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Research articles published in water resources journals: A bibliometric analysis

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ABSTRACT

This study was designed to evaluate the global scientific output in the ISI subject category of "water resources" for the past 16 years. Data were based on the online version of the Science Citation Index Expanded, Web of Science, from 1993 to 2008. Articles referring to water resources were assessed for many aspects, including distributions of source countries, institutes, words in the title, author keywords, and KeyWords Plus. The *h*-index was also calculated in terms of the characteristics of publications. Distributions of paper titles, the author's keywords, and KeyWords Plus at different periods were applied to evaluate research trends. The analysis showed that researchers paid most attention to groundwater and water quality parameters. Modeling and adsorption were the most popular techniques in water resources research. In addition, the relationship between the impact factor and *h*-index was significant for journals in the first group. The impact of the most cited articles each year were also discussed along with the article life information.

Keywords: Scientometrics; Research trend; Power model; Exponential model; Water resources

1. Introduction

Three-quarters of the Earth's surface is covered by oceans, which dominate the overall impact on the weather and climate system [1]. Water is the most precious global commodity with its myriad uses like drinking, industrial production, irrigation and the production of fish, waterfowl and shellfish [2]. These include water for freshwater systems that provides many nonextractive or instream benefits like flood control, transportation, recreation, waste processing, hydroelectric power, and habitat for aquatic life [3]. Some benefits, such as irrigation and hydroelectric power, are achieved only by major changes to the flow regime and flow paths from dams and water diversions [4]. Degradation of water resources with time is a social concern. Therefore, researchers have investigated the unbalanced distribution of water resources [5–7]. According to a review on history of water resource studies, the earliest research was presented in 1910 [8], and many investigations were implemented in the following years, for example about central and east African water resources [9], and the geology and ground-water resources of Iwo Jima [10], whereas today, water resources science has become one of the most important areas in the water research field. The issue of water resources plays an important role in the global environment. Over the years, a great deal of progress has been made in water resource monitoring [11,12], water treatment techniques [13–15], and water resource management [16–18]. The bibliometric

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method has been widely applied to the analysis of scientific production and research trends in environment-related topics, for example, geostatistics [19], adsorption technology [20], aerosol [21], hydrologic sciences [22], hydrogeology [23,24], wetland [25], solid waste [26], and desalination [27]. The Science Citation Index Expanded (SCI-Expanded), from the Institute for Scientific Information (ISI) Web of Science databases, is the most important and frequently used source database of choice for a broad review of scientific accomplishment in all fields [28]. Many bibliometric investigations have been carried out in various subject areas, for example the medical fields of oncology [29], radiology, nuclear medicine and medical imaging [30], otolaryngology [31], tropical medicine [32], virology [33], and dentistry, oral surgery & medicine [34] as well as the science and engineering fields ecology [35], microbiology [36], psychology [37], biology [38], and ocean engineering [39]. Conventional bibliometric methods often evaluate research trends by the publication outputs of countries [40], research institutes [21], journals [41], and research fields [42] as well as by citation analysis [22–24,70]. However, merely depending on the change in the citations or publication counts of countries and organizations cannot completely define developmental trends or the future orientation of the research field. More information, closer to the research itself, such as words in the title [21,43], author keywords [21], KeyWords Plus [44], and words in the abstract [45] should be introduced in the study of research trends. The KeyWords Plus in the SCI-Expanded database supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes [46]. Recently, data was separated into 4 four-year periods in order to analyze the variations of trends thoroughly and more precisely [21,43]. In this study, we aimed to synthetically use the traditional method, such as the analysis of languages, source countries, source institutes, and the most cited papers to describe performance in water resources research. In addition, the distributions of words in the title, author keywords, and KeyWords Plus were analyzed.

2. Data sources and methodology

The data were collected by analyzing articles and citations from the Thomson Reuters Web of Science database which is based on the online version of SCI-Expanded. According to Journal Citation Reports (JCR), it indexed 6,426 major journals with citation references across 172 scientific disciplines in 2007. All journals that publish articles mostly on water resources, were selected from among 59 journals listed in the category of "water resources" indexed by ISI in 2007. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as from the United Kingdom (UK). Papers addressed in Hong Kong were not included in China. The impact factor (IF) of a journal is defined by the JCR, and is derived by dividing the number of current citations to articles published in the two previous years by the total number of articles published in the two previous years. It is a measure of the frequency with which the average article in a journal has been cited in a particular year. The IF is used to evaluate a journal's relative importance, especially when compared to others in the same field [37,58]. The IF of each journal was obtained from the 2008 JCR. Contributions from different institutes and countries were estimated by the affiliation of at least one author to the article. Collaboration type was determined by the addresses of the authors, where the term "single country article" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from more than one country. The term "single institute article" was assigned if the researchers' addresses were from the same institute. The term "inter-institutionally collaborative article" was assigned if authors were from different institutes. All the articles referring to the subject category of water resources during 1993–2008 were assessed from the following aspects: document type and language of article, characteristics of article output, distribution of output in journals, article output of source country, source institute, author number per single country or institute article, and analysis of words in the title, author keywords, and KeyWords Plus. Keywords were defined as comma-separated items of one or more words. All keywords, both those reported by authors and those assigned by ISI, as well as words in the title were identified and separated into 4 four-year spans (1993–1996, 1997–2000, 2001–2004, and 2005–2008), then their ranks and frequencies were calculated, and different words with identical meaning and misspelled keywords were grouped and considered as a single keyword. In addition, the *h*-index was also calculated as a representative indicator of scientific achievement [47]. It was defined as the number of papers with citation number greater than or equal to *h* [47]. Hirsch suggests that the *h*-index has a better predictive power than other measures such as total number of published papers and total number of acquired citations [48]. Studies assessing the efficacy of the *h*-index have pointed out its convergent validity as a major advantage [49–51]. Moreover, quantity and quality of output are usually assessed by "number of publications" and "total citation counts", respectively [50,51]. Therefore, as a quality measure of publication activity, the *h*-index of languages, journals, research institutes and countries were calculated to evaluate achievements.

