Journal of Hydrology 519 (2014) 966–975

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review Paper

Twenty years of global groundwater research: A Science Citation Index Expanded-based bibliometric survey (1993–2012)

Beibei Niu [a,b], Hugo A. Loáiciga [b], Zhen Wang [a,b], F. Benjamin Zhan [c], Song Hong [a,c,*]

[a] School of Resource and Environmental Science, Wuhan University, Wuhan 430079, China
[b] Department of Geography, University of California, Santa Barbara, CA 93106, USA
[c] Department of Geography, Texas State University, San Marcos, TX 78666, USA

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 25 July 2014
Accepted 31 July 2014
Available online 17 August 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Roseanna M. Neupauer, Associate Editor

Keywords:
Groundwater
Bibliometric analysis
SCI-Expanded
Geographical distribution
Research trends

SUMMARY

A bibliometric analysis was conducted to evaluate groundwater research from different perspectives in the period 1993–2012 based on the Science Citation Index-Expanded (SCIE) database. The bibliometric analysis summarizes output, categorical, geographical, and institutional patterns, as well as research hotspots in global groundwater studies. Groundwater research experienced notable growth in the past two decades. "Environmental sciences", "water resources" and "multidisciplinary geosciences" were the three major subject categories. The *Journal of Hydrology* published the largest number of groundwater-related publications in the surveyed period. Major author clusters and research regions are located in the United States, Western Europe, Eastern and Southern Asia, and Eastern Australia. The United States was a leading contributor to global groundwater research with the largest number of independent and collaborative papers, its dominance affirmed by housing 12 of the top 20 most active institutions reporting groundwater-related research. The US Geological Survey, the Chinese Academy of Sciences, and the USDA Agricultural Research Service were the three institutions with the largest number of groundwater-related publications. A keywords analysis revealed that groundwater quality and contamination, effective research technologies, and treatment technologies for water-quality improvement were the main research areas in the study period. Several keywords such as "arsenic", "climate change", "fluoride", "groundwater management", "hydrogeochemistry", "uncertainty", "numerical modeling", "seawater intrusion", "adsorption", "remote sensing", "land use", "USA"(as study site), and "water supply" received dramatically increased attention during the study period, possibly signaling future research trends.

Contents

* Corresponding author at: School of Resource and Environmental Science, Wuhan University, China. Tel.: +86 27 68778381; fax: +86 27 68778893.
E-mail address: environmentalanalytics@gmail.com (S. Hong).

http://dx.doi.org/10.1016/j.jhydrol.2014.07.064
0022-1694/

1. Introduction

Groundwater, an active component of the hydrologic cycle, is widely recognized as a critical and vulnerable resource (Vörösmarty et al., 2000; Aeschbach-Hertig and Gleeson, 2012). Recent decades have witnessed rising rates of falling aquifer water levels, drying of wetlands, seawater intrusion, and general deterioration of water quality (Kinzelbach et al., 1998; Reichard and Johnson, 2005; Famiglietti and Rodell, 2013). Simultaneously, groundwater research has increased steadily covering a variety of topics, such as geochemical and hydrological process of groundwater (Wang and Cheng, 2000; El-fiky et al., 2010), interactions among groundwater, surface-water, land use and climate changes (Sophocleous, 2002; Chen et al., 2009; Wang and Hejazi, 2011), hydrogeochemical characteristics and water quality contamination (Chae et al., 2009; Alam et al., 2010), techniques for groundwater modeling and assessment (Brunner et al., 2006; Singh and Minsker, 2008), and groundwater management and policies (Aeschbach-Hertig and Gleeson, 2012; Choi et al., 2013). Groundwater studies have been reviewed from different viewpoints (Welch et al., 2000; Scanlon et al., 2002; Mandal and Suzuki, 2002; Böhlke, 2002), and those of Schwartz and Ibaraki (2001) and Schwartz et al. (2005) are most relevant to hydrologic sciences in using bibliometric analyses. Citation analysis has been by others used to examine the maturity and vitality of hydrogeology and to assess its impact in the hydrologic sciences. This paper's focus is on groundwater-related research, relying for this purpose on a comprehensive statistical review of the characteristics and trends of groundwater research contents of accessible documents over the past two decades.

Bibliometrics was first introduced as an application of mathematical and statistical methods to books and other media of communication (Pritchard, 1969). In recent years, it has been widely applied in various fields to (i) evaluate scholarly productivity of institutions and countries, (ii) explore research trends in specific fields, and (iii) identify geographic distributions and international collaborations by investigating authorship, sources, subjects, geographic origins, and keywords (Persson et al., 2004; Wang et al., 2009; Sun et al., 2012). Several new statistical methods and advanced technologies were gradually added to bibliometric research, such as CiteSpace for visualizing patterns and trends in scientific literatures (Chen, 2003), and social network analysis for building co-word and collaboration networks (Zhuang et al., 2013).

In this study, bibliometric approaches were used to quantitatively and qualitatively investigate global groundwater research trends during the period of 1993–2012. Specifically, this article aims at (i) identifying general patterns for publication outputs, journals, and subject categories in groundwater research; (ii) evaluating national and institutional research outputs; and (iii) summarizing global research trends and hot issues, which may serve as a potential guide for future research.

2. Data sources and methods

The data for this paper were collected from the online version of Science Citation Index Expanded (SCIE) bibliographic database, which is maintained by Thomson Reuters. SCI-Expanded, which indexes the world's leading journals of science and technology, is a leading and frequently used metric of scientific accomplishment in most fields of human creativity (Kostoff et al., 2000; Li et al., 2009). Series of search terms, including "groundwater*", "ground water*", "underground water*", "subsurface water*", "subterranean water*", "unconfined water*", "confined water*", "artesian water*", "phreatic water*", "crack water*", "fracture water*", "fissure water*", "crevice water*", "karst water*", "karstic water*", "well water*", and "spring water*" were used to locate publications that contained these words in publications' titles, abstracts, and keyword lists. The terms listed above could help retrieve the vast majority of groundwater-related publications. Although there may be other less common groundwater-related terminology, they account for a small number of publications and may have marginal relation to groundwater research.

Articles originating in England, Scotland, Northern Ireland, and Wales were grouped under the UK (United Kingdom) heading. Articles from Hong Kong were excluded from China. Author affiliations were statistically analyzed to evaluate the contributions of different institutions and countries. The term "single country/institution" was assigned if researchers' addresses were from the same country/institution and the term "international/inter-institutionally collaboration" was designated to those articles that were co-authored by researchers from multiple countries/institutions. The affiliations of authors were geocoded using CiteSpace 3.8 R1 (Chen, 2004), and the worldwide geographic distribution of authors was plotted using ArcGIS 10.0. Our keywords analysis took author keywords as analysis objects, using 5-year intervals to minimize year-to-year fluctuations.

3. Results and discussion

3.1. Research output trend

The earliest papers indexed in the SCIE database appeared in 1900: *Removal of iron from groundwater* authored by G. Oesten (Germany), and *Movements of ground water* by B.S. Lyman (England). A substantial interest in groundwater studies did not emerge until 1972, when the annual output reached over 100. A series of organizations and activities promoted the development of hydrological science internationally. In 1956, a world-wide organization, the International Association of Hydrogeologists (IAH), was founded with the mission of understanding groundwater processes and pursuing the wise use and protection of groundwater resources. The International Hydrological Programme (IHP), a broad-based intergovernmental science program of the UN system devoted to hydrology and water resources, was initiated in 1975 (Al-Weshah, 2003). Later on, the First Scientific Assembly of the International Association of Hydrological Sciences (IAHS) was held at Exeter in July 1982 (IAHS, 1982). After a slow steady growth, the number of groundwater publications soared in the past two decades.

Groundwater-related research gained momentum in the 21st century synchronously with increasing concerns about groundwater supply and quality and their social implications, which are ubiquitous around the world. Based on the aforementioned

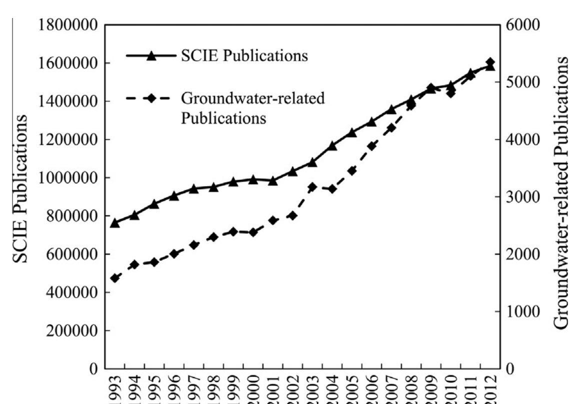

Fig. 1. Growth of SCIE publications and groundwater-related publications.

Table 1
The 20 most active journals in groundwater-related research.

