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Review

Global Isotopic Hydrograph Separation Research History and Trends: A Text Mining and Bibliometric Analysis Study

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Abstract: Scientific research into isotope hydrograph separation (IHS) has rapidly increased in recent years. However, there is a lack of systematic and quantitative research to explore how this field has evolved over time. In this study, the methods of text mining and bibliometric analysis were combined to address this shortcoming. The results showed that there were clear periodical characteristics in IHS studies between 1986 and 2019. High-frequency words, e.g., catchment, stable isotope, runoff, groundwater, precipitation, runoff generation, and soil, were the basic topics in IHS studies. Forest and glacier/snow were the main landscapes in this research field. 'Variation', 'spatial', and 'uncertainty' are hot issues for future research. Today, studies involving the geographical source, flow path, and transit/residence time of streamflow components have enhanced our understanding of the hydrological processes by using hydrometeorological measurements, water chemistry, and stable isotope approaches. In the future, new methods, such as path analysis and ensemble hydrograph separation, should be verified and used in more regions, especially in remote and mountainous areas. Additionally, the understanding of the role of surface water in streamflow components remains limited and should be deeply studied in the future.

Keywords: isotope hydrology; text mining; bibliometric indicator; web of science

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1. Introduction

In 1969, Hubert et al. [1] published their pioneering paper on hydrograph separation using stable isotope tracers. Since then, isotope hydrograph separation (IHS) has gradually become the principal method for determining the relative contributions of different sources of runoff or streamflow (i.e., event or pre-event water) [2–5]. Buttle [6] summarized the hydrological processes, including groundwater ridging, lateral throughflow, preferential flow, saturation overland flow, kinematic waves, and output from surface storage, which significantly improved the knowledge of the mechanisms of runoff generation. In 2013, Klaus and McDonnell [7] published a qualitative and comprehensive review of IHS and concluded that, despite certain limitations, water stable isotopes were still the most effective technology for understanding runoff generation processes and mechanisms. Moreover, several IHS reviews have focused on streamflow generation and associated processes and methods in special environmental settings, which has accelerated the accumulation of IHS studies [8,9]. Since 2013, there has been a rapid increase in scientific output in the field, which provides an unprecedented opportunity to explore the dynamics of IHS research based on data from a large body of published scientific work. However, to our knowledge, there has not been a quantitative assessment of the publication data in this field, and there are limited documents on text mining and relevant data science methods applied in hydrology research. Utilizing a quantitative and systemic method, we can analyze the characteristics and performances of documents to gain both macro- and micro-insights into the history and development of the field.

Similar to all scientific fields, the study of IHS has changed over time. Interests in certain themes have emerged and disappeared, and the breadth and depth of research content have expanded [10]. The most significant advances were made around the five well-known assumptions implicit in IHS models [9]. The five underlying assumptions are listed as follows: (1) significant isotopic differences occurred between the pre-event (old) and event (new) water; (2) the new water retains a constant isotopic signature in space and time, or any variations can be accounted for; (3) the isotopic signature of the old water is constant in space and time, or any variations can be accounted for; (4) contributions of water from the vadose zone must be negligible, or the isotopic content of soil water must be similar to that of groundwater; and (5) the contributions from surface storage to streamflow are negligible. Many IHS studies have concentrated on the validity and effects of these assumptions in recent decades [2,11–17]. Tracing IHS literature by quantitative approaches is interesting and vital for enhancing the understanding of runoff generation and relevant hydrological processes.

Text mining is the process of automatically extracting high-quality information from unstructured or structured texts with diverse formats and types using linguistic and statistical techniques [18,19]. Thematic analysis is an important subject of textual data mining. Studies have found that temporal changes in themes, usually represented by keywords for a given research domain, can help to uncover the evolution of a topic and its trend [20–22]. For example, Yao et al. [23] analyzed the frequency changes in author keywords related to nitrogen in eutrophic lakes or reservoirs at five-year intervals and successfully determined the current and future trends in nitrogen field research. Chen et al. [24] analyzed research trends in management science and engineering in China based on co-keyword analysis and concluded that the foci were game theory, supply chain management, complex networks, data mining, optimization, risk management, and data envelopment analysis. In addition, theme variations based on keyword analysis can also help new researchers to situate themselves and their topics within the field and within changing research interests. Similarly, a systemic analysis of the thematic changes in IHS research is indispensable to understanding how this field evolved over time and predicting future research trends.

Bibliometric analysis is a popular, powerful, and systematic way to analyze the performance of scientific production using mathematical and statistical methods [25,26]. The results of bibliometric analyses can provide objective views of scientific productions in a given research field and provide effective support for the subjective perceptions of researchers. Many research fields have applied this methodology to assess and predict scientific productivity, development, and future trends [27,28]. Padilla et al. [29], for example, conducted a bibliometric analysis of global nitrate leaching publications and found an overriding interest in recent decades on the theme of soil nitrogen loss in agroecosystems. Moreover, many different bibliometric indicators can be used to evaluate the literature characteristics as well as thematic influences, such as the number of documents, number of citations, and rank [30]. A quantitative analysis of bibliometric indicators can reveal the most cited papers, hot issues, and other valuable information in a given research field, which can help scientists to quickly develop an understanding of the research situation in their field [31,32]. Therefore, an analysis of the performance of themes with bibliometric indicators is of vital importance in understanding the global state of IHS.

Based on the techniques of text mining and bibliometric analysis, this study analyzed the evolving history and future trends of IHS research from a global perspective by using the Web of Science (WoS) database. The aims of this study were to (1) quantitatively summarize the characteristics of yearly publication and explore the development nature of IHS; (2) mine and assess IHS themes in different subperiods and reveal how these themes enhance our understanding of hydrological processes related to IHS, and (3) discuss the upcoming research trends and provide a certain guide for future IHS research.

2. Materials and Methods

2.1. Data Sources

The WoS is a powerful literature database that can provide good access to bibliometric indicators of the published items and allow us to explore the literature in scientific fields. Moreover, the WoS database includes complete citation data of specific domains, covering more than 20,000 journals, conference proceedings, and books. Thus, our bibliometric analysis was conducted based on the literature from the WoS database. We started by searching for the topic keywords (including 'Title', 'Abstract', 'Author Keywords', and 'Keywords Plus') 'hydrograph separation*' and 'isotope' or 'isotopic' from the core WoS collection. We limited the research period to 1969 to 2019 and limited the document types to articles, proceedings, and reviews. Keywords and abstracts from before 1990 are not available on the WoS, so the number of documents collected before 1990 is limited [33,34]. In total, 392 publications from 1986 to 2019 met the selection criteria, and the full records and cited references of each were downloaded in plain text format for further analysis. Most publications (389) are written in English, two are written in French, and one is written in Spanish.

