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Review

A Scientometric Review for Uncertainties in Integrated Simulation–Optimization Modeling System

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Highlights:

- Conducted a comprehensive review analysis of over 2000 articles in integrated simulation–optimization modeling systems, revealing significant advancements in hydrologic modeling and water resource management.
- Unveiled the knowledge structure, frontiers, influential regions, scholars, and publications in the field using advanced visualization techniques.
- Integrated GIS, environmental science, and data science to present a multidimensional perspective on water resource management.
- Highlighted the impact of climate change on water resource management, offering adaptive management methods and contributing to policy making, guiding future research directions and practical applications.

Abstract: Water resources management is a challenging task caused by huge uncertainties and complexities in hydrological processes and human activities. Over the last three decades, various scholars have carried out the study on hydrological simulation under complex conditions and quantitatively characterized the associated uncertainties for water resources systems. To keep abreast of the development of the collective knowledge in this field, a scientometric review and metasynthesis of the existing uncertainty analysis research for supporting hydrological modeling and water resources management has been conducted. A total of 2020 publications from 1991 to 2018 were acquired from the Web of Science. The scientific structure, cooperation, and frontiers of the related domain were explored using the science mapping software CiteSpace V5.4.R3. Through co–citation, collaboration, and co–occurrence network study, the results present the leading contributors among all countries and hotspots in the research domain. In addition, synthetical uncertainty management for hydrological models and water resource systems under climatic and land use change will continue to be focused on. This study comprehensively evaluates various aspects of uncertainty analysis in hydrologic simulation–optimization systems, showcasing advanced data analysis and artificial intelligence technologies. It focuses on current research frontiers, aiding decision–makers in better understanding and managing the complexity and uncertainties of water resource systems, thereby enhancing the sustainability and efficiency of responses to environmental changes.

Keywords: uncertainty; hydrologic modeling; water resources management; visualization analysis; CiteSpace; review

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1. Introduction

Hydrological processes are affected by several elements such as the land–use type, surface conditions, and climatic and meteorological conditions, which vary spatially and temporally [1–5]. The increasing complexity of hydrological models, coupled with the diversity of data sources, amplifies uncertainties in simulation and prediction. As a result, the prediction of water availability and integrated watershed management becomes a necessary and challenging issue restricted by the implementation of water shortages [6–8]. Meanwhile, the enormous complexities associated with human–environmental interactions make it even more challenging to develop reliable models and schemes to support effective hydrological modelling and water resource management. This dual challenge necessitates innovative solutions and a deeper understanding of the uncertainties involved.

Several scholars have previously applied stochastic analysis and fuzzy mathematics to delve into the intricate uncertainties within water resources systems. Generally, there are three aspects of uncertainties in hydrological modeling: the systematic bias of model input, uncertainty parameters, and structural uncertainty in hydrologic models [9–12]. Notably, parameter uncertainty has been the subject of extensive study, with the Generalized Likelihood Uncertainty Estimation (GLUE) and Bayesian methods serving as commonly utilized tools for evaluating model parameters [13–15]. Both the GLUE and Bayesian methods estimate parameter uncertainty based on likelihood functions [16–19]. As there exist lots of uncertainties for water resources management, the decision makers are usually confronted with challenges to satisfy numerous or contradictory requests [20,21]. The stochastic and fuzzy mathematical programming methods have been adopted by various researchers to address such uncertainties [22–26]. Due to the uncertainties and complexities of research on hydrologic simulation and water resources management, it is essential to keep up with the scientific structure and frontier in a certain domain of science. Then, researchers and decision makers can stay abreast of the latest developments and insights, ensuring the continued advancement of knowledge in hydrological sciences. Recently, an integrated modeling system from hydrological modeling of the natural system to optimization management of the social system has been applied to real–world problems. Zhuang et al. [27] proposed an innovative method that combines simulation and optimization techniques to evaluate the influence of climate change on water resource dynamics. Their findings underscore the substantial impact of uncertainties within the system, which have a pronounced effect on the allocation of water resources, including target and shortage. Li et al. [28] developed an integrated simulation–optimization modeling system for water resources management under the coupled impacts of climate and land use variabilities with priority in ecological protection. The system has tremendous significance for evaluating hydrologic variations with complicated uncertainties and providing optimal water allocation schemes responding to the coupled impacts of climate and land–use variations among society, the economy, and the environment.