Journal	TA (%)	AAGR (%)	TA/TJA (%)	TC/TA
Journal of Hydrology	2136(3.55)	5.45	32.53	17.22
Water Resources Research	1868(3.10)	0.14	25.94	25.25
Environmental Earth Sciences[a]	1766(2.93)	12.80	36.72	6.37
Environmental Science & Technology	1673(2.78)	9.75	9.19	37.23
Groundwater	1272(2.11)	1.11	67.23	15.79
Hydrogeology Journal	1088(1.81)	5.73	88.03	9.32
Journal of Contaminant Hydrology	896(1.49)	4.41	49.86	19.32
Hydrological Processes	893(1.48)	16.60	21.51	13.54
Applied Geochemistry	825(1.37)	8.99	31.11	16.25
Journal of Environmental Quality	777(1.29)	2.73	18.05	23.03
Water Research	776(1.29)	7.12	8.43	26.21
Water Science and Technology	732(1.22)	−1.11	5.31	8.87
Science of the Total Environment	596(0.99)	11.19	6.22	22.16
Chemosphere	573(0.95)	8.84	4.40	19.26
Water Air and Soil Pollution	557(0.92)	8.34	9.58	10.04
Journal of Hazardous Materials	547(0.91)	13.80	4.85	14.41
Environmental Monitoring and Assessment	507(0.84)	11.14	9.22	5.25
Ground Water Monitoring and Remediation	479(0.8)	1.59	64.99	9.07
Advances in Water Resources	463(0.77)	11.92	26.79	15.21
Desalination	443(0.74)	4.94	5.22	12.00

TA(%): total number of groundwater-related articles published in a journal (followed by the percentage of groundwater-related articles in the journal of the total groundwater-related articles); AAGR: average annual growth rate of the number of groundwater-related articles in a journal; TA/TJA: the percentage of groundwater-related articles in a journal of the total number of articles published in the journal; TC: Total number of citations; TC/TA: the average number of citations that groundwater-related articles in a journal received.
[a] Environmental Earth Sciences: prior to Volume 59 this journal was published as Environmental Geology.

retrieval methods, a total of 64,376 papers were identified as groundwater-related in the Science Citation Index Expanded database during 1993–2012. Along with the expansion of SCIE databases, most scientific fields experienced rapid growth of publication outputs (Gattuso et al., 2005). Therefore, exploring whether groundwater-related research increased absolutely, or whether it grew faster than the total of science, is insightful in the analysis of trends in output. The two curves shown in Fig. 1 show that groundwater-related publications present a steeper growth (6.62% growth from 1993 to 2012) than the total SCIE publications (3.90%), and the proportion of groundwater publications increased from 0.21% in 1993 to 0.34% in 2012. In addition, among the various document types (article**s**, letter**s**, software review**s**, book review**s,** etc.), articles (60,227) constituted the majority (93.6%) of documents used in this survey. To ensure data consistency, our analysis was further restricted to research articles published during 1993–2012.

3.2. Subject categories and major journals

Due to the assignment of journals to multiple subject categories, groundwater-related research covered 189 Web of Science categories. The three most common categories were Environmental Sciences (19,766 articles; 17.34% of the total), Water Resources (18,950; 16.62%), and Multidisciplinary Geosciences (13,854; 12.15%), followed by Environmental Engineering (6394; 5.61%), Civil Engineering (5001; 4.39%), and Geochemistry & Geophysics (3537; 3.10%). Although groundwater studies have also covered subjects in other engineering subjects, earth sciences, and social sciences, the concentration of groundwater articles in the above-mentioned subject categories reveals that the gravity center of groundwater studies revolves about environmental sciences and geosciences.

Overall, 3164 different academic journals have published scholarly articles related to groundwater, and the 20 most active journals are presented in Table 1. There was a high concentration of groundwater-related articles in these top journals; the 20 most active journals (0.63% out of the 3164 journals) account for 18,867 or 31.3% of the 60,227 articles in the totality. The *Journal of Hydrology* published the largest number of groundwater-related articles (2136; 3.55% of the total), followed by *Water Resources Research* (1868; 3.10%), *Environmental Earth Sciences*[a](1766; 2.93%) and *Environmental Science & Technology* (1673; 2.78%). Except for *Water Science and Technology*, the number of groundwater-related articles in other 19 journals has varying degrees of growth, with *Hydrological Processes* (16.60%), *Journal of Hazardous Materials* (13.80%) and *Environmental Earth Sciences* (12.80%) presenting the top 3 increasing interests in groundwater studies. Furthermore, the ratio of the number of groundwater-related articles (TA) to the total number of articles published (TJA) in a journal during 1993–2012 (the TA/TJA %) was also calculated and shown in Table 1. The *Hydrogeology Journal* (TA/TJA % = 88.03%) and *Groundwater* (TA/TJA % = 67.23%) devote substantial emphasis to groundwater studies. Their percentages herein reported reflect the number of papers that specifically cite the theme of groundwater in their contents (titles, abstracts, and keywords). Therefore, papers that deal with subsurface topics but did not explicitly cite groundwater are not included in the percentage statistics. Groundwater-related articles published in the 20 most active journals have received, on average, 17.61 citations. *Environmental Science & Technology* (37.23), *Water Research* (26.21) and *Water Resources Research* (25.25) have higher citation rates, indicating these journals have had wider influences in the broad field of groundwater.

3.3. Geographic and institutional distribution

To visualize the worldwide distribution of groundwater-related publications, the affiliations of authors were geocoded using CiteSpace and mapped worldwide using red[1] dots as shown in Fig. 2. The number of groundwater-related publications by country/territory was color mapped in Fig. 2, also. It is seen that author clusters and major research regions are mainly located in the United States, Western Europe, Eastern and Southern Asia, and Eastern Australia. The cluster of Western Europe gravitates towards Germany, the UK, and France. Eastern China, India, and Japan were the major areas

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

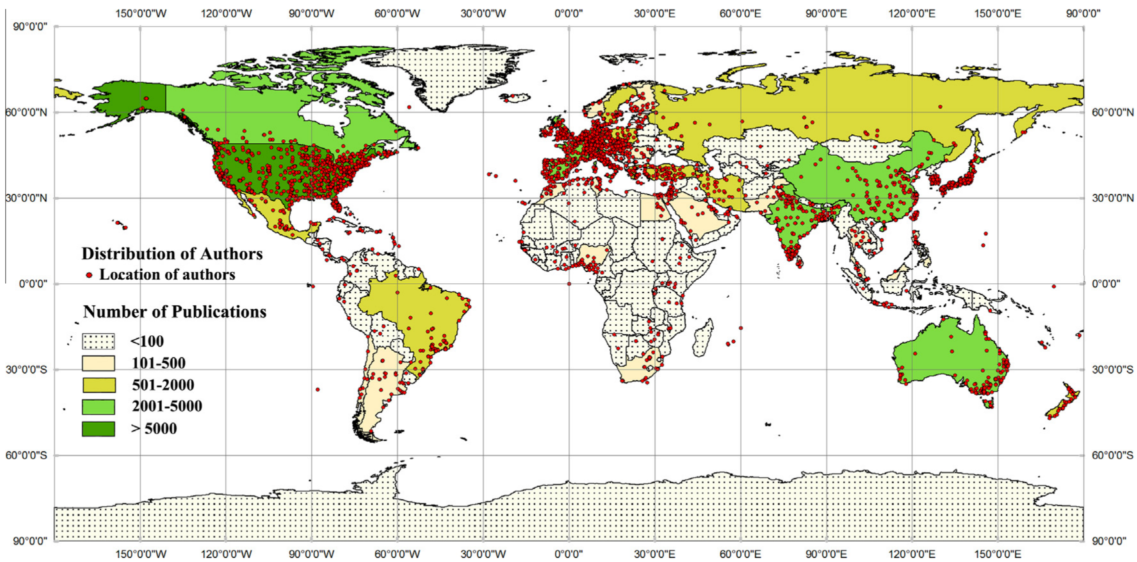

Fig. 2. Global geographic distribution of authors according to the total number of articles by country/territory.

Table 2
The 20 most active countries/territories in groundwater-related research.