2.2. Analytical Methods

We extracted various performance indicators from 392 downloaded IHS recodes to conduct a bibliometric analysis that included frequency calculation, co-word analysis, and science mapping. Science mapping is a spatial representation of how disciplines, domains, specialities, and individual research units relate to one another [35]. Frequency calculations are widely used in bibliometric analyses to investigate the influence of research units, such as publications, authors, and countries/regions, by counting the number of documents and total citations (TC) or global citation scores (GCS), local citation scores (LCS), and themes based on counting words of interest [28]. LCS is the number of citations of one document by other documents in the collected dataset, while TC or GCS is the number of citations of one document by the documents in the WoS core collection [23]. More information on the relevant bibliometric indicators in this study is shown in Table 1. In this study, the primary bibliometric index of assessing the influence of research activities was LCS, followed by the number of publications, then others.

Author keywords (AKs), which are one part of most articles that name 'Keywords' added by authors, play a prominent role within the different sections of a document. Keywords Plus (PKs), which can be considered an extension of AKs that added by the WoS, could increase retrieval effectiveness. AKs and PKs generally represent the main ideas, content, and other valuable information contained in a paper [36]. Therefore, many studies have applied AKs or PKs or have coupled AKs with PKs in different time intervals to investigate themes, hotspots, or trends during specific research subperiods [23,29,37]. We chose to jointly use the document AKs and PKs because some documents lacked AKs. A normalization process was conducted before beginning the theme evolution analysis. First, spelling errors were corrected. Then, the plural forms of keywords were changed to their singular forms. Finally, acronyms were added to the respective keywords. We used an approach that included co-word analysis, strategic and Sankey diagrams, and performance analysis of themes developed by Cobo et al. [38] to detect, quantify, and visualize the evolution and trends in IHS research. Several studies have employed this method to explore the thematic developments and trends in analyzed research domains [39].

Table 1. Bibliometric indicators and their formulas.

Indicator	Definition or Description	Formula
Publication (Pub)	Pub is the number of documents	
Local citation scores (LCS)	LCS is the number of citations by other papers in the analyzed collection.	
LCS per paper (*Lpp*)	LCS per paper is the ratio of total LCS in terms of papers.	$Lpp = \frac{LCS}{P}$ P is the number of papers.
Total citation (TC) or global citation scores (GCS)	TC or GCS is the number of citations by the documents in the WoS core collection in this study.	
GCS per paper (*Gpp*)	GCS per paper is the ratio of GCS in terms of papers.	$Gpp = \frac{GCS}{P}$ P is the number of papers.
h-index	A set of papers has a h-index h if h is the highest rank such that each top h papers have at least h citations.	$h = max_k\left(\sum_{i=1}^{k} C_i \;\geq k\right),\; k = 1, 2, \ldots, p$ C_i is the citation of paper i. The *h-index* is equal to or less than the total of papers P of an author. [40]
g-index	g-index is as a variant of the *h-index.* A set of papers has a *g-index* g if g is the highest rank such that top g papers have, together, at least g^2 citations.	$g = max_k\left(\sum_{i=1}^{k} C_i \;\geq k^2\right),\; k = 1, 2, \ldots, p$ [41]
Equivalence index (*e*)	Equivalence index is a measure of similarities between i keywords.	$e_{ij} = \frac{c_{ij}^2}{c_i c_j}$ e_{ij} is the measure of similarities between items in frequencies of keyword's co-occurrences. c_{ij} is the number of publications in which two keyword i and j co-occur. c_i is the number of publications in which the keyword i occurs. c_j is the number of publications in which the keyword j occurs. [42]
Callon's centrality (*c*)	Callon's centrality measures the intensity of links between a given community and other communities. The value can be represented as a measure of the importance of a theme in the whole collection.	$c = 10 \times \sum e_{nm}$ Keywords n and m belong to different themes. e_{nm} is the equivalence index between keywords n and m. [42]
Callons' density (*d*)	Callon's density measures the internal strength of the community. This value can be represented as a measure of the theme's development.	$d = 100 \times \sum \frac{e_{ij}}{w}$ Keyword i and j belong to the same theme. w is the number of keywords in the theme. e_{ij} is the equivalence index between keywords i and j. [42]
Inclusion index (*In*)	*Inclusion index* is a similarity measure for themes in different subperiods. The *inclusion index* will be equal to 1 if the keywords of the theme V (subperiod II) are fully contained in the theme U (subperiod I).	$In = \frac{\#(U \cap V)}{\min(\#U, \#V)}$ [38]

The main concepts of a specific field could be discovered using co-word analysis. Moreover, co-word analysis is a powerful method to discover and describe the interactions between different research topics [38]. The methodological foundation of co-word analysis is the idea that the co-occurrence of keywords describes the contents of the documents in a file [42]. An equivalence index and clustering were applied to measure the keyword co-occurrence matrix [42,43] (Table 1). In this study, co-word analysis, including the co-occurrence and clustering of keywords, was used to detect themes through each subperiod. It was possible that there was more than one theme in one paper.

Then, two indicators, Callon's centrality and Callon's density, can be used to measure the performance of the themes in each subperiod [42] (Table 1). Callon's centrality is an indicator of the importance of a theme across a full set of publications, while Callon's density is an indicator of the theme's development. Then, a strategic diagram was applied to show the themes with different Callon's centrality (x-axis) and density (y-axis) [37] (Figure 1). The themes with high density and high centrality were named motor themes (important and developed topics that show strong links with other themes in other quadrants), which were located in quadrant I; those with low density and high centrality were developed and isolated themes, which were located in quadrant II; those with low density and low centrality were emerging or declining themes, which were located in quadrant III; and those with low density and high centrality were basic and transversal themes (focusing on general issues that were transversal to the different research areas of a domain), which were located in quadrant IV. Then, a strategic diagram was constructed to assess the role of each theme in each subperiod qualitatively. Severe bibliometric indicators were used to quantify the impact of themes in different subperiods. Finally, a Sankey diagram was applied to present how different themes were connected and developed over previous decades. Thematic analysis and visualization, supplemented by the interpretation of important documents, help us clearly capture the details of IHS development and enhance our understanding of hydrological processes in streamflow generation.