3. Results and discussion

3.1. Document type and language of publication

The distribution of document type identified by ISI was analyzed. From this study, 18 document types were found in the total 96,574 publications during 1993–2008. Journal articles (62,258) were the most-frequently used document type with 64% of the total production, followed by proceedings papers (19,769; 20%), editorial materials (5,743; 5.9%), and reviews (1,806; 1.9%). The others were less significant, including news items (799), letters (660), corrections (569), discussions (513), notes (485), addition corrections (208), biographical items (136), software reviews (38), meeting abstracts (30), items about an individual (25), reprints (21), bibliographies (8), book reviews (6), and database review (1). As journal articles were dominant in the document types and peer-reviewed within this field, they were identified and further analyzed. The emphasis of the following discussion was to determine the pattern of scientific production and research activity trends which consisted of authorship, institutes, countries, and trends in the research subjects addressed. Ninety-eight percent of all these journal articles were published in English (60,793) with an *h*-index of 151. Compared with other investigations, English was the dominant language [21,43,52], followed by French (913), Spanish (407), German (130), Afrikaans (10), Dutch (2), Rumanian (2), and Danish (1) with *h*-indexes of 14, 6, 11, 2, 0, 1, and 1 for each respectively. A significant correlation was found between the yearly cumulative number of articles and the year from 1993 to 2008 [53,54]. The relationship between the cumulative number of articles published each year (P) and the number of consecutive years (Y) studied from 1993 to 2008 was found to be: $P = 2088Y^{1.144}$ ($r^2 = 0.997$) until 2002 and $P = 9568\exp(0.1173Y)$ ($r^2 = 1.000$) for 2002–2008 (Fig. 1).

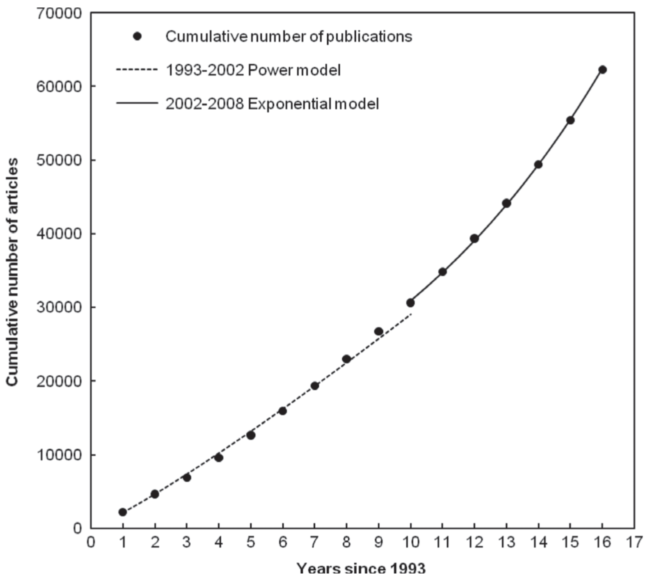

Fig. 1. Cumulative number of articles by year during 1993–2008.

3.2. Distribution of outputs in journals

All journals with their impact factor, impact factor rank, number of articles in 2007, and *h*-index were statistically analyzed (Table 1). In total, 62,258 articles were published in the 59 searched journals under the category of water resources. Seventeen journals had more than 1,000 published articles referring to water resources research from 1993 to 2008. The *h*-index provides a new indicator for the research performance and the impact factor is a mature indicator. *Water Research* published the most articles (6,880; 11%), and had the highest *h*-index (117). The coefficients of determination between the *h*-index and the impact factor of journal outputs were calculated (Figs. 2 and 3). Group 1 journals had a coefficient of determination (r^2) of 0.81 while group 2 had 0.63.

Moreover, Bradford's Law of Scattering [55] was applied. The journals were sorted in descending order in terms of number of articles, and then divided into three "zones". Zone 1 represents the most productive one-third of the total articles, with 5 (8.5%) of 59 journals. Zone 2 represents the next most productive one-third of total articles, with 14 (24%) of 59 journals, and Zone 3 represents the least productive one-third of total articles with 40 (68%) of 59 journals. The number of journals in the three zones approximately followed Bradford's law. To reiterate, the number of journals was approximately 1: n: n^2 (1: 2.8: 8). The water resources category contained five Bradford's core journals, *Water Research*, *Water Resources Research*, *Journal of Hydrology*, *Water Air and Soil Pollution*, and *Environmental Geology*.

3.3. Distribution of country/territory articles

The contributions of different countries/territories were estimated by the location of the affiliation of at least one author of the published paper. The 914 articles without any author address information were excluded. Of all the 61,334 articles with author addresses, 49,338 (80%) were single country articles and 12,006 (20%) were internationally collaborative articles. Among the top 20 productive countries/territories were two North American countries, ten European countries, six Asian countries, South Africa, and Australia (Table 2). There was no country from South America in the top productive countries. Most of the 7 major industrial countries (G7: Canada, France, Germany, Italy, Japan, the UK, and the USA) were among the top 10 productive countries except for Japan (ranked 11th). The USA, the UK, and Canada had high productivity in terms of total, independent, internationally collaborative, first author,