Countries/territories	TA (%)	SC (%)	IC (%)	In 5-year window	
				CPA	*h*-Index
USA	20,872(34.9)	15,634(74.9)	5238(25.1)	8.38	59
Germany	4373(7.3)	2332(53.3)	2041(46.7)	7.97	38
Canada	3713(6.2)	2201(59.3)	1512(40.7)	7.19	32
UK	3671(6.1)	1930(52.6)	1741(47.4)	8.52	35
China	3634(6.1)	2000(55.0)	1634(45.0)	6.17	35
India	3048(5.1)	2395(78.6)	653(21.4)	5.08	29
France	3023(5.1)	1438(47.6)	1585(52.4)	7.28	32
Australia	2746(4.6)	1558(56.7)	1188(43.3)	6.95	29
Japan	2350(3.9)	1501(63.9)	849(36.1)	5.19	24
Spain	2131(3.6)	1306(61.3)	825(38.7)	7.62	31
Italy	2110(3.5)	1284(60.9)	826(39.2)	7.17	28
Netherlands	1697(2.8)	936(55.2)	761(44.8)	8.23	27
Switzerland	1391(2.3)	503(36.2)	888(63.8)	8.92	29
Taiwan	1166(2.0)	824(70.7)	342(29.3)	6.16	22
South Korea	1118(1.9)	691(61.8)	427(38.2)	5.52	23
Sweden	1094(1.8)	554(50.6)	540(49.4)	7.46	22
Turkey	862(1.4)	698(81)	164(19.0)	4.71	22
Denmark	852(1.4)	467(54.8)	385(45.2)	8.61	23
Brazil	834(1.4)	516(61.9)	318(38.1)	4.7	20
Israel	774(1.3)	449(58)	325(42.0)	6.27	18

TA: total groundwater-related articles published by the country/territory; SC: single-country articles; IC: internationally-collaborated articles, CPA: average number of citations per article; *h*-index: defined by the number *h* of papers among a country's number of publications (*Np*) that have at least *h* citations each.

for groundwater-related publications in Asia. These clusters of authors were consistent with the fact that these regions are developed economies and house a large number of academic institutions.

There were 358 articles without any author address information, and thus the total number of articles for the distribution analysis by country and institutional publications was 59,869. Groundwater studies have been conducted worldwide, with researchers from 179 countries/territories. Table 2 lists the 20 most active countries/territories with the number of single-country articles and internationally-coauthored articles. The United States accounts for the largest number of articles (20,872; or 34.9% of the total), which includes single-country publications (15,634) and internationally co-authored publications (5238). Germany comes second and features 4373 articles, followed by Canada (3713), the UK (3671), and China (3634). Because older articles inherently had a higher number of citations, the academic impact of countries based on a 5-year fixed window of analysis (2008–2012) was evaluated, and the impact criteria are reported in Table 2. The CPA (the average number of citations per article) indicates the average impact of the articles published by a country, and the *h*-index (defined as the number *h* of papers among a country's number of publications (*Np*) that have a least h citations each) is used to find which country has the largest number of high-quality articles in the groundwater field. It is seen in Table 2 that groundwater-related articles authored in Switzerland have the highest average impact (CPA, 8.92). Although the United States ranked 4th in the CPA index, it has the largest number of high-quality and high-impact articles (59 articles with more than 59 citations each) in the groundwater field.

Single-country articles make up the largest share of the total number of articles in most countries, except for France and Switzerland. Nevertheless, internationally-coauthored articles exhibit an increasing trend during 1993–2012. Compound annual growth rates (CAGR) of internationally-coauthored articles (IC), single-country articles (SC), and total articles (TA) of the top 20 most active countries/territories were separately calculated based on the following formula:

$$\mathrm{CAGR}(t_0, t_n) = (N(t_n)/N(t_0))^{\frac{1}{t_n - t_0}} - 1 \quad (1)$$

in which t_0 is the beginning year (1993), t_n is the ending year (2012), and $N(t_n), N(t_0)$ represent the number of articles published in 2012 and 1993, respectively.

Fig. 3 shows that the compound annual growth rates of internationally-coauthored articles (ICGR) of most countries appear to be significantly higher than those of single-country articles (SCGR). This means that international research collaboration has become more prevalent over time, and the fruits of cooperation contributed to the overall scientific output in various countries and in the broad field of groundwater. It is noticeable in Fig. 3 that the outputs of China and South Korea exhibited strong increase, with total articles growth rate (TAGR) equal to 21.83% and 21.79%, respectively.

At the institutional level, there were 22,712 institutions that contributed articles on groundwater studies, and the 20 most active institutions are displayed in Table 3. The latter shows the United States' dominant position in world groundwater research, as there are 12 research institutions in the United States ranking among the 20 most active institutions. The US Geological Survey (USGS) led institutional activity, with 1948 articles, followed by the Chinese Academy of Sciences (CAS, 1033) and the USDA's Agricultural Research Service (ARS, 688). However, the USGS, CAS, and ARS are institutions that have branches in many locations, and dividing the articles among the branches would yield different rankings. The University of Waterloo, the University of Arizona, and the University of California at Berkeley, were the three most active single-site institutions. Our analysis of international collaborations revealed that an average of 68.25% of total articles by the 20 most active countries/territories were inter-institutionally coauthored. In addition, it was determined that institutions that are more likely to cooperate with foreign organizations were from Russia, Spain, Canada, Germany, and China, whereas American institutions preferred to collaborate with domestic partners. The major collaborators of each institution shown in Table 3 revealed their vital research partners in groundwater research. As to the academic effects of these institutions during 2008–2012, Stanford University had the highest average citation (CPA, 11.89), while the US Geological Survey had the highest quality index (h-index, 27).

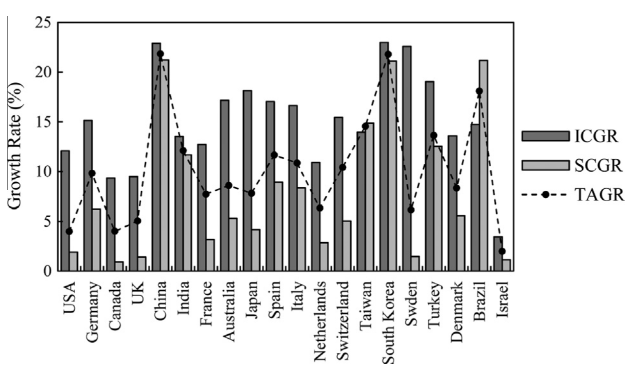

Fig. 3. Compound annual growth rate comparison of internationally-coauthored (ICGR), single-country (SCGR), and total articles (TAGR) of the 20 most active countries/territories during 1993–2012.

3.4. Research trends and hotspots

Author keywords provide a reasonable description of an article's theme, and could reveal the profile of an author's research preferences (Sun et al., 2012). Therefore, keyword analysis can be used to identify the subjective focus and emphasis specified by authors, explore research hotspots, and discover scientific research trends (Xie et al., 2008; Li et al., 2009). The keyword analysis in our study utilized author keywords as statistical objects. To obtain accurate results, we preprocessed the keywords by merging the singular and plural forms of the same terminology, and those keywords with the same meaning while using different expressions

Table 3
The 20 most active institutions in groundwater-related research.

Institution	TA (%)	SI (%)	CI (%)	IC/CI	MC	In 5-year window	
						CPA	h-Index
US Geol Survey, USA	1948(3.25)	749(38.45)	1199(61.55)	26.69	Univ Arizona, USA (52)	7.26	27
Chinese Acad Sci, China	1033(1.73)	265(25.65)	768(74.35)	56.25	Lanzhou Univ, China (36)	5.18	24
USDA ARS,USA	688(1.15)	217(31.54)	471(68.46)	20.59	Univ Georgia, USA (27)	7.11	16
Univ Waterloo, Canada	620(1.04)	184(29.68)	436(70.32)	59.17	Environm Canada, Canada (23)	6.23	16
Univ Arizona, USA	562(0.94)	161(28.65)	401(71.35)	41.40	US Geol Survey, USA (52)	6.48	17
US EPA, USA	559(0.93)	143(25.58)	416(74.42)	19.95	Univ Cincinnati, USA (31)	7.74	17
Univ Calif Berkeley, USA	533(0.89)	132(24.77)	401(75.23)	42.89	Pacific NW Natl Lab, USA (42)	8.94	24
Univ Florida, USA	522(0.87)	187(35.82)	335(64.18)	37.31	Purdue Univ, USA (23)	4.44	13
CSIC, Spain	432(0.72)	139(32.18)	293(67.82)	60.41	Univ Barcelona, Spain (31)	7.28	20
Univ Calif Davis, USA	428(0.71)	132(30.84)	296(69.16)	35.14	US Geol Survey, USA (29)	6.85	14
Stanford Univ, USA	427(0.71)	116(27.17)	311(72.83)	37.30	Oak Ridge Natl Lab, USA (29)	11.89	22
UFZ Helmholtz Ctr Environm Res, Germany	414(0.69)	103(24.88)	311(75.12)	56.59	Univ Tubingen, Germany (32)	6.29	18
Indian Inst Technol, India	413(0.69)	182(44.07)	231(55.93)	38.53	Natl Inst Hydrol, India (20)	5.18	14
Russian Acad Sci, Russia	399(0.67)	199(49.87)	200(50.13)	61.50	Moscow MV Lomonosov State Univ, Russia (32)	1.40	6
Natl Taiwan Univ, Taiwan	380(0.63)	80(21.05)	300(78.95)	31.67	Acad Sinica, Taiwan (36)	5.50	14
Texas A&M Univ, USA	360(0.60)	87(24.17)	273(75.83)	48.72	USDA ARS, USA (12)	6.12	15
Univ Nebraska, USA	360(0.60)	158(43.89)	202(56.11)	40.10	Hohai Univ, China (12); USDA ARS, USA (12)	4.45	11
CSIRO, Australia	347(0.58)	89(25.65)	258(74.35)	46.90	Univ Western Australia, Australia (30)	4.62	8
Univ Wisconsin, USA	341(0.57)	111(32.55)	230(67.45)	21.74	US Geol Survey, USA (33)	6.89	15
Univ Illinois, USA	334(0.56)	90(26.95)	244(73.05)	31.97	Illinois State Geol Survey, USA (14); US Geol Survey, USA (14)	7.10	16

TA: total number of groundwater-related articles published by an institution, SI: Single-institution articles, CI**:** inter-institutionally coauthored articles, IC/CI: ratio of internationally coauthored articles over inter-institutionally coauthored articles, MC: major collaborator(s) and the number of collaborated articles (within parentheses), CPA: average number of citations per article; h-index: defined by the number h of papers among an institution's number of publications (Np) that have at least h citations each.

