The continuous isolations and identifications provide many microbial candidates responsible for bioremediation. Further, the advanced understanding of microbial community and genetic analysis drive a new research direction on defined/engineered microbial community design and application (Lewis et al., 2016). For example, the number of patented microbial consortia that enhance biodegradation has been increasing over the past 20 years (Fig. 7).

3.2.5.3. Chemical oxidation and reduction. Chemical oxidation-related publications have been dramatically increasing since 2006, and chemical reduction-related publications are slowly growing (Fig. 8). As described previously, *in situ* groundwater remediation provides a sustainable opportunity to treat contamination on site. *In situ* chemical oxidation (ISCO) provides a high removal efficiency over a short timeline in field applications (Crimi, 2016; Krembs et al., 2010). Among the five commonly used oxidants (permanganate, catalyzed hydrogen peroxide (CHP), persulfate, ozone and percarbonate) (Crimi, 2016), hydrogen peroxide, persulfate and permanganate have been studied the most (Fig. 9). A similar result was concluded from the study of ISCO projects implemented from 1995 to 2007 (Krembs et al., 2010; Kuppusamy et al., 2016). This correlation between scientific publications and field application suggests the role of fundamental science research as a guideline for technology field demonstrations. The total number of chemical reduction publications (302) within the

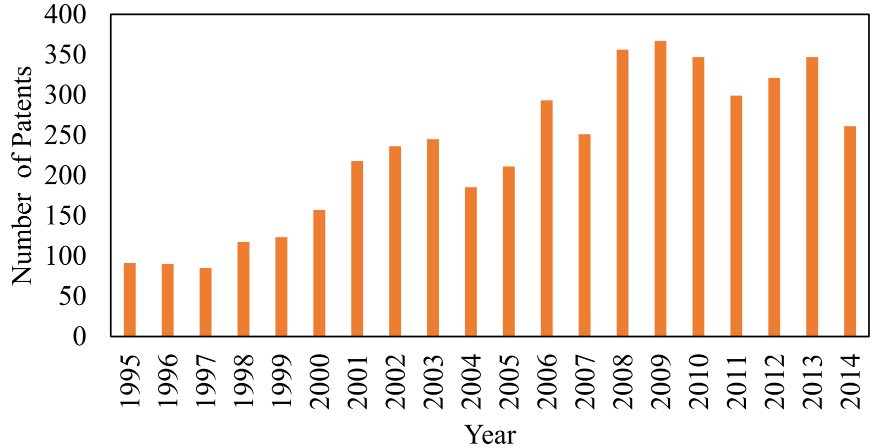

Fig. 7. Number of patents (microbial consortium & biodegradation)- from Google patents search.

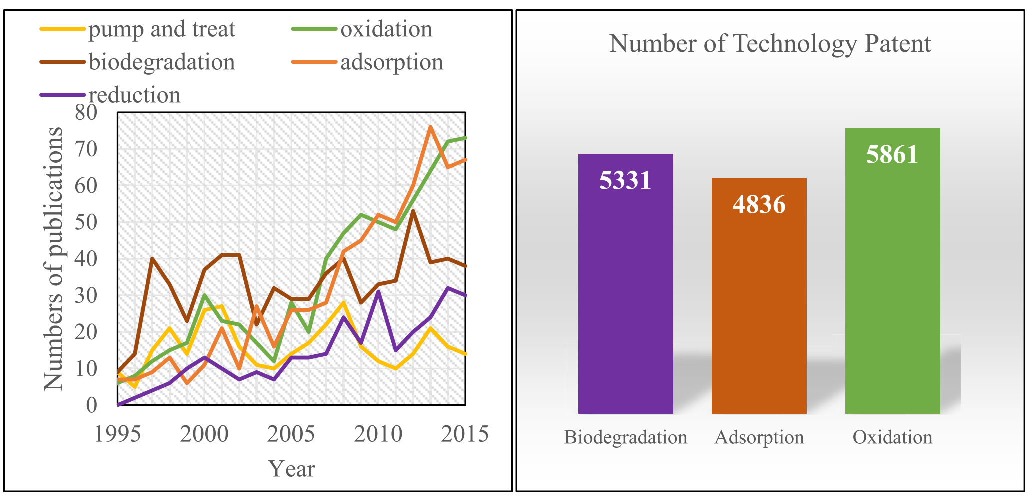

Fig. 8. Publication trends of major remediation technologies from 1995 to 2015.

groundwater remediation field is approximately half the number of chemical oxidation publications (715).

3.2.5.4. Adsorption. Adsorption is considered an effective environmental control technology. Activated carbon adsorption to remove environmental contaminants has been successfully applied for many decades. Organic compounds, such as chlorinated solvents trichloroethylene and inorganic metals (copper, zinc and

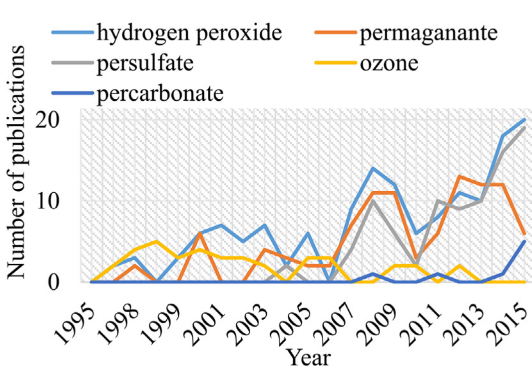

Fig. 9. Trends in *in situ* chemical oxidation research from 1995 to 2015.