Table 1
All journals in the category of water resources in SCI-Expanded

Journal title	TA (%)	IF	IFR	TA (2007)	*h*-index
Water Research	6,880 (11)	3.587	1	509	117
Water Resources Research	5,345 (8.6)	2.398	2	505	109
Journal of Hydrology	4,223 (6.8)	2.305	3	404	78
Water Air and Soil Pollution	2,961 (4.8)	1.398	15	249	50
Environmental Geology	2,674 (4.3)	1.026	31	459	26
Hydrological Processes	2,396 (3.8)	2.002	7	415	50
Journal of Hydraulic Engineering-ASCE	1,855 (3.0)	1.272	20	185	30
Journal American Water Works Association	1,678 (2.7)	0.561	51	91	21
Desalination	1,602 (2.6)	1.155	25	747	15
Ground Water	1,522 (2.4)	1.304	18	84	34
Water Environment Research	1,480 (2.4)	0.966	36	153	25
Ocean Engineering	1,444 (2.3)	0.857	41	163	19
Agricultural Water Management	1,386 (2.2)	1.646	12	138	29
Journal of the American Water Resources Association	1,285 (2.1)	1.208	23	117	39
Journal of Contaminant Hydrology	1,253 (2.0)	2.106	6	97	63
Clays and Clay Minerals	1,169 (1.9)	1.171	24	47	2
Advances in Water Resources	1,129 (1.8)	2.235	4	137	47
Journal of Hydraulic Research	991 (1.6)	0.883	40	92	22
Journal of Soil and Water Conservation	984 (1.6)	1.121	28	87	31
Journal of Irrigation and Drainage Engineering-ASCE	981 (1.6)	0.822	42	115	23
Water SA	946 (1.5)	0.721	46	82	20
Catena	907 (1.5)	1.874	11	147	44
Hydrological Sciences Journal-Journal des Sciences Hydrologiques	906 (1.5)	1.216	22	90	43
Houille Blanche-Revue Internationale de L Eau	815 (1.3)	0.096	57	66	7
Water Science and Technology	757 (1.2)	1.005	33	604	19
Journal of Water Resources Planning and Management-ASCE	750 (1.2)	1.275	19	61	37
Hydrogeology Journal	732 (1.2)	1.100	29	115	28
Hydrology and Earth System Sciences	719 (1.2)	2.167	5	104	39
Ocean & Coastal Management	697 (1.1)	1.036	30	72	32
Journal of Hydrologic Engineering	694 (1.1)	1.007	32	134	11
Natural Hazards	684 (1.1)	0.989	35	108	27
China Ocean Engineering	659 (1.1)	0.430	53	46	11
Water International	616 (1.0)	0.315	55	30	8
Journal of Waterway Port Coastal and Ocean Engineering-ASCE	602 (1.0)	0.789	43	32	18
Ground Water Monitoring and Remediation	583 (0.94)	0.957	37	25	28
Vadose Zone Journal	567 (0.91)	1.441	14	122	41
Environmental Toxicology	531 (0.85)	1.899	9	92	39
Aquatic Conservation-Marine and Freshwater Ecosystems	506 (0.81)	1.619	13	107	35
Journal of Water Supply Research and Technology-Aqua	489 (0.79)	0.626	49	57	11
Water Resources Management	488 (0.78)	1.350	16	112	53
Acta Hydrochimica et Hydrobiologica	476 (0.76)	0.907	39	0	19
Environmental Geochemistry and Health	457 (0.73)	1.238	21	61	28
Natural Hazards and Earth System Sciences	448 (0.72)	1.345	17	131	50
Ingenieria Hidraulica en Mexico	409 (0.66)	0.112	56	51	14
River Research and Applications	387 (0.62)	1.959	8	92	52
Water Quality Research Journal of Canada	373 (0.60)	N/A	59	N/A	5
Stochastic Environmental Research and Risk Assessment	367 (0.59)	0.951	38	77	31
Irrigation Science	331 (0.53)	1.891	10	49	50
Irrigation and Drainage	318 (0.51)	0.480	52	45	10
Physics and Chemistry of the Earth	287 (0.46)	1.138	27	186	29
Nordic Hydrology	270 (0.43)	0	58	40	8
International Journal of Water Resources Development	243 (0.39)	0.738	45	42	25
Lake and Reservoir Management	209 (0.34)	0.746	44	0	5
Water and Environment Journal	173 (0.28)	0.648	48	36	24
Clean-Soil Air Water	170 (0.27)	1.145	26	118	40
Environmental Fluid Mechanics	142 (0.23)	1.000	34	42	29
Proceedings of the Institution of Civil Engineers-Water Management	133 (0.21)	0.333	54	38	8
Journal of Hydroinformatics	107 (0.17)	0.681	47	24	17
Proceedings of the Institution of Civil Engineers-Maritime Engineering	72 (0.12)	0.571	50	14	18

TA (%): total number and percentage of articles; IF: impact factor in 2008; IFR: rank in descending order of impact factor; TA (2007): total number of articles in 2007.

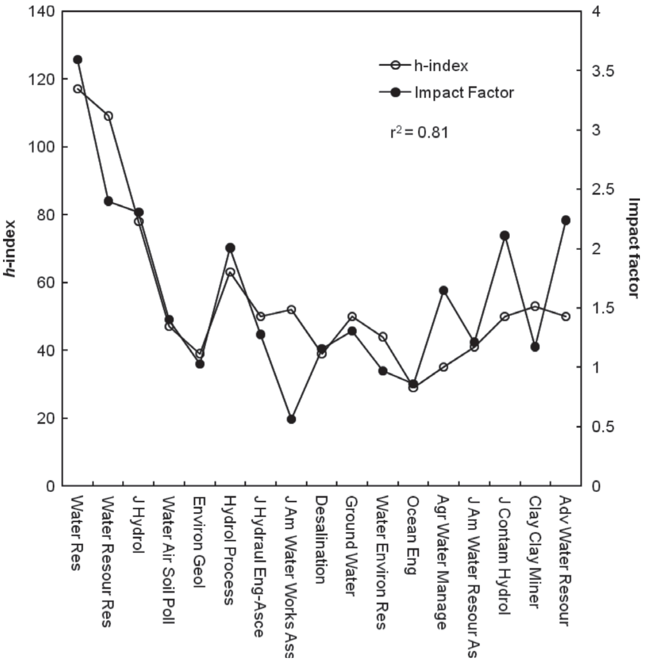

Fig. 2. Relationship between *h*-index and impact factor (Group 1).

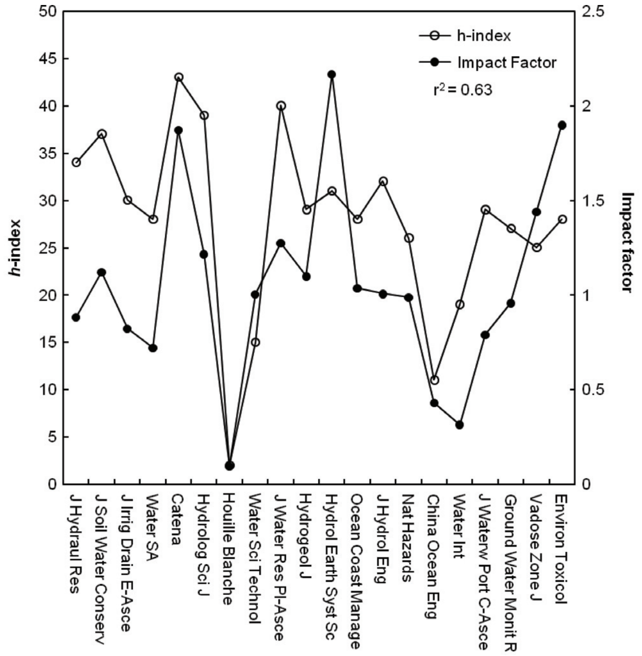

Fig. 3. Relationship between *h*-index and impact factor (Group 2).