(for example, "ground water" and "groundwater", "modelling" and "modeling", "climatic change" and "climate change", and "GIS" and "geographic information systems").

3.4.1. Hot topics and directions

Only 2494 keywords (3.47% of the total number) were used in more than 10 articles, and these keywords were present in mainstream groundwater-related research. Keywords ranking changes in the four 5-year intervals are indicative of changes in the hot fields. The top 20 most frequently used keywords for the study period are listed in Table 4. With the exception of "Groundwater", which is the search word in this study, the three most frequently used keywords were "Arsenic", "Nitrate(s)" and "Water Quality". Obviously, the topics of water quality and contamination attracted the greatest attention in groundwater-related research, which involved various themes of research, such as (i) the study of pollutant reduction, evaluation and simulation of pollutants' migration and their transformation under different situations, (ii) detection of multiple contaminations and their interactive effect, and (iii) their overall influence on human health and the environment (Leonard et al., 1987; Lovley, 1991; Kolpin et al., 2002). "Arsenic", a toxic metalloid, first ranked 24th during 1993–1997, then increased to second in the latest period. Dangerous arsenic concentrations in natural waters are a threat in many regions of the world and it is often referred to as a 20th and 21st centuries calamity, which motivated the notorious attention devoted to arsenic contamination, arsenic removal, arsenic exposure and health effects (Smedley and Kinniburgh, 2002; Rahman et al., 2003; Mohan and Pittman, 2007; Kanel et al., 2013). Nitrate in groundwater remained a hot research topic during the past 2 decades. Meanwhile nitrate contamination of groundwater has increased alarmingly in various parts of the world due to increased usage of nitrogenous fertilizers, changes in land-use patterns, and increased recycling of domestic wastewater (Sharma and Sobti, 2012). Furthermore, "heavy metal(s)" experienced a significant increase from 29th in 1993–1997 to 8th in 2008–2012. Instances of soil and groundwater contamination by heavy metals due to wastewater drainage and mining are markedly increasing in various parts of the world (Lee et al., 2005; Bhagure and Mirgane, 2011), which drew the attention of the environmental community to undertake investigations and assessments, and to remediation and management technologies (Demirel, 2007; Hseu et al., 2010). The umbrella name, "contamination" also had increasing rank, while the ranks of "pesticide(s)" and "nitrogen" exhibited obvious decline. In recent years, regulations on pesticides have reduced their use (Waibel, 1993), and thus, research related to their treatment and harm to the environment has dwindled in number. Besides, although nitrogen-containing compounds are still pervasive in waters, it is inferred that researchers preferred to use specific words "nitrates" or "ammonia nitrogen" to describe nitrogenous pollutants.

"Modeling" continues to be a frequently-used method in groundwater research, as it is useful in approximating groundwater-related environmental processes (Seyf-Laye et al., 2012). In addition, management/planning models and water rights models were also implemented extensively in exploring management plans and making administrative decisions (Rossman and Zlotnik, 2013). "Geographic Information System (GIS)" and "Stable Isotope(s)" methods have made steady gains in popularity in groundwater-related research, with ranks rising by 25 and 41, respectively, during the study period. GIS provides unique capabilities (especially for spatial analysis and visualization) in the assessment and management of groundwater resources, contamination, and environmental impacts (Corwin et al., 1997; Scibek and Allen, 2006). Stable isotopes are mainly used to quantify groundwater/surface-water interactions and probe pollutants' sources and transformation processes (Williams, 1997; Cook, 2013). In recent years, the integrated application of stable isotopes and GIS technology in the groundwater field became a thriving area of research (Tetzlaff et al., 2007).

"Soil(s)" remained among the top 10 most frequently used keywords during the study period. Because of it being an essential media of groundwater interacting with the surface environment, a large number of studies focusing on soil properties, the movement of contaminants through soil, and the mutual influence of soil and groundwater (Beldring et al., 1999; Seeboonruang, 2012; Cuevas et al., 2012). Groundwater serves as a vital source of "drinking water" in most countries worldwide (especially in arid and rural areas). Hence, the related water-quality, health risk-assessment, contamination remediation, and regulation attracted growing attention in the study period (Amaral et al., 2003; Thirunavukkarasu et al., 2003; Reimann and Banks, 2004; Suthar, 2011). "Adsorption", a remediation method for water

Table 4
The 20 most frequently used keywords for the study period.

Keywords	Total	1993–1997		1998–2002		2003–2007		2008–2012	
		Cnt	R	Cnt	R	Cnt	R	Cnt	R
Groundwater	6428	637	1	1305	1	1905	1	2581	1
Arsenic	1219	41	24	130	7	411	2	637	2
Nitrate(s)	1034	95	3	220	2	301	3	418	3
Water quality	878	115	2	171	3	260	4	332	4
Modeling	715	64	9	170	4	230	5	251	11
Soil(s)	657	80	5	138	6	188	8	251	11
Geographic Information System (GIS)	646	37	31	88	20	212	6	309	6
Drinking water	627	42	22	109	11	190	7	286	7
Adsorption	608	40	26	79	29	173	10	316	5
Heavy metal(s)	559	38	29	85	23	161	12	275	8
Stable isotope(s)	556	24	51	107	12	170	11	255	10
Hydrochemistry	530	22	59	105	14	176	9	227	13
Aquifer(s)	519	77	6	98	16	155	13	189	20
Hydrology	508	72	7	124	8	146	19	166	26
Pesticide(s)	502	90	4	150	5	119	28	143	33
Denitrification	492	44	18	116	10	149	17	183	22
Contamination	490	34	33	121	9	155	13	180	23
Irrigation	482	46	16	83	25	126	22	227	13
Nitrogen	473	70	8	98	16	151	16	154	31
Groundwater flow	467	27	44	81	27	154	15	205	16

Cnt: count of occurrences; R: rank.

contamination, has received growing attention with a large rank advancement during the study period. "Denitrification" has risen and fallen in rank. It is the key mechanism for nitrate removal, especially biological denitrification has potential for the elimination of nitrate with high reliability (Foglar et al., 2005; Tong et al., 2013). "Hydrochemistry" and "hydrology" are two other major fields of inquiry in groundwater research. The rank of "hydrochemistry" rose significantly while that of "hydrology" declined in the period 1993–2012. The study of water in aquifers and the characterization of aquifers are key topics of Hydrogeology, a discipline concerned with groundwater research. Stream/tide-aquifer interaction, "groundwater flow" in aquifers, aquifer overexploitation, and climate change impacts on aquifers have remained hot research fields (Loáiciga et al., 2000; Custodio, 2002; Nastev et al., 2005; Intaraprasong and Zhan, 2009; Singh and Jha, 2011). Numerical simulation of "groundwater flow" and related contaminants and heat transport have attracted increasing attention during the past two decades. In addition, groundwater is vital for irrigation. "Irrigation" alters groundwater fluxes and flow patterns, and also groundwater quality and salinity (Garcia-Garizabal and Causape, 2010; Lehrsch et al., 2011), thus its prominence among keywords.