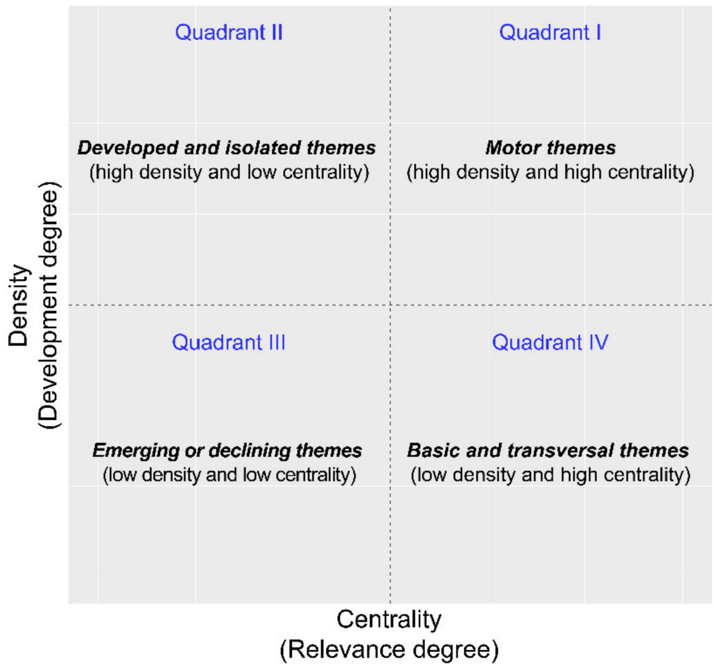

Figure 1. Strategic diagram modified from Cobo et al. [38].

All analyses were performed using R 4.0.2 software (R Core Team, 2020). The bibliometric and thematic analysis was mainly carried out using an open-source R package named the *bibliometrix* package built by Aria and Cuccurullo [44].

3. Results

3.1. Publication and Keyword Performance

The primary information and statistics regarding the analyzed IHS collection are reported in Table 2. The 392 IHS documents published in 87 sources were written by 1138 authors from 453 institutions in 53 countries. The numbers of TC and average citations per document were 12,413 and 31.67, respectively. The annual growth rate was, on average, 11.3%. Figure 2 shows the yearly output of IHS documents published from 1986 to 2019. The output presented obvious periodical characteristics in terms of the mean value of yearly publications. The whole period could be divided into three subperiod based on the significant changes in average publication output. Before 2000 (subperiod I), the literature output grew slowly, with only 50 documents in 13 years and an average annual output of only 3.6. From 2000 to 2014 (subperiod II), the annual volume of documents increased, with an average production of 11.7 documents per year. The most influential literatures were published in subperiods I and II (Table 3). During 2015 and 2019 (subperiod III), there was a significant upward trend in the number of cumulative publications, increasing from 225 in 2014 to 392 in 2019. The mean output of 33.4 in this subperiod was much higher than that in the other two subperiods. No important literature was published in subperiod III, but this may be due to delayed citing. The number of cumulative documents grew from 1986, following a quadratic function in the form of $y = 157{,}000 - 158x + 0.04x^2$ (adjusted $R^2 = 0.988$, $p < 0.001$), indicating that there is a generally increasing trend in IHS publications.

Table 2. Principal information about the 1986–2019 IHS collection.

Description	Results
Total documents	392
Timespan	1986:2019
Annual growth rate	11.28%
Total citations (TC)	12,413
Average citations per document	31.67
Sources	87
Authors	1138
Institutions	453
Countries	53

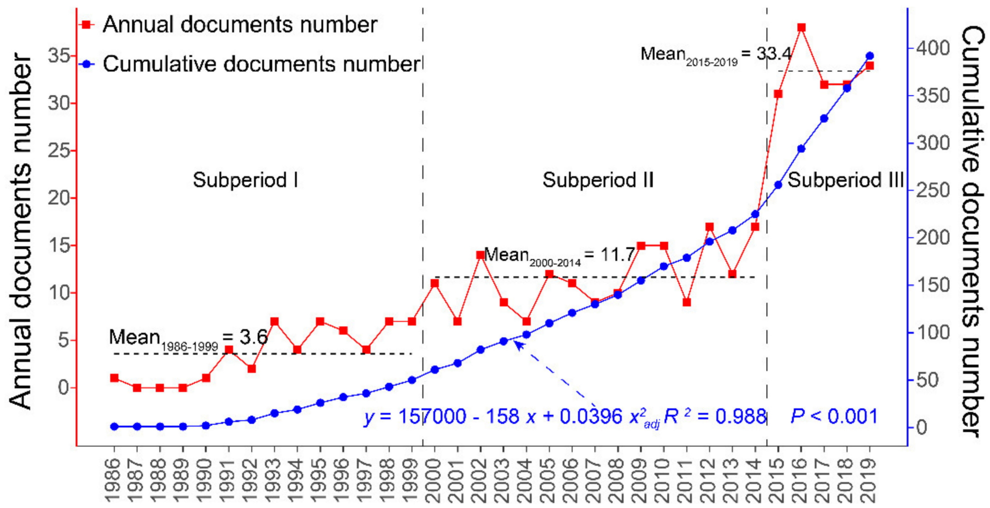

Figure 2. The publication output of IHS between 1986 and 2019. The transverse dashed lines present the mean values of the number of documents per year in each subperiod.

Table 3. Twenty most influential papers based on LCS.