Although methodologies developed in previous studies can be effective in addressing various uncertainties in hydrological modeling and water resources management, very little analysis has been carried out from a scientometric and bibliometric perspective. Furthermore, no previous review has provided the development process and the structural relationship of scientific knowledge through visual maps in this field. Therefore, we will use CiteSpace, a graphical tool on account of collaboration, co–citation, and co–occurrence networks, to provide valuable, timely, repeatable, and flexible perspectives to explore the new emerging trends and recognize critical evidence [29–32]. This systematic review utilizes visualization software as a key instrument for mapping the development process and structural relationships of scientific knowledge. In doing so, our research contributes to track the trajectory of emerging trends and pinpoint critical evidence for future advancements in these critical domains.

The main objectives for this research are to supply cooperation, co–citation, and co–occurrence networks with related references obtained from the Web of Science (WOS) Core Collection. Firstly, the study identifies innovative scholars, providing a comprehensive perspective on their contributions from a global and institutional standpoint. Secondly, a distributed network is constructed, delving into the intricate relationships among articles, authors, and journals. Thirdly, through a co–occurrence analysis of keywords and classes, the research unveils pivotal themes and subjects, contributing to the delineation of critical knowledge domains within the field. By employing visual research methodologies, this study goes beyond conventional analyses, scrutinizing the intellectual structure, knowledge characteristics, and research frontiers. In summary, the study contributes to the development of more informed and effective strategies for water system management, especially in addressing challenges such as water scarcity, land use, and climate change. This research not only advances our understanding of hydrological processes but also provides sustainable adaptive solutions for water resource management.

2. Methodology and Materials

2.1. Data Sources

The literature data adopted for this research were acquired from two common and influential scientific databases, i.e., the Science Citation Index Expanded (SCI–E) and the Social Science Citation Index (SSCI) of WOS [11]. The following terms were used to retrieve related publications: TS = ("uncertain*" AND "water" AND ("modeling" OR "simulat*") AND ("basin" OR "watershed") AND ("manage*" OR "allocation")) ("TS" represents an article subject and "*" represents a fuzzy search). Under these conditions, a total of 2020 documents with full bibliographic records were retrieved and downloaded as related research from 1991 to 2018.

2.2. Statistical Methods

In the realm of bibliometric studies, CiteSpace has emerged as a widely utilized tool for visualizing frontier knowledge and constructing networks within scientific domains [29]. This tool employs view maps that translate complex data into visual representations, with nodes representing various entities such as keywords, authors, journals, and countries, while links denote co–citation structures. Each node is characterized by three types of colors and different thicknesses, signifying its centrality value within the network [33,34]. For instance, a red ring around a node signifies a burst discovery, while a purple rim indicates high betweenness centrality ($\geq$0.1), which represents the significance of the node in the overall network structure [35–38].

A bibliometric study was conducted using CiteSpace, focusing on publications from 1991 to 2018 and leveraging data from the 50 most–cited journals to construct an initial knowledge network. Afterwards, each network was generated and enclosed 2020 references. The time horizon from 1991 to 2018 was divided into three periods (i.e., 1991–1999, 2000–2009, and 2010–2018). Five types involving author, institution, country, keyword, and cited reference were aligned with the research requirements, and a few default settings were maintained. Subsequently, collaboration and co–occurrence networks were systematically analyzed, considering factors such as frequency, burst, and centrality. This analytical approach aimed to identify and characterize research trends and patterns in uncertainty modeling and management within watershed studies. Through these analyses, the study sought to uncover the dynamics of collaboration among authors and institutions, highlight key research themes through co–occurrence networks, and ascertain the significance of specific contributions through burst analysis.