3.4.2. Quick rising themes

The Compound Annual Growth Rate (CAGR) and Growth Ratio (GR, defined as the total number of keywords occurrences during 2003–2012 divided by the number of occurrences during 1993–2002) were used to identify the top 100 most frequently used keywords and to select quick rising themes of groundwater research, which could be indicators of future research directions. The CAGR provides smoothed growth rates free from the annual fluctuations of keywords occurrences during the study period. Table 5I lists the top 13 among the top 20 keywords according to the CAGR and the GR, and sorted them by their average rank. The ranks in Table 5I show that "Arsenic" and "climate change" are two leading hot issues that continue to attract broad attention. "Arsenic" (CAGR, 28.88%; GR, 6.13) kept its dominance in terms of total quantity and annual growth rate. An increasing number of publications appeared in recent years dealing with "climate change" and its groundwater impacts, such as variations in groundwater level fluctuation (Chen et al., 2004), alteration of groundwater flow regimes (Scibek and Allen, 2006), changes in the volume and quality of groundwater resources (Priyantha Ranjan et al., 2006; Bloomfield et al., 2006), and effects on groundwater recharge (Loáiciga, 2003; Herrera-Pantoja and Hiscock, 2008; Jyrkama and Sykes, 2007). It also has been established that sea level rise due to climate change may accelerate "seawater intrusion" (Abd-Elhamid and Javadi, 2011a; Loáiciga et al., 2012). Seawater intrusion is a serious threat to water-quality in coastal areas (Abd-Elhamid and Javadi, 2011b; Loáiciga et al., 2012). As a result, the growing concern has triggered research on the mechanisms and extent of seawater intrusion, on the evaluation of groundwater quality and soil salinity changes, and on exploring cost-effective control methods (Sadeg and Karahanoðlu, 2001; Narayan et al., 2007; Zghibi et al., 2013). More recently, the number of people reportedly suffering from "fluoride" poisoning has been found to be large, mainly due to naturally occurring fluoride in groundwater. Thus, research has been devoted to identifying the origins and hydrogeochemistry of high-fluoride groundwater (Gupta et al., 2005), analyzing the health effects on local consumers (Hussain et al., 2010), determining the mechanism for fluorine migration and enrichment (Li et al., 2013), and investigating the effective treatment and removal methods and devices (Singh et al., 2013). The dramatic change of "land use" during the past 20 years, especially in developing countries, has significantly affected groundwater resources. A growing number of researches concentrated on the impact of land use on groundwater level, recharge and discharge, groundwater quality and contamination (Scanlon et al., 2005; Ritter et al., 2007; Lerner and Harris, 2009; Cho et al., 2009; Leterme and Mallants, 2012). As a result of the worsening stresses upon groundwater, "hydrogeochemistry" characteristics of groundwater and their responses/evolution to external influence have risen as important research topics (Nicholson et al., 1983; Zhao et al., 2010). The keyword "USA/United states" also enjoyed a quick rise as an area of concern in groundwater research.

Several prevalent research technologies and methods were statistically detected. With the development of computer technology, "numerical modeling" has become a powerful tool of quantitative research in the groundwater field, with wide-ranging applications in various directions including thermal/solute transport (Abramov and Kring, 2004; Sikdar et al., 2013), groundwater and surface-water interactions (Chen et al., 2013), seawater intrusion (Qahman and Larabi, 2006), and groundwater resource assessment/management (Sophocleous et al., 1999). "Uncertainty" is inherently a complexity in the assessment of groundwater systems, and the commonly used deterministic method of groundwater analysis is limited by inaccuracy and limited-scope management decisions. Therefore, uncertainty analysis in groundwater modeling, as well as uncertainty methods applied to groundwater assessment and simulation have gained in popularity in groundwater research (Singh and Minsker, 2008; Wu and Zeng, 2013). "Remote sensing", has broadened the scope of groundwater assessment, modeling, and management at regional and continental scales (Brunner et al., 2006). Recently, the combined application of geographical information system (GIS), remote sensing (RS) and geostatistics appeared in the study of interactions among groundwater, surface water, and land-use cover changes (Chen et al., 2009).

The growing stresses upon groundwater resources and the awareness and interest in managing those resources sustainably have engendered a growing body of pertinent research (Jha et al., 2008; Riemann et al., 2012). There is also a growing reliance on

Table 5
27 Quick rising themes based on Compound Annual Growth Rate (CAGR) and Growth Ratio (GR).

Keywords	CAGR (%)	R1	GR	R2	Ave. rank
I					
Arsenic	28.88	1	6.13	5	3
Climate change	21.51	3	5.38	7	5
Fluoride	20.80	5	5.94	6	5.5
Groundwater management	20.58	6	4.93	9	7.5
Hydrogeochemistry	21.23	4	4.22	13	8.5
Uncertainty	18.11	9	5.29	8	8.5
Numerical modeling	21.59	2	3.80	17	9.5
Seawater intrusion	16.59	18	9.06	2	10
Adsorption	19.46	7	4.11	16	11.5
Remote sensing	16.54	19	7.64	3	11
Land use	17.08	15	4.22	12	13.5
USA/United States	17.08	16	4.29	11	13.5
Water supply	17.67	11	3.66	19	15

II			III		
Keywords	CAGR (%)	R1	Keywords	GR	R2
Stable isotope(s)	18.58	8	China	9.94	1
Precipitation	17.94	10	India	7.55	4
Hydrochemistry	17.30	12	Bangladesh	4.80	10
Wastewater	17.27	13	Geostatistics	4.18	14
Monitoring	17.08	14	Geographic Information System (GIS)	4.17	15
Uranium	16.76	17	Water management	3.66	18
Isotope(s)	15.79	20	Heavy metal(s)	3.54	20

CAGR: compound annual growth rate; R1: rank according to CAGR results; R2: rank according to the Growth Ratio (GR); Ave. Rank: the average rank of a keyword in R1 and R2.

groundwater for "water supply" around the world, although this function is threatened by groundwater over-exploitation, seawater intrusion, and water-quality deterioration (Stevanovic and Eftimi, 2010). Therefore, research has focused on optimizing water-supply schemes to (i) minimize environmental degradation (Voivontas et al., 2003), (ii) solve health problems resulting from exposure to contaminated groundwater (Dangendorf et al., 2002), and (iii) explore efficient technologies for clean water supply (Macedonio et al., 2012).

Table 5II and III list two sets of 7 keywords among the top 27 keywords according to the CAGR (Table 5II) and GR (Table 5III), excluding the 13 terms shown on Table 5I. The left-column keywords (Table 5II) show a steady and relatively rapid growth, while the right-column keywords (Table 5III) exhibited a rapid, yet fluctuating increase during the study period. Here we mainly discuss the quick rising themes listed in Table 5II and III except for the hot issue keywords "Stable Isotope(s)", "Hydrochemistry", "Geographic Information System (GIS)", and "Heavy Metal(s)". Groundwater systems are vulnerable to changes in "precipitation", and numerous researches explored the groundwater response to variations in the quantity and quality of precipitation in various regions (Dzhamalov and Zlobina, 1995; Johnson et al., 2003; Han et al., 2008). "Wastewater" infiltration deteriorates groundwater quality, which prompted studies assessing, monitoring, and controlling the impact of wastewater on groundwater quality (Tang et al., 2004; Humphrey et al., 2010). Groundwater "monitoring" is essential for the understanding of groundwater conditions (Jørgensen and Stockmarr, 2008; Uddameri and Andruss, 2013). "Uranium" mining and milling operations have taken place in several countries, which caused radioactive contamination and posed health risk to residents (Neves and Matias, 2007). Hence, there is an urgent and increasing need to explore effective Uranium immobilization and removal methods from groundwater (Phillips et al., 2008; Cao et al., 2010). Meanwhile, Uranium "isotope" is vital evidence for groundwater chemical evolution and a tracer used in groundwater transport studies (Grabowski and Bem, 2011; Roback et al., 2001). Furthermore, various isotopes are commonly used in studies of groundwater recharge and groundwater-surface water interactions (Tweed et al., 2011; Kamdee et al., 2013).

The GR on the right-column keywords (Table 5III) during 2003–2012 are about 3.54–9.94 times of those during 1993–2002. China, India, and Bangladesh, are increasing hot topics of groundwater-related research. The largest population at risk among the 21 countries with known groundwater arsenic contamination is in Bangladesh, followed by West Bengal in India (Mohan and Pittman, 2007). In addition, some of the largest rates of groundwater depletion currently occur in Bangladesh and northern India (Aeschbach-Hertig and Gleeson, 2012). China is facing a deteriorating groundwater situation in terms of quality and quantity, and the situation may persist in the coming decades (Varis and Vakkilainen, 2001). "Geostatistics", an effective management and decision-making tool, has become more prevalent in groundwater research, especially in the analysis of groundwater-level fluctuation, chemical contamination, evaluation of groundwater quality, and in the assessment of groundwater storage and reservoir capacity (Uyan and Cay, 2013). Groundwater management has become more prevalent worldwide. Likewise, research on integrated "water management" has also generated widespread interest due to its holistic approach to the study of water systems and their interaction with people and the environment (Bouwer, 2002; Wolf et al., 2006).