Paper	Digital Object Identifier (DOI)	LCS	GCS	LCS Per Year	GCS Per Year
Buttle JM, 1994, Prog Phys Geog (IF: 3.580) [6]	10.1177/030913339401800102	118	297	4.4	11.0
Klaus J, 2013, J Hydrol (IF: 5.722) [7]	10.1016/j.jhydrol.2013.09.006	92	221	11.5	27.6
Hooper RP, 1986, Water Resour Res (IF: 5.240) [45]	10.1029/WR022i010p01444	88	252	2.5	7.2
Wels C, 1991, J Hydrol [46]	10.1016/0022-1694(91)90181-G	60	139	2.0	4.6
Laudon H, 2002, Water Resour Res [47]	10.1029/2002WR001510	51	80	2.7	4.2
Brown VA, 1999, J Hydrol [3]	10.1016/S0022-1694(98)00247-9	46	187	2.1	8.5
Taylor S, 2001, Water Resour Res [13]	10.1029/2000WR900341	44	129	2.2	6.5
Ogunkoya OO, 1993, J Hydrol [48]	10.1016/0022-1694(93)90005-T	43	93	1.5	3.3
Kong YL, 2012, J Hydrol [49]	10.1016/j.jhydrol.2012.02.029	41	78	4.6	8.7
Hinton MJ, 1994, Water Resour Res [50]	10.1029/93WR03246	39	110	1.4	4.1
Laudon H, 1997, J Hydrol [51]	10.1016/S0022-1694(97)00030-9	38	85	1.6	3.5
Ladouche B, 2001, J Hydrol [52]	10.1016/S0022-1694(00)00391-7	38	136	1.9	6.8
Taylor S, 2002, Hydrol Process (IF: 3.565) [53]	10.1002/hyp.1232	38	69	2.0	3.6
Shanley JB, 2002, Hydrol Process [54]	10.1002/hyp.312	35	94	1.8	4.9
Lyon SW, 2009, Hydrol Process [55]	10.1002/hyp.7326	35	56	2.9	4.7
Liu YH, 2008, J Hydrol [56]	10.1016/j.jhydrol.2008.02.017	33	62	2.5	4.8
Mcdonnell JJ, 1991, Water Resour Res [4]	10.1029/91WR02025	31	126	1.0	4.2
Bazemore DE, 1994, J Hydrol [57]	10.1016/0022-1694(94)90004-3	31	137	1.1	5.1
Unnikrishna PV, 2002, J Hydrol [58]	10.1016/S0022-1694(01)00596-0	28	66	1.5	3.5
Weiler M, 2003, Water Resour Res [59]	10.1029/2003WR002331	28	146	1.6	8.1

IF: Impact Factor of 2020 Journal Citation Reports.

Two papers published before 1991 were excluded from the textual analysis because there were no keywords in these documents. Table 4 presents the number of publications and keywords per period. The number of keywords used per year was 17.6, 42.1, and 125.8 in subperiods I, II, and III, respectively, showing a noticeable expansion in research topics over time. There were 158 keywords in all of subperiod I, including ‘runoff’ (19), ‘storm’ (19), ‘groundwater’ (17), ‘catchment’ (16), and ‘flow’ (14), located in the center of the word cloud of subperiod I (Figure 3a). There was a significant increase to 632 keywords in subperiod II. ‘Catchment’ (99) rose in rank from the fourth to first position (in the center of the word cloud of subperiod II), and ‘soil’ rose from the thirteenth (6) to third position (51), which was close to the ‘catchment’ (Figure 3b). There were 629 keywords in subperiod III, including ‘stable-isotope’ (99), ‘catchment’ (90), ‘groundwater’ (61), ‘runoff’ (60), ‘precipitation’ (59), ‘river’ (55), and ‘basin’ (51) (in the center of the word cloud of subperiod III (Figure 3c)). Some keywords, such as ‘variation’ and ‘spatial’, merely appeared in subperiods II and III, and the sum frequency of the two terms increased from subperiod II to subperiod III.

3.2. Thematic Distribution and Evolution

To further explore the topics of IHS, the co-word matrix and clustering methods were applied to determine the themes in different subperiods. The themes of different subperiods using strategic diagrams are presented in Figure 4a–c. Moreover, their evolution paths from subperiod I to subperiod III are clearly shown using a Sankey diagram in Figure 4d. Table 5 shows the top 10-most frequent keywords of each theme. The bibliometric indicators in Table 6 were used to measure the influence of each theme in different subperiods.

Table 4. Principal information in each subperiod.

Subperiod	Publication	Percentage of Total Publications (%)	Keywords	Percentage of Total Keywords (%)	Keywords Per Year
1991–1999	44	11.5	158	11.1	17.6
2000–2014	173	45.1	632	44.5	42.1
2015–2019	167	43.5	629	44.3	125.8

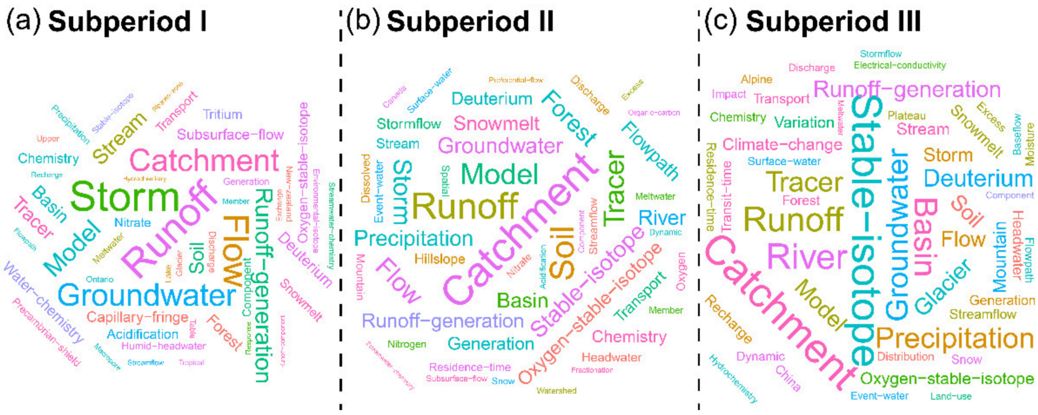

Figure 3. Word cloud of the most widely used IHS keywords in each subperiod. The size is proportional to the frequency of each keyword. The larger the word size is, the more important it is. For highlighting the important keywords, the keywords with high frequencies and large sizes locate in the center of the word could. (**a**) Subperiod I, (**b**) Subperiod II, (**c**) Subperiod III.