and corresponding author articles. Domination in articles from the mainstream countries was not surprising since this pattern occurs in other scientific fields [43]. The USA was predominant in global water resources research and published the most articles (21,851; 36%). The USA was also the most frequent partner accounting for 42% of all the internationally collaborative articles. However, the collaborative articles represented only 23% of the total articles from the USA, which was lower than that of European countries (Table 2). The article impact of the USA was excellent with the highest *h*-index (123) among all the countries, followed by

Table 2
Top 20 most productive countries/territories of articles during 1993–2008

Countries	Region	TA	TA R (%)	SA R (%)	CA R (%)	FA R (%)	RA R (%)	%C	*h*-index
USA	American	21,851	1 (36)	1 (34)	1 (42)	1 (31)	1 (31)	23	123
UK	European	4,647	2 (7.6)	2 (5.9)	2 (14)	2 (6.1)	2 (6.1)	37	77
Canada	American	4,293	3 (7.0)	3 (5.7)	3 (12)	3 (5.7)	3 (5.6)	34	76
China	Asian	3,209	4 (5.2)	4 (4.0)	5 (10)	4 (4.2)	4 (4.3)	39	47
France	European	3,158	5 (5.1)	6 (3.7)	4 (11)	5 (3.9)	5 (3.9)	42	62
Germany	European	2,847	6 (4.6)	8 (3.3)	6 (10)	7 (3.4)	7 (3.5)	43	66
Australia	Oceania	2,693	7 (4.4)	7 (3.5)	7 (8.2)	6 (3.5)	6 (3.5)	37	66
India	Asian	2,338	8 (3.8)	5 (3.7)	13 (4.1)	8 (3.4)	8 (3.4)	21	49
Italy	European	2,326	9 (3.8)	9 (3.0)	10 (6.9)	9 (3.1)	9 (3.2)	36	59
Spain	European	2,171	10 (3.5)	10 (3.0)	11 (5.8)	10 (3.0)	10 (3.0)	32	57
Japan	Asian	2,138	11 (3.5)	11 (2.5)	9 (7.3)	11 (2.6)	11 (2.7)	41	53
Netherlands	European	1,834	12 (3.0)	14 (1.9)	8 (7.6)	12 (2.2)	12 (2.1)	49	61
Taiwan	Asian	1,282	13 (2.1)	12 (2.1)	24 (2.1)	13 (1.9)	13 (2.0)	20	51
Turkey	European	1,216	14 (2.0)	13 (2.0)	25 (2.0)	14 (1.8)	14 (1.9)	20	42
Switzerland	European	1,142	15 (1.9)	20 (1.0)	12 (5.3)	17 (1.3)	18 (1.3)	56	51
South Korea	Asian	1,127	16 (1.8)	16 (1.3)	14 (3.9)	16 (1.5)	16 (1.5)	41	46
South Africa	African	1,093	17 (1.8)	15 (1.8)	27 (1.7)	15 (1.7)	15 (1.6)	19	29
Sweden	European	1,026	18 (1.7)	17 (1.2)	15 (3.8)	18 (1.3)	17 (1.3)	44	47
Israel	Asian	872	19 (1.4)	19 (1.1)	17 (2.7)	19 (1.1)	19 (1.2)	37	45
Belgium	European	814	20 (1.3)	23 (0.76)	16 (3.7)	22 (1.0)	22 (1.0)	54	41

TA: total number of articles; TA R (%), SA R (%), CA R (%), FA R (%), RA R (%): rank and percentage of total articles of one country, single country articles, internationally collaborative articles, first author articles, corresponding author articles in total articles; C%: percentage of internationally collaborative articles in total articles of one country.

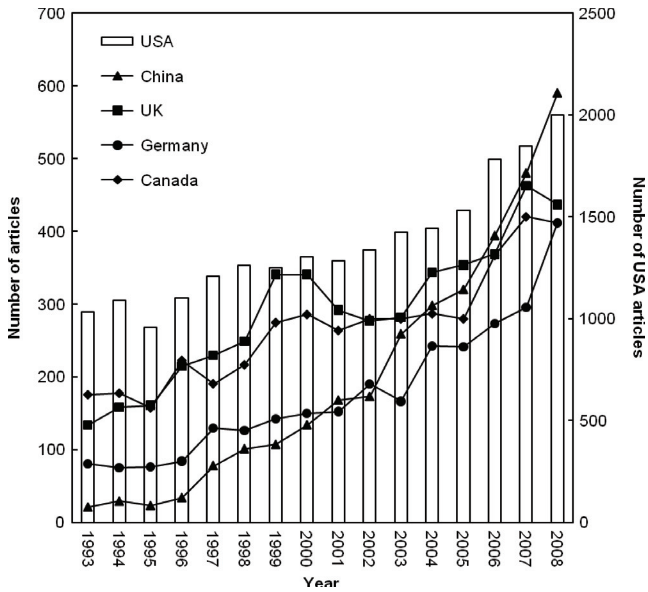

Fig. 4. Comparison of the trends of the top 5 productive countries during 1993–2008.

Canada (77) and the UK (76). The trends of the top 5 productive countries in 2008 with more than 400 articles are shown in Fig. 4. Besides the USA, China had the highest growth rate in the number of articles and ranked second in 2008.