4. Conclusions

An evaluation of global groundwater research trends during 1993–2012 was obtained by statistical analysis of the patterns of publication outputs, journals, subject categories, geographic and institutional contributions, and the temporal evolution of keyword frequencies. The amount of groundwater-related publication outputs rose at an average annual growth rate of 6.62% over the past two decades, faster than overall SCIE publications. "Environmental sciences", "Water resources" and "multidisciplinary Geosciences" were the three major subject categories. The *Journal of Hydrology* published the most articles (2136), while the *Hydrogeology Journal* and *Groundwater* focused publications dedicated to groundwater studies. Meanwhile, 19 of the 20 evaluated journals have increased their numbers of groundwater articles during the study period.

The worldwide geographic distribution of authors in groundwater-related research was visualized cartographically, with major spatial clusters in the USA, Western Europe, Eastern and Southern Asia, and Eastern Australia. The United States produced the largest number of single-country and internationally-coauthored articles followed by Germany and Canada. China and South Korea exhibited steady increases of outputs at the highest rates. Moreover, the rapid growth of internationally-coauthored articles demonstrated that international collaboration of groundwater-related research became more prevalent over time. The US Geological Survey, the Chinese Academy of Sciences, and the USDA Agricultural Research Service were the three most active institutions. The USA's dominant position in world groundwater research was affirmed by housing 12 research institutions that ranked among the 20 most active institutions.

Keywords analysis revealed the hot directions and quick rising themes in groundwater studies, which were in the areas of groundwater quality and contamination, effective research technologies, and treatment technologies. In addition, sixteen hot issues (arsenic, climate change, fluoride, groundwater management, hydrogeochemistry, seawater intrusion, adsorption, land use, water supply, precipitation, hydrochemistry, wastewater, monitoring, uranium, water management, and heavy metals), six research technologies and methods (uncertainty analysis, numerical modeling, remote sensing, isotope/stable isotope, geostatistics, and Geographic Information System (GIS)), and four countries (the United States, China, India, and Bangladesh) received steadily increasing attention, pointing to likely future groundwater-related research.

Acknowledgements

This research was supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20130141110061) and the National Natural Science Foundation of China (Grant No. 41101567). We also thank the scholarship fund from China Scholarship Council (File No. 201306270098 and No. 201308420279) to support the research at University of California, Santa Barbara, and Texas State University, San Marcos.

References

Abd-Elhamid, H., Javadi, A., 2011a. Impact of sea level rise and over-pumping on seawater intrusion in coastal aquifers. J. Water Clim. Change 2 (1), 19–28.
Abd-Elhamid, H.F., Javadi, A.A., 2011b. A cost-effective method to control seawater intrusion in coastal aquifers. Water Resour. Manage. 25 (11), 2755–2780.
Abramov, O., Kring, D.A., 2004. Numerical modeling of an impact-induced hydrothermal system at the Sudbury crater. J. Geophys. Res. 109 (E10).
Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5 (12), 853–861.
Alam, M.G.M., Allinson, G., Stagnitti, F., Westbrooke, M., Division, E.C., 2010. Arsenic contamination in Bangladesh groundwater: a major environmental and social disaster. Int. J. Environ. Health Res. 12 (3), 235–253.
Al-Weshah, R., 2003. The role of UNESCO in sustainable water resources management in the Arab World. Desalination 152 (1), 1–13.
Amaral, L.A. do, Nader Filho, A., Rossi Junior, O.D., Ferreira, F.L.A., Barros, L.S.S., 2003. Drinking water in rural farms as a risk factor to human health. Rev. Saude Publica 37 (4), 510–514.

Beldring, S., Gottschalk, L., Seibert, J., Tallaksen, L., 1999. Distribution of soil moisture and groundwater levels at patch and catchment scales. Agric. For. Meteorol. 98–9, 305–324.

Bhagure, G.R., Mirgane, S.R., 2011. Heavy metal concentrations in groundwaters and soils of Thane Region of Maharashtra, India. Environ. Monit. Assess. 173, 643–652.

Bloomfield, J.P., Williams, R.J., Gooddy, D.C., Cape, J.N., Guha, P., 2006. Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater—a UK perspective. Sci. Total Environ. 369 (1), 163–177.

Böhlke, J.-K., 2002. Groundwater recharge and agricultural contamination. Hydrogeol. J. 10 (1), 153–179.

Bouwer, H., 2002. Integrated water management for the 21st century: problems and solutions. J. Irrig. Drain. Eng. 128 (4), 193–202.

Brunner, P., Hendricks Franssen, H.-J., Kgotlhang, L., Bauer-Gottwein, P., Kinzelbach, W., 2006. How can remote sensing contribute in groundwater modeling? Hydrogeol. J. 15 (1), 5–18.

Cao, B., Ahmed, B., Beyenal, H., 2010. Immobilization of uranium in groundwater using biofilms. In: Shah, V. (Ed.), Emerging Environmental Technologies, Springer, vol. II. Netherlands, Dordrecht, pp. 1–37.

Chae, G.-T., Yun, S.-T., Mayer, B., Choi, B.-Y., Kim, K.-H., Kwon, J.-S., Yu, S.-Y., 2009. Hydrochemical and stable isotopic assessment of nitrate contamination in an alluvial aquifer underneath a riverside agricultural field. Agric. Water Manage. 96 (12), 1819–1827.

Chen, C., 2003. Mapping Scientific Frontiers: The Quest for Knowledge Visualisation. Springer.

Chen, C., 2004. Searching for intellectual turning points: progressive knowledge domain visualization. Proc. Natl. Acad. Sci. USA 101 (Suppl. 1), 5303–5310.

Chen, Z., Grasby, S.E., Osadetz, K.G., 2004. Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. J. Hydrol. 290 (1), 43–62.

Chen, X., Yan, J., Chen, Z., Luo, G., Song, Q., Xu, W., 2009. A spatial geostatistical analysis of impact of land use development on groundwater resources in the Sangong Oasis Region using remote sensing imagery and data. J. Arid Land 1 (1), 1–8.

Chen, X., Zhang, Y., Zhou, Y., Zhang, Z., 2013. Analysis of hydrogeological parameters and numerical modeling groundwater in a karst watershed, southwest China. Carbonates Evaporites 28 (1–2), 89–94.

Cho, J., Barone, V.A., Mostaghimi, S., 2009. Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed. Agric. Water Manage. 96 (1), 1–11.

Choi, M., Lin, B., Hamm, R., Viehweger, G., Tolera, H., Kolb, T., 2013. Site groundwater management strategies: groundwater metal remediation using Permeable Reactive Barriers.

Cook, P.G., 2013. Estimating groundwater discharge to rivers from river chemistry surveys. Hydrol. Process. 27 (25), 3694–3707.

Corwin, D.L., Vaughan, P.J., Loague, K., 1997. Modeling nonpoint source pollutants in the vadose zone with GIS. Environ. Sci. Technol. 31 (8), 2157–2175.

Cuevas, J., Ruiz, A.I., de Soto, I.S., Sevilla, T., Procopio, J.R., Da Silva, P., Jesus Gismera, M., Regadio, M., Sanchez Jimenez, N., Rodriguez Rastrero, M., Leguey, S., 2012. The performance of natural clay as a barrier to the diffusion of municipal solid waste landfill leachates. J. Environ. Manage. 95, S175–S181.

Custodio, E., 2002. Aquifer overexploitation: what does it mean? Hydrogeol. J. 10 (2), 254–277.

Dangendorf, F., Herbst, S., Reintjes, R., Kistemann, T., 2002. Spatial patterns of diarrhoeal illnesses with regard to water supply structures – a GIS analysis. Int. J. Hyg. Environ. Health 205 (3), 183–191.

Demirel, Z., 2007. Monitoring of heavy metal pollution of groundwater in a phreatic aquifer in Mersin-Turkey. Environ. Monit. Assess. 132 (1–3), 15–23.

Dzhamalov, R., Zlobina, V., 1995. Precipitation pollution effect on groundwater hydrochemical regime. Environ. Geol. 25 (1), 65–68.

El-fiky, A.A., Jeddah, P.O.B., Arabia, S., 2010. Hydrogeochemical characteristics and evolution of groundwater at the Ras Sudr-Abu Zenima Area, Southwest Sinai, Egypt. J. King Abdulaziz Univ. Earth Sci. 21 (1), 79–109.

Famiglietti, J.S., Rodell, M., 2013. Water in the balance. Science 340, 1300–1301.

Foglar, L., Briski, F., Sipos, L., Vukovic, M., 2005. High nitrate removal from synthetic wastewater with the mixed bacterial culture. Bioresour. Technol. 96 (8), 879–888.

Garcia-Garizabal, I., Causape, J., 2010. Influence of irrigation water management on the quantity and quality of irrigation return flows. J. Hydrol. 385 (1–4), 36–43.