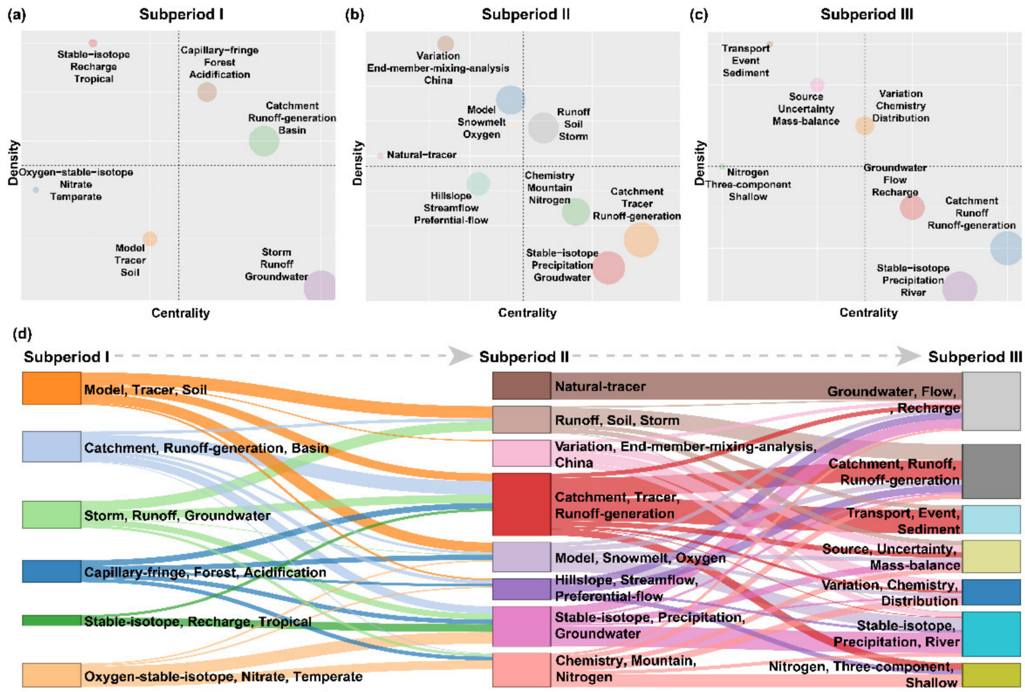

Figure 4. Thematic maps (strategic diagrams: **a**–**c**) and evolution (Sankey graph: **d**) of IHS. (**a**–**c**): The circle size is proportional to the total frequency of terms in each theme. Each theme is labeled with the corresponding three most frequent keywords; (**d**): Each theme is labeled with the corresponding three most frequent keywords. The thickness of the edges is proportional to the inclusion index.

Table 5. Keywords of IHS themes in each subperiod.

Theme	Frequency	Top 10 Most Frequent Keywords in Each Theme; the Number Following each Word Is the Frequency of the Word	Subperiod
Storm; Runoff; Groundwater	132	Storm 19; Runoff 19; Groundwater 17; Flow 14; Stream 8; Chemistry 5; Transport 4; Discharge 3; Environmental-Isotope 3; Watershed 2	1991–1999
Catchment; Runoff-Generation; Basin	100	Catchment 16; Runoff-Generation 13; Basin 6; Deuterium 6; Subsurface-Flow 6; Water-Chemistry 6; Humid-Headwater 4; Component 4; Tritium 4; New-Zealand 3	1991–1999
Capillary-Fringe; Forest; Acidification	52	Capillary-Fringe 6; Forest 5; Acidification 5; Snowmelt 4; Precambrian-Shield 4; Generation 3; Meltwater 3; Precipitation 3; Streamflow 2; Ontario 2	1991–1999
Model; Tracer; Soil	39	Model 10; Tracer 6; Soil 6; Streamwater-Chemistry 3; Member 2; Macropore 2; Stormflow 1; Three-Component 1; Two-Component 1; End-Member-Mixing-Analysis 1	1991–1999
Stable-Isotope; Recharge; Tropical	26	Stable-Isotope 3; Recharge 2; Tropical 2; Exchange 2; Tectonic 1; Humid 1; Landform 1; Development 1; Etch 1; Africa 1	1991–1999
Oxygen-Stable-Isotope; Nitrate; Temperate	23	Oxygen-Stable-Isotope 6; Nitrate 4; Temperate 1; Solute 1; Shallow 1; Ecosystem 1; Boreal 1; Leaching 1; Topmodel 1; Mixing-Model 1	1991–1999
Catchment; Tracer; Runoff-Generation	597	Catchment 99; Tracer 46; Runoff-Generation 43; Flow 38; Forest 37; Flowpath 31; Generation 31; Transport 24; Stormflow 23; Residence-Time 19	2000–2014
Stable-Isotope; Precipitation; Groundwater	437	Stable-Isotope 48; Precipitation 44; Groundwater 44; Oxygen-Stable-Isotope 41; Basin 30; River 30; Deuterium 29; Discharge 16; Surface-Water 13; Canada 9	2000–2014
Runoff; Soil; Storm	298	Runoff 70; Soil 51; Storm 39; Event-Water 16; Dissolved 15; Member 11; Dynamic 10; Streamwater-Chemistry 10; Organic-Carbon 10; Water-Chemistry 8	2000–2014
Model; Snowmelt; Oxygen	239	Model 50; Snowmelt 33; Oxygen 15; Meltwater 13; Snow 10; Fractionation 10; Component 10; Snowpack 9; Baseflow 8; Spring 8	2000–2014
Chemistry; Mountain; Nitrogen	187	Chemistry 26; Mountain 15; Nitrogen 13; Nitrate 12; Acidification 11; Watershed 10; Alpine 8; USA 7; Sierra-Nevada 6; Mixing-Model 6	2000–2014
Hillslope; Streamflow; Preferential-Flow	85	Hillslope 19; Streamflow 17; Preferential-Flow 11; Subsurface-Flow 11; Unsaturated 6; Subsurface 4; Shallow 4; Response 4; Macropore 3; Runoff-Component 3	2000–2014
Variation; End-Member-Mixing-Analysis; China	28	Variation 9; End-Member-Mixing-Analysis 6; China 4; Semi-Arid 3; Management 3; Sandy 3;	2000–2014
Natural-Tracer	5	Natural-Tracer 5	2000–2014
Stable-Isotope; Precipitation; River	760	Stable-Isotope 99; Precipitation 59; River 55; Basin 51; Deuterium 40; Oxygen-Stable-Isotope 33; Glacier 33; Climate-Change 29; Mountain 27; Snowmelt 23	2015–2019
Catchment; Runoff; Runoff-Generation	696	Catchment 90; Runoff 60; Runoff-Generation 47; Tracer 41; Model 34; Soil 25; Storm 24; Headwater 22; Stream 22; Residence-Time 19	2015–2019
Groundwater; Flow; Recharge	243	Groundwater 61; Flow 27; Recharge 21; Streamflow 19; Baseflow 13; Hydrochemistry 12; USA 8; Geochemistry 7; Recession 7; Karst 6	2015–2019
Variation; Chemistry; Distribution	124	Variation 22; Chemistry 17; Distribution 15; Spatial 9; Connectivity 8; Snowpack 7; Canada 7; Control 6; Elevation 5; Seasonal 5	2015–2019
Source; Uncertainty; Mass-Balance	73	Source 10; Uncertainty 10; Mass-Balance 8; Melt 7; Mixing-Model 7; End-Member-Mixing-Analysis 7; Balance 6; Contribution 4; Colorado 4; Water-Chemistry 4	2015–2019
Transport; Event; Sediment	31	Transport 18; Event 8; Sediment 5	2015–2019
Nitrogen; Three-Component; Shallow	30	Nitrogen 6; Three-Component 5; Shallow 5; Nitrate 5; Nutrient 3; Contaminant 3; Denitrification 3	2015–2019

Frequency represents the sum of the frequency of all keywords' appearance.