3.4. Distribution of institute analysis

The contributions of different institutes were estimated by the affiliation of at least one author. Taking EU member states as an example, a previous study pointed out the complexity in the use of address data, and concluded that this can be used at the level of "main organization", such as a university, a company, or a research institute [56], but for countries with a complex system, such as France, a list of organizations should be compiled beforehand. In our data we used institute names from the ISI database. Furthermore, country and institute information were used jointly to avoid errors in aggregating papers to institutions. Of all the 61,334 articles with author addresses, 30,619 (49.9%) were independent articles and 30,725 (50.1%) were collaborations by two or more institutes. Among the top 20 institutes (Table 3), 13 were in the USA, 2 in Canada and one each in China, India, Taiwan, Spain, and the Netherlands. A bias in institute analysis should be noted that both the Chinese Academy of Sciences and the Indian Institute of Technology have over 100 branches in different cities. At present, the articles of

Table 3
Top 20 most productive institutes during 1993–2008

Institute	TA	TA R (%)	SA R (%)	CA R (%)	FA R (%)	RA R (%)	*h*-index
U.S. Geological Survey, USA	1,343	1 (2.2)	1 (1.9)	1 (2.5)	1 (1.5)	1 (1.6)	64
Agricultural Research Service, United States Department of Agriculture (USDA ARS), USA	820	2 (1.3)	3 (0.83)	3 (1.8)	4 (0.8)	4 (0.85)	56
Chinese Academy of Sciences, China	813	3 (1.3)	5 (0.74)	2 (1.9)	3 (0.86)	2 (0.87)	33
Indian Institute of Technology, India	765	4 (1.2)	2 (1.1)	6 (1.4)	2 (0.89)	3 (0.85)	35
University of Arizona, USA	693	5 (1.1)	6 (0.73)	4 (1.5)	5 (0.71)	5 (0.60)	58
US Environmental Protection Agency, USA	607	6 (1.0)	11 (0.49)	5 (1.5)	9 (0.53)	8 (0.54)	41
University of California (Davis), USA	596	7 (1.0)	8 (0.59)	7 (1.4)	8 (0.58)	9 (0.53)	38
University of Waterloo, Canada	591	8 (1.0)	7 (0.67)	8 (1.3)	6 (0.66)	7 (0.55)	51
University of California (Berkeley), USA	548	9 (0.89)	4 (0.77)	12 (1.0)	7 (0.60)	6 (0.56)	49
Texas A&M University, USA	491	10 (0.80)	10 (0.50)	10 (1.1)	11 (0.49)	11 (0.46)	27
Colorado State University, USA	473	11 (0.77)	21 (0.38)	9 (1.2)	13 (0.45)	14 (0.40)	37
University of Illinois, USA	458	12 (0.75)	13 (0.46)	11 (1.0)	12 (0.47)	12 (0.44)	41
National Taiwan University, Taiwan	419	13 (0.68)	9 (0.54)	18 (0.82)	10 (0.52)	9 (0.53)	33
University of Colorado, USA	411	14 (0.67)	16 (0.40)	14 (0.94)	14 (0.42)	15 (0.38)	47
Cornell University, USA	402	15 (0.66)	31 (0.32)	13 (1.0)	17 (0.37)	21 (0.32)	41
Spanish National Research Council (CSIC), Spain	391	16 (0.64)	16 (0.40)	17 (0.88)	16 (0.39)	13 (0.41)	35
University of Florida, USA	356	17 (0.58)	19 (0.39)	20 (0.77)	15 (0.41)	17 (0.36)	30
Delft University of Technology, Netherlands	353	18 (0.58)	60 (0.23)	15 (0.92)	27 (0.31)	32 (0.27)	36
University of British Columbia, Canada	344	19 (0.56)	26 (0.35)	20 (0.77)	23 (0.33)	26 (0.30)	35
Oregon State University, USA	343	20 (0.56)	68 (0.21)	16 (0.90)	30 (0.30)	34 (0.26)	37

TA: total number of articles; TA R (%), SA R (%), CA R (%), FA R (%), RA R (%): rank and percentage of total articles of one institute, single institute articles, inter-institutionally collaborative articles, first author articles, corresponding author articles in total articles.

these two institutes were pooled under one heading, and articles divided into branches would result in different rankings [58]. This kind of identity raised these two institutes' ranks in global water resources research. The U.S. Geological Survey (USGS) published the most total articles (1,343), independent articles, inter-institutionally collaborative articles, first author articles and corresponding author articles. Furthermore, the *h*-index (64) of USGS was the highest among all the institutes. The most cited paper from the USGS was "evaluating the use of goodness-of-fit measures in hydrologic and hydro-climatic model validation" [57]. The USGS is a scientific agency of the United States government, and its major aim is to study the landscape of the United States, its natural resources, and the natural hazards that threaten it. This organization has four major science disciplines, hydrology, biology, geography, and geology (www.usgs.gov).

4. Distribution of paper titles, author keywords and KeyWords Plus

4.1. Distribution of paper titles analysis

The title of an article always includes the information that the author would most like to express to the readers. It can be used to identify the subjective focus and emphasis specified by authors. The analysis of paper titles was first applied in mapping trends in aerosol research [21], and then in stem cell [43], and atmospheric simulation research [58]. All single words in the title of water resources-related articles were statistically analyzed in this study. Some prepositions, articles and common words such as "using", "under", "the", and "during" were discarded, as they were meaningless for further analysis. The 25 most frequently used substantives in titles were grouped in 4 four-year periods (Table 4). "Model" ranked second and was the most frequent method used in the analysis of paper titles. In 1998, Arnold et al. developed a conceptual, continuous time model called SWAT (Soil and Water Assessment Tool) to assist water resource managers in assessing the impact of management on water supplies and nonpoint source pollution in watersheds and large river basins [59]. This paper in the *Journal of the American Water Resources Association* had a great impact on the subsequent water resources research.

4.2. Distribution of author keywords analysis

Author keywords offer information about research trends that concern researchers. Bibliometric methods

Table 4
Top 25 most frequent substantives in article titles during 1993–2008 and 4 four-year periods