Gattuso, J.-P., Dawson, N.A., Duarte, C.M., Middelburg, J.J., 2005. Patterns of publication effort in coastal biogeochemistry: a bibliometric survey (1971 to 2003). Mar. Ecol. Prog. Ser. 294, 9–22.

Grabowski, P., Bem, H., 2011. Uranium isotopes as a tracer of groundwater transport studies. J. Radioanal. Nucl. Chem. 292 (3), 1043–1048.

Gupta, S.K., Deshpande, R.D., Agarwal, M., Raval, B.R., 2005. Origin of high fluoride in groundwater in the North Gujarat-Cambay region, India. Hydrogeol. J. 13 (4), 596–605.

Han, S., Yang, Y., Lei, Y., Tang, C., Moiwo, J.P., 2008. Seasonal groundwater storage anomaly and vadose zone soil moisture as indicators of precipitation recharge in the piedmont region of Taihang Mountain, North China Plain. Hydrol. Res. 39 (5–6), 479.

Herrera-Pantoja, M., Hiscock, K.M., 2008. The effects of climate change on potential groundwater recharge in Great Britain. Hydrol. Process. 22 (1), 73–86.

Hseu, Z.-Y., Su, S.-W., Lai, H.-Y., Guo, H.-Y., Chen, T.-C., Chen, Z.-S., 2010. Remediation techniques and heavy metal uptake by different rice varieties in metal-contaminated soils of Taiwan: new aspects for food safety regulation and sustainable agriculture. Soil Sci. Plant Nutr. 56 (1), 31–52.

Humphrey, C.P., O'Driscoll, M.A., Zarate, M.A., 2010. Controls on groundwater nitrogen contributions from on-site wastewater systems in coastal North Carolina. Water Sci. Technol. 62 (6), 1448–1455.

Hussain, J., Hussain, I., Sharma, K.C., 2010. Fluoride and health hazards: community perception in a fluorotic area of central Rajasthan (India): an arid environment. Environ. Monit. Assess. 162 (1–4), 1–14.

IAHS, 1982. First IAHS scientific general assembly: exeter, UK. Hydrol. Sci. J. 27 (2), 173.

Intaraprasong, T., Zhan, H., 2009. A general framework of stream–aquifer interaction caused by variable stream stages. J. Hydrol. 373 (1–2), 112–121.

Jha, M.K., Kamii, Y., Chikamori, K., 2008. Cost-effective approaches for sustainable groundwater management in alluvial aquifer systems. Water Resour. Manage. 23 (2), 219–233.

Johnson, R., Thoms, R., Zogorski, J., 2003. Effects of daily precipitation and evapotranspiration patterns on flow and VOC transport to groundwater along a watershed flow path. Environ. Sci. Technol. 37 (21), 4944–4954.

Jørgensen, L.F., Stockmarr, J., 2008. Groundwater monitoring in Denmark: characteristics, perspectives and comparison with other countries. Hydrogeol. J. 17 (4), 827–842.

Jyrkama, M.I., Sykes, J.F., 2007. The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). J. Hydrol. 338 (3), 237–250.

Kamdee, K., Srisuk, K., Lorphensri, O., Chitradon, R., Noipow, N., Laoharojanaphand, S., Chantarachot, W., 2013. Use of isotope hydrology for groundwater resources study in Upper Chi river basin. J. Radioanal. Nucl. Chem. 297 (3), 405–418.

Kanel, S.R., Malla, G.B., Choi, H., 2013. Modeling and study of the mechanism of mobilization of arsenic contamination in the groundwater of Nepal in South Asia. Clean Technol. Environ. Policy 15 (6), 1077–1082.

Kinzelbach, W., Bauer, P., Siegfried, T., Brunner, P., 1998. Sustainable groundwater management—problems and scientific tools. Episodes 26, 279–284.

Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B., Buxton, H.T., 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance. Environ. Sci. Technol. 36 (6), 1202–1211.

Kostoff, R.N., Braun, T., Schubert, A., Toothman, D.R., Humenik, J.A., 2000. Fullerene Data Mining Using Bibliometrics and Database Tomography. J. Chem. Inf. Comput. Sci. 40 (1), 19–39.

Lee, J.Y., Choi, J.C., Lee, K.K., 2005. Variations in heavy metal contamination of stream water and groundwater affected by an abandoned lead–zinc mine in Korea. Environ. Geochem. Health 27 (3), 237–257.

Lehrsch, G.A., Sojka, R.E., Reed, J.L., Henderson, R.A., Kostka, S.J., 2011. Surfactant and irrigation effects on wettable soils: runoff, erosion, and water retention responses. Hydrol. Process. 25 (5), 766–777.

Leonard, R.A., Knisel, W.G., Still, D.A., 1987. GLEAMS: groundwater loading effects of agricultural management systems. Trans. ASAE 30 (5), 1403–1418.

Lerner, D.N., Harris, B., 2009. The relationship between land use and groundwater resources and quality. Land Use Policy 26, S265–S273.

Leterme, B., Mallants, D., 2012. Climate and land-use change impacts on groundwater recharge. Model. – Repos. Knowl. 355, 313–319.

Li, J., Zhang, Y., Wang, X., Ho, Y., 2009. Bibliometric analysis of atmospheric simulation trends in meteorology and atmospheric science journals. Croat. Chem. ACTA 82 (3), 695.

Li, L., Wang, Y., Wu, Y., Li, J., 2013. Major geochemical controls on fluoride enrichment in groundwater: a case study at Datong Basin, northern China. J. Earth Sci. 24, 976–986.

Loáiciga, H.A., 2003. Climate change and ground water. Ann. Assoc. Am. Geogr. 93 (1), 30–41.

Loáiciga, H.A., Maidment, D.R., Valdes, J.B., 2000. Climate-change impacts in a regional karst aquifer, Texas, USA. J. Hydrol. 227 (1–4), 173–194.

Loáiciga, H., Pingel, T.J., Garcia, E.S., 2012. Sea water intrusion by sea-level rise: scenarios for the 21st century. Ground Water 50, 37–47.

Lovley, D., 1991. Dissimilatory Fe(III) and Mn(IV) reduction. Microbiol. Rev. 55 (2), 259–287.

Macedonio, F., Drioli, E., Gusev, A.A., Bardow, A., Semiat, R., Kurihara, M., 2012. Efficient technologies for worldwide clean water supply. Chem. Eng. Process. Process Intensif. 51, 2–17.

Mandal, B.K., Suzuki, K.T., 2002. Arsenic round the world: a review. Talanta 58 (1), 201–235.

Mohan, D., Pittman, C.U., 2007. Arsenic removal from water/wastewater using adsorbents – a critical review. J. Hazard. Mater. 142 (1–2), 1–53.

Narayan, K.A., Schleeberger, C., Bristow, K.L., 2007. Modelling seawater intrusion in the Burdekin Delta irrigation area, North Queensland, Australia. Agric. Water Manage. 89 (3), 217–228.

Nastev, M., Rivera, A., Lefebvre, R., Martel, R., Savard, M., 2005. Numerical simulation of groundwater flow in regional rock aquifers, southwestern Quebec, Canada. Hydrogeol. J. 13 (5–6), 835–848.

Neves, O., Matias, M.J., 2007. Assessment of groundwater quality and contamination problems ascribed to an abandoned uranium mine (Cunha Baixa region, Central Portugal). Environ. Geol. 53 (8), 1799–1810.

Nicholson, R.V., Cherry, J.A., Reardon, E.J., 1983. Migration of contaminants in groundwater at a landfill: a case study 6. Hydrogeochem. J. Hydrol. 63 (1), 131–176.

Persson, O., Glänzel, W., Danell, R., 2004. Inflationary bibliometric values: the role of scientific collaboration and the need for relative indicators in evaluative studies. Scientometrics 60 (3), 421–432.

Phillips, D.H., Gu, B., Watson, D.B., Parmele, C.S., 2008. Uranium removal from contaminated groundwater by synthetic resins. Water Res. 42 (1–2), 260–268.

Pritchard, A., 1969. Statistical bibliography or bibliometrics. J. Doc. 25 (4), 348–349.

Priyantha Ranjan, S., Kazama, S., Sawamoto, M., 2006. Effects of climate and land use changes on groundwater resources in coastal aquifers. J. Environ. Manage. 80 (1), 25–35.

Qahman, K., Larabi, A., 2006. Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine). Hydrogeol. J. 14 (5), 713–728.

Rahman, M.M., Mandal, B.K., Chowdhury, T.R., Sengupta, M.K., Chowdhury, U.K., Lodh, D., Chanda, C.R., Basu, G.K., Mukherjee, S.C., Saha, K.C., Chakraborti, D., 2003. Arsenic groundwater contamination and sufferings of people in north 24-Parganas, one of the nine arsenic affected Districts of West Bengal, India. J. Environ. Sci. Health Part A 38 (1), 25–59.