Table 6. Performance measures for the themes of each subperiod.

Theme	Publication	LCS	GCS	LCS per Paper	GCS per Paper	h-Index	g-Index	Subperiod
Storm; Runoff; Groundwater	38	62	2485	1.63	65.39	26	38	1991–1999
Catchment; Runoff-Generation; Basin	31	44	2145	1.42	69.19	21	31	1991–1999
Capillary-Fringe; Forest; Acidification	16	14	1277	0.88	79.81	14	16	1991–1999
Model; Tracer; Soil	15	17	1108	1.13	73.87	14	15	1991–1999
Oxygen-Stable-Isotope; Nitrate; Temperate	8	1	341	0.13	42.63	7	8	1991–1999
Stable-Isotope; Recharge; Tropical	5	0	307	0.00	61.40	5	5	1991–1999
Catchment; Tracer; Runoff-Generation	156	425	7233	2.72	46.37	52	77	2000–2014
Stable-Isotope; Precipitation; Groundwater	146	401	6741	2.75	46.17	49	75	2000–2014
Runoff; Soil; Storm	117	264	5477	2.26	46.81	43	69	2000–2014
Model; Snowmelt; Oxygen	111	265	4986	2.39	44.92	40	66	2000–2014
Chemistry; Mountain; Nitrogen	78	123	3586	1.58	45.97	35	58	2000–2014
Hillslope; Streamflow; Preferential-Flow	53	41	2204	0.77	41.58	27	46	2000–2014
Variation; End-Member-Mixing-Analysis; China	22	10	884	0.45	40.18	16	22	2000–2014
Natural-Tracer	5	0	172	0.00	34.40	5	5	2000–2014
Stable-Isotope; Precipitation; River	156	300	1432	1.92	9.18	19	35	2015–2019
Catchment; Runoff; Runoff-Generation	153	281	1569	1.84	10.25	20	37	2015–2019
Groundwater; Flow; Recharge	105	131	1039	1.25	9.90	16	30	2015–2019
Variation; Chemistry; Distribution	68	73	723	1.07	10.63	14	24	2015–2019
Source; Uncertainty; Mass-Balance	45	45	384	1.00	8.53	13	17	2015–2019
Transport; Event; Sediment	25	4	256	0.16	10.24	7	15	2015–2019
Nitrogen; Three-Component; Shallow	18	1	167	0.06	9.28	8	12	2015–2019

IHS publications in subperiod I were defined by six themes (Figure 4a). 'Capillary fringe', 'forest', and 'acidification' (frequency: 52, Table 5) were the motor themes of IHS, indicating that publications containing these keywords were more important in the research domain. Moreover, 'catchment' that linked with 'runoff-generation' and 'deuterium' showed a motor theme, which showed high centrality and high density and thus represented the processes and mechanisms of streamflow generation at the catchment scale. 'Storm'/'runoff'/'groundwater' (frequency: 132) appeared as a general theme with the highest centrality, the greatest number of publications (38), and the highest LCS (62, Table 6). 'Stable-isotope'/'recharge'/'tropical' (publications: 5; LCS: 0) in quadrant II were isolated themes regarding tropical climates. One specialized theme, 'oxygen-stable-isotope'/'nitrate'/'temperate' (publications: 8; LCS: 1), had low density and the lowest centrality. These themes had little influence on IHS research, with few publications and low LCS. However, the final theme for subperiod I linked with 'model'/'tracer'/'soil' attained certain attention, with 15 articles and 17 LCSs.

In subperiod II (Figure 4b), eight principal topics emerged. The theme 'runoff', 'soil', and 'storm' (frequency: 298, Table 5) developed mainly from 'model'/'tracer'/'soil' and 'storm'/'runoff'/'groundwater' in subperiod I and shifted to quadrant I as a motor theme with a significant increase in the number of publications (117) and LCS (264) (Table 6). 'Stable-isotope', which was inherited from the previous 'stable-isotope' and 'oxygen-stable-isotope', moved to quadrant IV as a basic theme, with the largest centrality and lowest density and was especially linked with 'groundwater' and 'precipitation'. This theme had the second-largest LCS (401), indicating that it was cited widely by other themes. 'Catchment' and 'runoff-generation' had changed to a basic theme in quadrant IV with the largest publication (156) and LCS (425), which came from five themes in subperiod I. A transversal theme in this subperiod includes 'chemistry', 'mountain', and 'nitrogen' (publication: 78; LCS: 123). A new theme named 'hillslope'/'streamflow'/'preferential flow' was located in quadrant III as an emerging theme with a certain number of publications (53) and LCS (41), which consisted of few terms in subperiod I. Some studies focused on 'variation'/'end-member mixing analysis'/'China' (publications: 22) with high density scattered in quadrant II as a marginal and new theme together with 'natural-tracer' (publications: 5). 'Model' shifted to quadrant II with relatively high centrality and approached quadrant I, and its focus changed from 'soil' to 'snowmelt' in IHS. In general, many new contents sprang up in this subperiod.

Subperiod III was characterized by seven clusters, all of which developed from the themes of subperiod II (Figure 4c,d). Three themes, 'stable-isotope'/'precipitation'/'river', 'catchment'/'runoff'/'runoff-generation', and 'groundwater'/'flow'/'recharge', consolidated their roles as basic themes with high centrality and low density. The number of publications and LCS of these themes were much greater than those of other themes in this subperiod (Table 6). More publications (68) focused on 'variation' in regions and/or countries other than China, with increasing centrality compared with subperiod II, and linked to 'chemistry' and 'distribution'. In addition, a new, similar theme was 'source'/'uncertainty'/'mass balance' with publications (45) and LCS (45), which combined the partial information of six themes from subperiod II. 'Transport'/'event'/'sediment' in quadrant II, almost from 'catchment'/'tracer'/'runoff-generation' in the previous subperiod, appeared as peripheral themes with 25 publications and 4 LCSs. The final theme was 'nitrogen'/'three component'/'shallow' (publications: 18; LCS: 1), which could be considered a marginal theme mainly from the theme 'chemistry'/'mountain'/'nitrogen' in subperiod II.