Words in title	93-08 TA	93-08 R (%)	93-96 R (%)	97-00 R (%)	01-04 R (%)	05-08 R (%)
water	8,892	1 (14)	1 (8.6)	1 (14)	1 (16)	1 (16)
model	3,937	2 (6.3)	2 (5.3)	2 (6.5)	2 (6.1)	2 (6.8)
Flow	3,696	3 (5.9)	5 (4.6)	3 (6.4)	2 (6.1)	3 (6.1)
Soil	2,992	4 (4.8)	4 (4.7)	4 (4.8)	5 (5.0)	7 (4.7)
River	2,989	5 (4.8)	11 (2.6)	7 (4.3)	4 (5.2)	4 (5.7)
Analysis	2,931	6 (4.7)	8 (3.5)	5 (4.6)	6 (4.6)	5 (5.4)
Groundwater	2,668	7 (4.3)	7 (3.8)	8 (3.7)	8 (3.9)	6 (5.1)
Transport	2,477	8 (4.0)	3 (4.8)	6 (4.4)	7 (4.0)	11 (3.4)
Modeling	2,308	9 (3.7)	6 (4.2)	10 (3.4)	10 (3.5)	8 (3.8)
Effects	2,276	10 (3.7)	9 (3.4)	9 (3.5)	9 (3.8)	9 (3.7)
Management	1,880	11 (3.0)	15 (2.4)	13 (2.9)	14 (3.0)	10 (3.4)
Effect	1,860	12 (3.0)	10 (3.1)	12 (2.9)	11 (3.1)	16 (2.9)
System	1,843	13 (3.0)	20 (2.2)	11 (3.0)	12 (3.1)	14 (3.2)
Treatment	1,748	14 (2.8)	24 (2.0)	18 (2.4)	15 (2.9)	12 (3.3)
Removal	1,706	15 (2.7)	18 (2.3)	16 (2.6)	13 (3.0)	17 (2.9)
Sediment	1,512	16 (2.4)	22 (2.0)	19 (2.4)	19 (2.4)	22 (2.6)
Assessment	1,506	17 (2.4)	48 (1.3)	29 (2.0)	23 (2.3)	13 (3.2)
Wastewater	1,495	18 (2.4)	179 (0.58)	20 (2.3)	17 (2.5)	15 (3.1)
Evaluation	1,467	19 (2.4)	21 (2.0)	26 (2.1)	20 (2.4)	23 (2.6)
Aquifer	1,452	20 (2.3)	12 (2.6)	17 (2.5)	25 (2.3)	31 (2.2)
Systems	1,452	20 (2.3)	14 (2.4)	15 (2.6)	27 (2.1)	28 (2.3)
Basin	1,446	22 (2.3)	39 (1.4)	31 (2.0)	18 (2.5)	18 (2.8)
Surface	1,424	23 (2.3)	28 (1.7)	14 (2.7)	24 (2.3)	27 (2.3)
Distribution	1,412	24 (2.3)	26 (1.8)	24 (2.3)	22 (2.3)	25 (2.4)
Quality	1,392	25 (2.2)	63 (1.1)	23 (2.3)	16 (2.7)	26 (2.4)
Irrigation	1,392	25 (2.2)	23 (2.0)	36 (1.7)	26 (2.2)	20 (2.7)

TA: total number of articles; R (%): rank and percentage of substantives in titles in total articles.

of author keyword analysis have been developed in recent years [52,60], whereas using the author keywords to analyze the trend of research in different periods is rare [21,43,58]. Examination of author keywords in this study revealed that altogether 74,992 were used, among which, 54,235 (72%) appeared only once and 8,731 (12%) appeared twice. The large number of once-only keywords probably indicates a lack of continuity in research and a wide disparity in research foci [61]. The author keywords which ranked top 25 in all articles are listed in Table 5. The top two most frequently used keywords were "groundwater" and "water quality", which are the most important topics in water resources research. Two highly cited articles with the author keyword "groundwater" were found. The first was "tracking persistent pharmaceutical residues from municipal sewage to drinking water" in the *Journal of Hydrology* [62]. This article had been cited 150 times from its publication in 2002 until 2008. The other was "arsenic in groundwater in six districts of West Bengal, India" in *Environmental Geochemistry and Health* [63]. Arsenic in groundwater above the WHO maximum permissible limit of 0.05 mg l^{-1} was found in six districts of West Bengal covering an area of 34,000 km^2 with a high population of 30 million [63]. This paper was cited 141 times up to 2008. The constant focus on "groundwater" during 1993–2008 is consistent with previous research results which demonstrated this mature but also challenging theme [23,64,65]. "The importance of trace metal speciation to water quality criteria" with "water quality" in the title was published in *Water Environment Research* [66] and was cited 131 times up to 2008. An interesting phenomenon in author keywords was found; the researchers paid more attention to the water resources issue that humans can really "use" such as "fresh water resources" than "ocean water". "Adsorption" and "modeling" were the most popular techniques in author keyword analysis. Some topics, such as "runoff", "wastewater", "irrigation", and "evapotranspiration" became new foci, whose ranks went up markedly. In contrast, the author keywords "activated sludge", "biodegradation", and "denitrification" decreased from 1st, 4th, and 5th during 1993–1996 to 18th, 35th, and 56th during 2005–2008.

Table 5
Top 25 most frequent author keywords used during 1993–2008 and 4 four-year periods

Author keywords	93–08 TA	93–08 R (%)	93–96 R (%)	97–00 R (%)	01–04 R (%)	05–08 R (%)
Groundwater	1,193	1 (2.9)	3 (2.9)	2 (2.8)	1 (3.1)	1 (2.7)
water quality	1,077	2 (2.6)	11 (1.9)	1 (2.9)	2 (2.9)	2 (2.4)
Adsorption	674	3 (1.6)	2 (3.1)	5 (1.7)	3 (1.5)	6 (1.4)
heavy metals	668	4 (1.6)	7 (2.1)	3 (2.3)	4 (1.5)	8 (1.3)
Runoff	584	5 (1.4)	99 (0.48)	6 (1.6)	6 (1.4)	3 (1.5)
Activated sludge	562	6 (1.4)	1 (4.8)	4 (1.8)	20 (0.91)	18 (0.89)
Modeling	540	7 (1.3)	8 (2.0)	8 (1.5)	5 (1.5)	13 (1.0)
Wastewater	538	8 (1.3)	68 (0.58)	7 (1.5)	8 (1.1)	5 (1.4)
Irrigation	524	9 (1.3)	43 (0.85)	28 (0.86)	7 (1.3)	4 (1.5)
Phosphorus	459	10 (1.1)	24 (1.2)	12 (1.2)	21 (0.91)	9 (1.2)
Sediment	450	11 (1.1)	24 (1.2)	11 (1.2)	13 (1.0)	11 (1.0)
evapotranspiration	445	12 (1.1)	68 (0.58)	38 (0.75)	16 (1.0)	7 (1.4)
modeling	424	13 (1.0)	89 (0.51)	15 (1.2)	9 (1.1)	12 (1.0)
Drinking water	422	14 (1.0)	20 (1.2)	17 (1.1)	12 (1.0)	16 (0.92)
Biodegradation	419	15 (1.0)	4 (2.7)	9 (1.3)	19 (0.93)	35 (0.63)
Nitrogen	403	16 (1.0)	34 (1.0)	13 (1.2)	14 (1.0)	23 (0.82)
Nitrate	385	17 (0.93)	43 (0.85)	24 (0.95)	10 (1.1)	24 (0.82)
Simulation	383	18 (0.92)	68 (0.58)	19 (1.0)	17 (0.94)	17 (0.92)
Hydrology	379	19 (0.91)	77 (0.54)	21 (1.0)	11 (1.1)	20 (0.84)
denitrification	375	20 (0.90)	5 (2.4)	10 (1.3)	27 (0.82)	56 (0.53)
Climate change	351	21 (0.84)	153 (0.34)	34 (0.78)	26 (0.83)	14 (1.0)
Precipitation	350	22 (0.84)	37 (1.0)	34 (0.78)	22 (0.89)	26 (0.81)
GIS	349	23 (0.84)	372 (0.17)	51 (0.65)	28 (0.80)	10 (1.1)
Wastewater treatment	342	24 (0.82)	32 (1.0)	31 (0.82)	36 (0.72)	19 (0.87)
Sorption	340	25 (0.82)	24 (1.2)	16 (1.2)	24 (0.85)	43 (0.59)