Reichard, E., Johnson, T., 2005. Assessment of regional management strategies for controlling seawater intrusion. J. Water Resour. Plan. Manage. 131 (4), 280–291.

Reimann, C., Banks, D., 2004. Setting action levels for drinking water: are we protecting our health or our economy (or our backs!)? Sci. Total Environ. 332 (1), 13–21.

Riemann, K., Chimboza, N., Fubesi, M., 2012. A proposed groundwater management framework for municipalities in South Africa. Water SA 38 (3), 445–452.

Ritter, A., Muñoz-Carpena, R., Bosch, D.D., Schaffer, B., Potter, T.L., 2007. Agricultural land use and hydrology affect variability of shallow groundwater nitrate concentration in South Florida. Hydrol. Process. 21 (18), 2464–2473.

Roback, R., Johnson, T., McLing, T., Murrell, M., Luo, S., Ku, T., 2001. Uranium isotopic evidence for groundwater chemical evolution and flow patterns in the eastern Snake River Plain aquifer, Idaho. Geol. Soc. Am. Bull. 113 (9), 1133–1141.

Rossman, N.R., Zlotnik, V.A., 2013. Review: regional groundwater flow modeling in heavily irrigated basins of selected states in the western United States. Hydrogeol. J. 21 (6), 1173–1192.

Sadeg, S., Karahanoðlu, N., 2001. Numerical assessment of seawater intrusion in the Tripoli region, Libya. Environ. Geol. 40 (9), 1151–1168.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10 (1), 18–39.

Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E., Dennehy, K.F., 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Glob. Change Biol. 11 (10), 1577–1593.

Schwartz, F.W., Ibaraki, M., 2001. Hydrogeological research: beginning of the end or end of the beginning? Ground Water 39, 492–498.

Schwartz, F.W., Fang, Y.C., Parthasarathy, S., 2005. Patterns of evolution of research strands in the hydrologic sciences. Hydrogeol. J. 13, 25–36.

Scibek, J., Allen, D.M., 2006. Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change. Glob. Planet. Change 50 (1), 50–62.

Seeboonruang, U., 2012. Relationship between groundwater properties and soil salinity at the Lower Nam Kam River Basin in Thailand. Environ. Earth Sci. 69 (6), 1803–1812.

Seyf-Laye, A.-S.M., Mingzhu, L., Djanéyé-Bouindjou, G., Fei, L., Lyutsiya, K., Moctar, B.L., Honghan, C., 2012. Groundwater flow and contaminant transport modeling applications in urban area: scopes and limitations. Environ. Sci. Pollut. Res. Int. 19 (6), 1981–1993.

Sharma, S.K., Sobti, R.C., 2012. Nitrate removal from ground water: a review. E-J. Chem. 9 (4), 1667–1675.

Sikdar, P.K., Sahu, P., Ray, S.P.S., Sarkar, A., Chakraborty, S., 2013. Migration of arsenic in multi-aquifer system of southern Bengal Basin: analysis via numerical modeling. Environ. Earth Sci. 70 (4), 1863–1879.

Singh, A., Jha, M.K., 2011. A data-driven approach for analyzing dynamics of tide–aquifer interaction in coastal aquifer systems. Environ. Earth Sci. 65 (4), 1333–1355.

Singh, A., Minsker, B.S., 2008. Uncertainty-based multiobjective optimization of groundwater remediation design. Water Resour. Res. 44 (2), W02404.

Singh, K., Lataye, D.H., Wasewar, K.L., Yoo, C.K., 2013. Removal of fluoride from aqueous solution: status and techniques. Desalin. Water Treat. 51 (16–18), 3233–3247.

Smedley, P., Kinniburgh, D., 2002. A review of the source, behaviour and distribution of arsenic in natural waters. Appl. Geochem. 17 (5), 517–568.

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeol. J. 10 (1), 52–67.

Sophocleous, M.A., Koelliker, J.K., Govindaraju, R.S., Birdie, T., Ramireddygari, S.R., Perkins, S.P., 1999. Integrated numerical modeling for basin-wide water management: the case of the Rattlesnake Creek basin in south-central Kansas. J. Hydrol. 214 (1), 179–196.

Stevanovic, Z., Eftimi, R., 2010. Karstic sources of water supply for large consumers in Southeastern Europe–sustainability, disputes and advantages. Geol. Croat. 63 (2), 179–185.

Sun, J., Wang, M.-H., Ho, Y.-S., 2012. A historical review and bibliometric analysis of research on estuary pollution. Mar. Pollut. Bull. 64 (1), 13–21.

Suthar, S., 2011. Contaminated drinking water and rural health perspectives in Rajasthan, India: an overview of recent case studies. Environ. Monit. Assess. 173 (1–4), 837–849.

Tang, C., Chen, J., Shindo, S., Sakura, Y., Zhang, W., Shen, Y., 2004. Assessment of groundwater contamination by nitrates associated with wastewater irrigation: a case study in Shijiazhuang region, China. Hydrol. Process. 18 (12), 2303–2312.

Tetzlaff, D., Soulsby, C., Waldron, S., Malcolm, I.A., Bacon, P.J., Dunn, S.M., Youngson, A.F., 2007. Conceptualization of runoff processes using a geographical information system and tracers in a nested mesoscale catchment. Hydrol. Process. 21 (10), 1289–1307.

Thirunavukkarasu, O.S., Viraraghavan, T., Subramanian, K.S., 2003. Arsenic removal from drinking water using granular ferric hydroxide. Water SA 29 (2), 161–170.

Tong, S., Zhang, B., Feng, C., Zhao, Y., Chen, N., Hao, C., Pu, J., Zhao, L., 2013. Characteristics of heterotrophic/biofilm-electrode autotrophic denitrification for nitrate removal from groundwater. Bioresour. Technol. 148, 121–127.

Tweed, S., Leblanc, M., Cartwright, I., Favreau, G., Leduc, C., 2011. Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia. J. Hydrol. 408 (3–4), 257–275.

Uddameri, V., Andruss, T., 2013. A GIS-based multi-criteria decision-making approach for establishing a regional-scale groundwater monitoring. Environ. Earth Sci. 71 (6), 2617–2628.

Uyan, M., Cay, T., 2013. Spatial analyses of groundwater level differences using geostatistical modeling. Environ. Ecol. Stat. 20 (4), 633–646.

Varis, O., Vakkilainen, P., 2001. China's 8 challenges to water resources management in the first quarter of the 21st Century. Geomorphology 41 (2–3), 93–104.

Voivontas, D., Arampatzis, G., Manoli, E., Karavitis, C., Assimacopoulos, D., 2003. Water supply modeling towards sustainable environmental management in small islands: the case of Paros, Greece. Desalination 156 (1), 127–135.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Waibel, H., 1993. Government intervention in crop protection in developing-countries. CIBA Found. Symp. 177, 76–93.

Wang, G., Cheng, G., 2000. The characteristics of water resources and the changes of the hydrological process and environment in the arid zone of northwest China. Environ. Geol. 39 (7), 783–790.

Wang, D., Hejazi, M., 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resour. Res. 47 (10), W00J12.

Wang, M.-H., Yu, T.-C., Ho, Y.-S., 2009. A bibliometric analysis of the performance of water research. Scientometrics 84 (3), 813–820.

Welch, A.H., Westjohn, D.B., Helsel, D.R., Wanty, R.B., 2000. Arsenic in ground water of the United States: occurrence and geochemistry. Ground Water 38 (4), 589–604.

Williams, A.E., 1997. Stable isotope tracers: natural and anthropogenic recharge, Orange County. California. J. Hydrol. 201 (1), 230–248.

Wolf, L., Klinger, J., Held, I., Hötzl, H., 2006. Integrating groundwater into urban water management. Water Sci. Technol. 54 (6–7), 395.

Wu, J., Zeng, X., 2013. Review of the uncertainty analysis of groundwater numerical simulation. Chinese Sci. Bull. 58 (25), 3044–3052.

Xie, S., Zhang, J., Ho, Y.-S., 2008. Assessment of world aerosol research trends by bibliometric analysis. Scientometrics 77 (1), 113–130.

Zghibi, A., Tarhouni, J., Zouhri, L., 2013. Assessment of seawater intrusion and nitrate contamination on the groundwater quality in the Korba coastal plain of Cap-Bon (North-east of Tunisia). J. African Earth Sci. 87, 1–12.

Zhao, M., Zeng, C., Liu, Z., Wang, S., 2010. Effect of different land use/land cover on karst hydrogeochemistry: a paired catchment study of Chenqi and Dengzhanhe, Puding, Guizhou, SW China. J. Hydrol. 388 (1), 121–130.

Zhuang, Y., Liu, X., Nguyen, T., He, Q., Hong, S., 2013. Global remote sensing research trends during 1991–2010: a bibliometric analysis. Scientometrics 96 (1), 203–219.