4. Discussion

4.1. Advances in IHS during Subperiod I

Although the development of IHS during 1991–1999 was slow, with an average of 3.6 publications per year, there were nine papers in the top 20 most influential documents (Figure 2 and Table 3). These papers focused on issues regarding the processes and methods of runoff generation and the role of soil and glacial water on IHS [6,45,51,57]. These results indicated that some advances occurred during subperiod I compared with the previous studies before 1986. Our results showed that 'storm'/'runoff'/'groundwater' and 'catchment'/'runoff-generation'/'basin', whose publication, LCS and LCS per paper were located at the top two positions, represented classified IHS research (Table 6). Moreover, 'catchment' (frequency: 16, Table 5) and 'basin' (6) indicated that IHS research was primarily conducted in small watersheds. This phenomenon was likely induced by two causes: (1) the larger the watershed size was, the larger the isotopic spatial–temporal variation in new and old water likely was. Consequently, these potential changes in events and pre-events in large-scale basins were difficult to characterize quantitatively, which would violate the IHS underlying assumptions 2 and 3; (2) If these variations were to be accounted for, a highly involved watershed sampling strategy should be adopted. However, the funds and labor forces were limited. Therefore, to ensure the accuracy of streamflow separation and save costs, many IHS studies have been implemented in small watersheds where changes in isotopic compositions of runoff sources were as small as possible [3,4,60]. Moreover, in this subperiod, a very important literature review was published that systematically summarized the processes and mechanisms of the event and pre-event water transfer to streamflow [6]. Several studies were carried out to test these processes in the forest catchment represented by 'capillary fringe'/'forest'/'acidification' [61,62]. These studies improved the understanding of how the end member water reached a stream in small watersheds. Enhanced recognition, in turn, inspired hydrologists to assess the effect of underlying assumptions on IHS, especially assumptions 2 and 4. McDonnell et al. (1990) [11] developed the incremental mean and incremental intensity mean techniques to capture the changes in the contributions of new water throughout events and considered that incremental weighting was better than the standard mean weighting technique. Therefore, the effect of time isotopic variation in event water on IHS began to be noticed by researchers using the within-storm incremental weighting approach [63,64]. 'Model' combined with 'three components' (1) and 'end-member mixing analysis' (1) suggests that research in subperiod I started to use multivariable methods to separate runoff into three or more components [3,4]. Among these components, 'soil' (6) has attracted more attention [57]. Harris et al. [65] considered that runoff sources came from three reservoirs (direct precipitation on saturated areas, a near-stream saturated zone, and subsurface water in upslope areas), and streamflow was composed of precipitation on saturated areas and soil water exfiltrated from the near-stream saturated zone. Oddly, the themes regarding 'stable-isotope' and 'oxygen-stable-isotope' were the marginal topics, which is likely because several IHS studies combined with 'chemistry' (5), 'water-chemistry' (6), or 'streamwater-chemistry' (6) weakened the role of stable water isotopes in the theme analysis. In addition, the conditions for stable water isotope use were not in all events, and the analysis of samples is expensive [45]. However, streamflow separation in many studies utilized deuterium (6) and oxygen stable isotopes as environmental tracers in this subperiod because of their unquestionably conservative nature [64,66,67]. In addition, several studies attempted to explore the contribution of water in ponds or wetlands to runoff, further improving our understanding of the role of surface storage in hydrograph separation [12,67]. In general, the associated IHS hydrological processes were reviewed, and new methods were built in this subperiod to better understand how pre-event and event water reached the stream.

4.2. Advances in IHS during Subperiod II

A significant development of IHS occurred in subperiod II. 'Catchment'/'tracer'/'runoff-generation' was used to characterize the 'flowpath' (frequency: 31, Table 5) of runoff formation and 'residence time' (19) of end-members at catchment scales. These results demonstrated that significant advances occurred in the flow path of end members of different geographic sources to runoff [68]. Moreover, the residence time could provide more information on the age of soil water/groundwater, which helped further differentiate soil water/groundwater from different soil profile layers/aquifers [69]. In addition, 'preferential flow' (11) and 'subsurface flow' (11), in the new theme of 'hillslope'/'streamflow'/'preferential flow', focused on the flow path ('macropore') of water movement from the 'unsaturated' hillslope to streamflow [70]. 'Runoff' developed into the motor theme from 'storm' and 'model' in subperiod I (Figure 4b,d). In this theme, the frequency of 'soil' (51) significantly increased relative to subperiod I, indicating that researchers paid more attention to the role of soil water on IHS [71]. Dissolved organic carbon (DOC) measurements were used to distinguish the dominating runoff processes (i.e., lateral subsurface flow), and DOC-rich water was considered from the upper soil horizons [72]. Moreover, 'forest' (37) was likely the main land cover in the theme [73,74]. Generally, these studies regarding the flow path and transit/residence time of streamflow components characterized the hydrological processes of the IHS domain in more detail.

Approximately 84% of publications in subperiod II were related to 'stable-isotope'/'groundwater'/'precipitation', indicating that these words were general IHS terms. In addition, the frequency of 'oxygen-stable-isotope' (41) was larger than that of 'deuterium' (29), suggesting that researchers favored the oxygen stable isotope in IHS studies. Overall, compared with subperiod I, stable water isotopes played a more important role in hydrological segmentation in subperiod II. Hydrogen (H) and oxygen (O) are part of the water molecule (H_2O), which can directly capture the movements or changes in water [7,75]. Consequently, compared with solute traces, stable water isotopes are more ideal tracers for water. Moreover, as the technology upgrades and costs decrease, the percentage of hydrological separation using stable water isotopes increases. However, solute tracers were also important in IHS studies, which could provide extra information to identify the different contributing areas or flow paths in many studies [54,76].

'Variation' and 'end-member mixing analysis' as a novel theme emerged in this subperiod. Approximately 16% of publications belong to these themes, suggesting that the isotopic variabilities of end members attracted IHS researchers' attention [76]. Several studies found that the temporal and spatial variability in stable water isotopic components occurred widely in event, pre-event, and runoff water [56,77–79]. In addition, there were 111 publications regarding 'model' with 'snowmelt' and 'meltwater', indicating that snow/glacier cover was a classic landscape in IHS research. Therefore, in this subperiod, many studies focused on revealing the spatiotemporal patterns of the meltwater from snowpack, snowmelt, glacier, and frozen soil and their effect on IHS results [80,81]. In addition, evaluating the effect of land use/cover and climate changes on IHS was accompanied by the above themes [49,82].