TA: total number of articles; R (%): rank and percentage of author keywords in total articles.

4.3. Distribution of KeyWords Plus analysis

KeyWords Plus provides search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI database, and substantially augments title-word and author-keyword indexing [46]. Unlike segmenting a whole title into single words as in paper title analysis, precise words that the authors wanted to transmit to the readers are preserved in author keywords analysis. The KeyWords Plus analysis, as an independent supplement, reveals the article contents in more details. There were some similar and dissimilar trends between their statistical results in this study period. The top four most frequently used KeyWords Plus were "water", "model", "flow", and "transport" (Table 6). The rank of "management", "waste-water", "runoff", and "variability" went up markedly from 62nd, 40th, 43rd, and 59th during 1993-1996 to 7th, 13th, 14th, and 15th during 2005-2008. Similar to the results of author keyword analysis, "waste-water" and "runoff" were also emphasized in KeyWords Plus analysis. The most cited article in 2004 was written by Carballa et al. who did a survey of "waste-water" treatment in Spain. The aim of this study was to investigate the behavior of 13 cosmetic and pharmaceutical compounds belonging to different groups (musks, anti-inflammatories, anti-epileptics, tranquillizers, antibiotics, natural and synthetic estrogens, and contrast media), and the removal efficiency from the water phase of each substance in each particular unit was determined [67]. "Runoff" was one of the key parameters in hydrological models [68, 69]. As in the analysis of author keywords, "model" and "adsorption" were the most popular techniques in the KeyWords Plus analysis.

4.4. Most cited articles

The time-dependence of citations might be informative for tracking the impact of an article. The most highly cited papers appear to be pioneers in the field with papers departing significantly from what has come before and to be effective in creating similar, follow-on papers [22]. The number of citations per year versus time was presented for article life. Article history has been investigated by the percentage of cited papers [54] and the citations per article [70] versus time. From 1993 to 2008, the most frequently cited article was "occur-

Table 6
Top 25 frequent KeyWords Plus used during 1993–2008 and 4 four-year periods

KeyWords plus	93–08 TA	93–08 R (%)	93–96 R (%)	97–00 R (%)	01–04 R (%)	05–08 R (%)
Water	3,960	1 (8.2)	1 (8.5)	1 (9.2)	1 (8.6)	2 (7.4)
Model	3,510	2 (7.3)	2 (5.9)	2 (6.9)	2 (7.5)	1 (7.8)
Flow	2,698	3 (5.6)	3 (4.9)	3 (5.1)	3 (5.7)	3 (6.0)
Transport	2,271	4 (4.7)	4 (4.4)	4 (5.0)	4 (4.7)	4 (4.7)
Soil	1,627	5 (3.4)	5 (4.0)	5 (3.4)	5 (3.3)	5 (3.2)
Porous-media	1,478	6 (3.1)	7 (3.8)	6 (3.2)	6 (3.2)	12 (2.7)
Groundwater	1,423	7 (3.0)	6 (3.8)	7 (3.1)	7 (2.8)	11 (2.7)
Simulation	1,376	8 (2.9)	11 (2.5)	9 (2.7)	9 (2.6)	6 (3.2)
Systems	1,348	9 (2.8)	10 (2.7)	11 (2.5)	10 (2.5)	9 (3.1)
Removal	1,273	10 (2.6)	17 (1.8)	14 (2.0)	8 (2.7)	8 (3.2)
Adsorption	1,168	11 (2.4)	8 (2.8)	8 (2.7)	11 (2.4)	16 (2.2)
Soils	1,097	12 (2.3)	12 (2.5)	10 (2.6)	13 (2.2)	23 (2.1)
System	1,049	13 (2.2)	38 (1.2)	25 (1.5)	12 (2.2)	10 (2.8)
Management	1,040	14 (2.2)	62 (0.80)	35 (1.2)	18 (1.9)	7 (3.2)
Waste-water	1,023	15 (2.1)	40 (1.2)	24 (1.5)	14 (2.2)	13 (2.7)
Solute transport	993	16 (2.1)	9 (2.8)	12 (2.4)	17 (2.0)	29 (1.7)
Runoff	986	17 (2.0)	43 (1.1)	19 (1.7)	16 (2.0)	14 (2.5)
Hydraulic conductivity	981	18 (2.0)	14 (2.0)	13 (2.2)	20 (1.9)	21 (2.1)
Models	921	19 (1.9)	18 (1.8)	16 (1.8)	25 (1.7)	17 (2.2)
Variability	917	20 (1.9)	59 (0.85)	43 (1.2)	15 (2.2)	15 (2.4)
Degradation	856	21 (1.8)	21 (1.7)	17 (1.8)	19 (1.9)	26 (1.8)
Precipitation	836	22 (1.7)	34 (1.2)	33 (1.2)	22 (1.8)	20 (2.1)
Growth	831	23 (1.7)	14 (2.0)	19 (1.7)	21 (1.8)	33 (1.6)
River	828	24 (1.7)	70 (0.75)	28 (1.4)	22 (1.8)	18 (2.1)
Aquifer	786	25 (1.6)	23 (1.6)	22 (1.5)	28 (1.6)	30 (1.7)