lead), can be adsorbed by granular activated carbons (GACs) (Crittenden et al., 1988; Goyal et al., 2001; Kilduff et al., 1998; Nakano et al., 2000). The increasing number of adsorption-related publications indicates that physical treatment to remove contaminants plays an important role in fundamental research and application. The search using the keyword "adsorption" also includes the subject of interaction between contaminants and soil/sediment particles, for example, the impact of adsorption on the bioavailability of organic chemicals and metal ions (Robertson and Jjemba, 2005; Yang et al., 2002). Thus, the related research, which may not have a direct connection with groundwater remediation, is attributed to the growth of adsorption publications. To further differentiate the categories of adsorption, we screened the keywords and titles of 501 articles which relate to adsorption subject. As a result, 261 articles were focusing on the polluted water remediation filed and 182 of these were in the groundwater filed. In addition, 73 articles address soil pollution remediation. Among them 29 articles were combination of soil and water or groundwater contaminated remediation using adsorption. Furthermore, because adsorption is unable to transform undesirable contaminants into non-harmless products, adsorption has been studied and applied in combination with biodegradation and/or chemical treatments. For instance, many studies reported successful groundwater remediation by using permeable reactive barriers (PRBs) packed with zeolites (Vignola et al., 2011). In addition, new material and absorbent inventions have triggered fundamental research in the laboratory for removal kinetics and efficiency evaluation, such as TiO_2-based adsorbents to simultaneously remove As(V), As(III), monomethylarsonic acid (MMA), and dimethylarsinic acid (DMA) (Jing et al., 2009) and Ambersorb™ 560 to remove 1,4-dioxane and chlorinated solvents (Simon, 2015). As a result, applying adsorption technology to remediate contaminated groundwater is expected to exhibit continuous growth in the near future.

3.2.5.5. Others. The increasing number of novel techniques have been developed by integrating the conventional treatments with modern technologies, such as nanotechnology, membrane and material science, and genetic and enzyme engineering. For example, Fu et al. (2014) reported the publication on nanoscale ZVI (nZVI) already accounted for 15.8% of total ZVI publications in 2013. The studies on nZVI immobilization and packaging materials have been increasingly reported to improve the decontamination efficiency. Similarly, the applications of environmental microbiology shorten the biodegradation potential evaluation period and greatly improve the monitoring sensitivities, such as biomarker development, microbial community analysis and enzyme activity assessment (Suthersan et al., 2016; Zhang et al., 2017). These findings suggest the interdisciplinary researches may stimulate the groundwater remediation publications and applications.

4. Conclusions

4.1. Summary

This study evaluated a total of 5486 groundwater remediation-related publications from 1995 to 2015 using a bibliometric analysis. The document types consisted of 72.9% articles, 21.7% proceedings papers, 3.6% reviews and 1.7% classified as others. We performed the keywords cluster analysis by OmniViz analyzer to identify the major research topics, including “contaminant, soil, model”, “model, transport, simulate”, “soil, metal, extract”, “iron, zero-valent, nanoparticle” and “iron, zero-valent, nanoscale”. These topics also reveal the current groundwater contamination and remediation research focuses, as well as the transition and combination between science and innovative technology developments, including nanomaterial application and model simulation analysis. The discussion of globally collaboration, journal performance and alternative remediation strategies provide a valuable reference and global overview for researchers, practitioners and decision makers who currently work on groundwater remediation and others with an interest in this area.

4.2. Future directions

4.2.1. Transition plans from laboratory study to field application

The challenge for field application is the complex environmental conditions that are not well represented in bench-scale experiments. To enhance field demonstration, transition plans are needed to bridge laboratory to field work. To date, laboratory microcosms, bench scale pilot studies are commonly applied approaches to examine the potential of selected remediation strategies to address contamination. However, these studies conducted with controllable parameters were unable to fully represented the environmental conditions. For example, biodegradation studies using pure microbial culture often reported positive results in the laboratory. However, the presence of co-contaminants and the competition with other microbial players in the groundwater may became problems prevent the successful biodegradation. These limitations highlight the importance of collecting empirical results, model prediction and transition plans in future research.

4.2.2. Development of field characterization tools

Site characterization is often required to identify groundwater problems, to determine the contamination area, to estimate the remediation time expenses and to design a practicable remediation plan. Therefore, the diagnostic assessment of groundwater geological condition and contamination texture and the development of a real-time monitoring system provide information for researchers and practitioners to adjust the remediation strategy and evaluate the performance of ongoing applications. However, less than 3% of groundwater remediation publications are related to “field characterization” and less than 2% of the publications are related to geological study, which suggests the need for research on the combination of geology and hydrology prior to demonstrate remedy plans.

4.2.3. Plan of site-reuse and site-reoccupation

Groundwater remediation is generally referred to the construction that removes contaminants from the contaminated sites. However, studies on post-remediation, including short-term and long-term monitoring and evaluation, risk assessment and site-reoccupation are limited reported from our analysis. The ecological recovery and redevelopment should also be considered as parts of groundwater remediation plan (Beames et al., 2014). The implementation of physical, chemical and biological treatments could alter the original ecosystem settings and increase/decrease the health risk to human and other organisms. In addition, the cost and time constrains of remedy design and construction may result in different challenges to sustain the development of sites and groundwater resources (Ren et al., 2017). The impact of various remediation strategies and prediction model simulation and assessment on the site sustainability should be well understood in future study.

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