4.3. Advances in IHS during Subperiod III

In subperiod III, the themes of 'stable-isotope'/'precipitation'/'river' (frequency: 760, Table 5) and 'catchment'/'runoff'/'runoff-generation' (696) developed from subperiod II. These two themes were the foundation of IHS, and there was a great deal of overlapping documents in these themes. Under 'climate change' (29), increasing attention has been directed toward cryosphere meltwater (alpine and cold regions) where glaciers shrink, snowpack melts, and frozen soil degrades [83,84]. The glaciers in the Tibetan Plateau are known as Asia's water tower, feeding the largest rivers and sustaining some 2.8 billion people [85]. Therefore, in this subperiod, most IHS documents concentrated on how changes in hydrological processes and runoff sources in the Tibetan Plateau and the surrounding mountains occur with climate warming [86–90]. A majority of these studies were in broad agreement on increasing cryosphere meltwater to runoff or lakes. In addition, 'soil' was grouped with 'catchment', suggesting that soil water became a common topic, and the fourth assumption should be considered in IHS research. 'Groundwater'/'flow'/'recharge' (243) with 'baseflow' (13) was mainly inherited from the themes 'natural-tracer' and 'groundwater' of subperiod II. Except for the traditional IHS topic, which evaluated the contribution and flow path of groundwater to stream, the recharge of groundwater was explored using stable isotope approaches in several studies [91,92].

In the 'variation'/'chemistry'/'distribution' relative to subperiod II, there was increasing interest in 'variation', with 68 publications, suggesting that more research focused on the spatiotemporal heterogeneity of runoff sources [5,16,17,93,94]. Moreover, many studies evaluated the 'uncertainty' of end-member contributions to runoff [87,95]. This result indicated that there was a strong interest in assessing the uncertainty of end-member contributions to runoff in this subperiod. Several studies have demonstrated that the uncertainty in IHS is mainly induced by the spatiotemporal variability in tracer concentrations [89,96]. The temporal isotopic variation is mostly attributed to the amount, intensity, and fractionation of water sources, especially event water [97,98]. Therefore, high-resolution sampling and measurement of events and streamflow water were adopted to characterize these changes in events, which could shed important light on catchment flow pathways, travel times, and short-term hydrological processes [99,100]. Moreover, the long time series of stable isotopes in precipitation, soil/groundwater, and stream water was used to evaluate seasonal and annual hydrological patterns of catchments [101]. The spatial changes were mainly induced by the characteristics of the watershed, such as topography, soil permeability and moisture, local climate, land use/cover change, landscape characteristics, and catchment size [54,102,103]. To account for these variations, combined hydrometric, chemical, and isotopic approaches have been utilized to elucidate streamflow generation mechanisms [104]. Moreover, tracer-aided hydrological modeling and remote sensing are becoming increasingly popular tools as they assist with process understanding and source separation [105,106]. In general, in subperiod III, quantitative estimates of the variations in different water sources and their flow paths became common issues in IHS studies using multiple technologies, further addressing the underlying assumptions two and three. In addition, two themes, 'nitrogen'/'three component'/'shallow' and 'transport'/'event'/'sediment', were also developed from the themes in subperiod II but had little influence on the field of IHS.

4.4. Future Research Trends

Based on the results of thematic analysis, there are several trends in IHS research for the future. The themes of 'catchment', 'runoff-generation', 'groundwater', and 'precipitation' are the core IHS issues with the greatest number of publications and largest LCS throughout the entire period. These themes will still be located in the center of IHS research in the coming years. Although there was a significant increase in the interest in how to address the effect of spatial and temporal isotopic heterogeneity of precipitation on IHS, similar studies regarding the isotopic spatial heterogeneity of groundwater remain limited [16,17,107,108]. Therefore, how the isotopic spatial and temporal changes in groundwater affect IHS will be one of the important trends. Scholars focused on soil water in subperiod II, making it a basic IHS theme in subperiod III. Studies on the contribution of soil water to runoff have been implemented mostly in humid regions, and most of these studies considered that soil water was the main source of runoff [70,103,109,110]. However, knowledge of the contribution of soil water to streamflow remains limited in arid and semi-arid areas [10]. More work is needed regarding the contribution of soil water to streamflow in these regions [111]. In addition, how to decrease the uncertainty of end-member contributions to streamflow is one of the important issues in the future trends in IHS research [87,112].

Many studies have applied a combined approach, including hydrometeorological measurements, water chemistry, and stable isotopes, to improve the understanding of hydrological processes in the IHS domain [113]. However, at the same time, there were significant increasing costs and labor when using the synthetic method in IHS studies, which would keep catchment hydrologists and administrators who had limited funds from understanding the behavior of hydrologic systems. Several studies have sought new, feasible methods for IHS. Xing et al. [114] introduced the path analysis method to separate the streamflow, which allowed multicomponent hydrograph separation using one tracer and could provide results similar to those of the end-member mixing approach. Kirchner [115] developed an ensemble approach to hydrograph separation, which was insensitive to the variations in end-member signatures and isotopic fractionation. These new methods should be applied for hydrograph separation in the heterogeneous remote regions or mountains, which could enable a wide range of future analyses of catchment hydrology [116].

5. Conclusions

IHS is a novel research field that has shown a great shift in separating runoff into pre-event and event water throughout its production lifetime. Although IHS has developed over several decades, many questions and challenges remain in the generation of runoff. This study used text mining and bibliometric analysis to present a quantitative and systematic review of IHS documents published from 1986 to 2019, thus tracing the evolution of the field. The number of IHS documents has increased rapidly in recent years, but the total sum of documents remains relatively small. The most influential documents in the field were published in subperiod I and subperiod II. Significant improvements can still be made. The topic analysis indicated that the contributions and mechanisms of precipitation, groundwater, and soil water to runoff were the core and base topics in the IHS field. Most IHS studies were carried out in watersheds covered with forest, glaciers, and snow. How to clearly characterize the process of runoff generation, the effects of spatial-temporal heterogeneity of precipitation and groundwater, the assessment of the uncertainty of the IHS result, the contribution of soil water in arid and semi-arid areas, and the verification and application of the new IHS methods are future trends in IHS research.

The study had some limitations caused by the method. First, documents published before 1986 were not included in our dataset. Second, it is possible that some IHS documents are not included in the WoS core database or that we did not retrieve some papers. A possible solution to overcome these limitations is the use of more sources and the retrieval of a larger number of IHS search terms. In general, however, this study has provided novel insights into the research characteristics and evolution of topics in the field of IHS. Moreover, the methods described in this study have great value for all research fields and thus have broad applicability.

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