TA: total number of articles; R (%): rank and percentage of KeyWords Plus in total articles.

rence of drugs in German sewage treatment plants and rivers", which was published in *Water Research* by Ternes from Germany in 1998 and had been cited 630 times by 2008. The most frequently cited articles every year that was cited more than 100 times up to 2008 are listed in Table 7. Five were published in *Water Research*, which ranked first in the category of water resources with an impact factor of 3.427. Three originated in the USA and Germany, two in the UK, and one each in Canada, Denmark, Hong Kong, Taiwan, and Spain. Five articles were published by a single author. The citation history of the most frequently cited articles listed in Table 7 are shown in Fig. 5. The citation times of the most frequently cited article [71] continued increasing and even reached 108 in 2006 and then decreased in the following years. The most frequently cited article in 2008 was published in 2000 by Ho and McKay with 99 citations. This paper is still in a high enough position to impact current water resources research. Moreover, Beven and Ho published two first author articles (Table 7).

Table 7
Most frequently cited articles every year during 1993–2004

Year	Article/Journal	Authors	TC	C/Y	Country
1993	Prophecy, reality and uncertainty in distributed hydrological modeling *Advances in Water Resources*	Beven, K	300	19	UK
1994	Enhanced degradation of halogenated aliphatics by zero-valent iron *Ground Water*	Gillham, RW; Ohannesin, SF	451	30	Canada
1995	Artificial neural-network modeling of the rainfall-runoff process *Water Resources Research*	Hsu, KL; Gupta, HV; Sorooshian, S	314	22	USA
1996	Extraction of extracellular polymers from activated sludge using a cation exchange resin *Water Research*	Frolund, B; Palmgren, R; Keiding, K; Nielsen, PH	300	23	Denmark
1997	A new method for the determination of flow directions and upslope areas in grid digital elevation models *Water Resources Research*	Tarboton, DG	273	23	USA
1998	Occurrence of drugs in German sewage treatment plants and rivers *Water Research*	Ternes, TA	630	57	Germany
1999	Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation *Water Resources Research*	Legates, DR; McCabe, GJ	289	29	USA
2000	The kinetics of sorption of divalent metal ions onto sphagnum moss peat *Water Research*	Ho, YS; McKay, Gs	367	41	Hong Kong
2001	Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology *Journal of Hydrology*	Beven, K; Freer, J	207	26	UK
2002	Tracking persistent pharmaceutical residues from municipal sewage to drinking water *Journal of Hydrology*	Heberer, T	150	21	Germany
2003	Removal of copper ions from aqueous solution by tree fern *Water Research*	Ho, YS	132	22	Taiwan
2004	Behavior of pharmaceuticals, cosmetics and hormones in a sewage treatment plant *Water Research*	Carballa, M; Omil, F; Lema, JM; Llompart, M; Garcia-Jares, C; Rodriguez, I; Gomez, M; Ternes, T	153	31	Spain, Germany

TC: total times cited of articles from publication until 2008; C/Y: times cited per year.

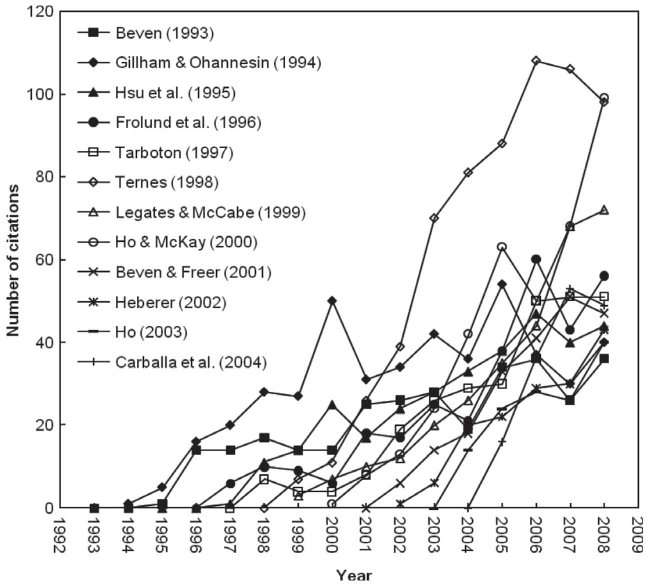

Fig. 5. Citation history of the most frequently cited articles each year during 1993–2004.

5. Conclusions

In this study on the articles in the category of water resources journals listed in SCI-Expanded, significant points on worldwide research performance from 1993 to 2008 were revealed. The effort provided a systematic structural picture, as well as clues to the impact of research on water resources. Even though English was the dominant language, eight other languages were also used, which indicated global concern about water resources. Apparently more authors, institutes, and countries were engaged in this research over the 16 years. The United States Geological Survey was the pioneer in the field of water resources, with the most independent, inter-institutionally collaborative, first author, and corresponding author articles. Furthermore, the *h*-index (64) of the United Stated Geological Survey was the highest. The G7 along with China, India, Australia, and Spain had a long research history in this field. China showed a rapidly ascending trend in the number of articles during the last 6 years. Not only did they have the absolute ascendancy of articles, but were also the most-frequent research partners and had higher *h*-indices. The number of journals published in three zones of articles approximately followed Bradford's law. We calculated the coefficients of determination of the impact factor and the *h*-indices, and found that the journals in the second group had a weaker relationship than that in the first group. In terms of the distributions of words in the paper titles, "river" and "groundwater" were the most concerned "water bodies". In the author keywords analysis, the two most frequently used keywords were "groundwater" and "water quality". The topics, "runoff", "wastewater", "irrigation", and "evapotranspiration" had become new foci. The top four most frequently used KeyWords Plus were "water", "model", "flow", and "transport". "Management", "waste-water", "runoff", and "variability" were active research areas. In addition, "modeling" and "adsorption" were the most popular techniques. The most frequently cited paper each year was a backstage pioneer in the research field. The article published in *Water Research* by Ternes in 1998 had been cited 630 times up to 2008. But its citation rate decreased in the past two years. Another paper published in 2000 by Ho and McKay still has a great impact on current water resources research. This study provided researchers with a panorama of global water resources research and established further research directions.

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