3. Results

3.1. Characteristics of Publications

The analysis of 2020 publications spanning the years 1991 to 2018, focusing on uncertainties in hydrologic simulation and water resources management, reveals a development tendency within the research landscape. These publications were categorized into three document types, with articles emerging as the dominant form, constituting a substantial 95% of the total publications. Following closely were proceedings papers and reviews, securing the second and third positions, respectively. Figure 1 illustrates the distribution of publication outputs across the 28–year period. Notably, the initial publication addressing uncertainty in the hydrological system surfaced in 1992. From this point, a remarkable escalation in publication outputs unfolded, with the number of publications soaring from a modest 1 in 1991 to a significant 390 in 2018. The exponential growth was particularly conspicuous in the last five years of the study period, indicating a surge in scholarly interest and engagement with the subject matter. This result thoroughly explains why research on uncertainty in hydrological modeling and management has attracted increasing attention from scholars.

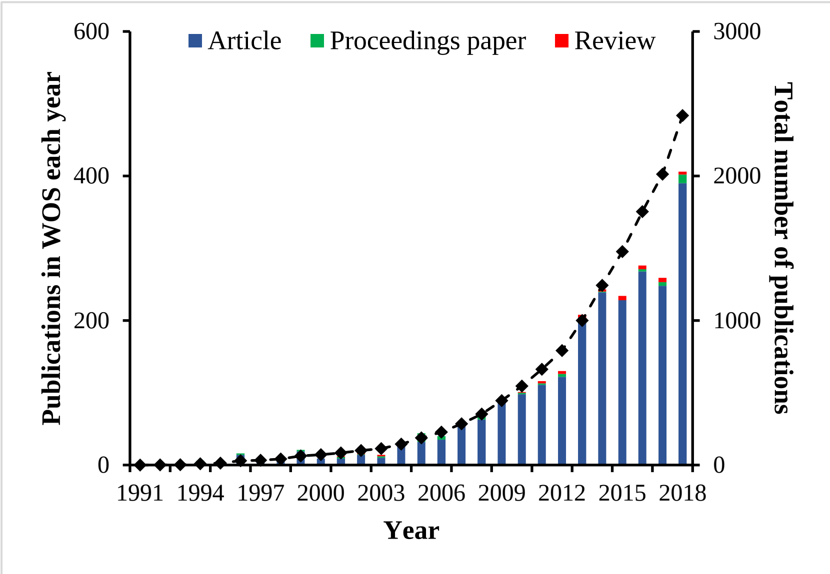


Figure 1. The characteristics of publications about uncertainties in hydrologic simulation and water resources management during 1991–2018.

3.2. Journal Co–Citation Analysis

Table 1 offers a comprehensive overview of the top ten frequently cited journals in the relevant domain, shedding light on the prominent sources shaping research on uncertainty in hydrological systems. The preeminent position is secured by the Journal of Hydrology, boasting an impressive 1430 publications, underscoring its pivotal role in advancing hydrological research. Following closely, Water Resources Research claims the second spot with 1368 publication. The dominance of these two journals signifies their pivotal role as major conduits for disseminating knowledge in this critical field. For the Impact Factor (IF) level, Water Resources Research and Hydrology and Earth System Sciences emerge as influential players with notably higher IF values (4.361 and 4.256, respectively). These robust IF values not only reflect the journals' academic rigor but also signify their significant impact within the broader realm of hydrological research. The higher IF values denote a more substantial influence in the related areas, further emphasizing the pivotal role that these journals play in shaping the discourse on uncertainty in hydrological systems. Researchers and practitioners in the field can leverage these insights to navigate the wealth of literature and stay informed about the latest developments, methodologies, and advancements in hydrological uncertainty analysis.

Table 1. Top10 journals according to frequency.

Journal	Frequency	Centrality	IF (2017)
Journal of Hydrology	1430	0.18	3.73
Water Resources Research	1368	0.29	4.36
Hydrological Processes	963	0.10	3.18
Journal of the American Water Resources Association	777	0.09	2.16
Water Resources Management	773	0.05	2.64
Hydrology and Earth System Sciences	744	0.03	4.26
Environmental Modelling Software	715	0.01	4.18
Advances in Water Resources	552	0.08	3.51
Hydrological Sciences Journal	547	0.10	2.06
Journal of Environmental Management	499	0.10	4.01

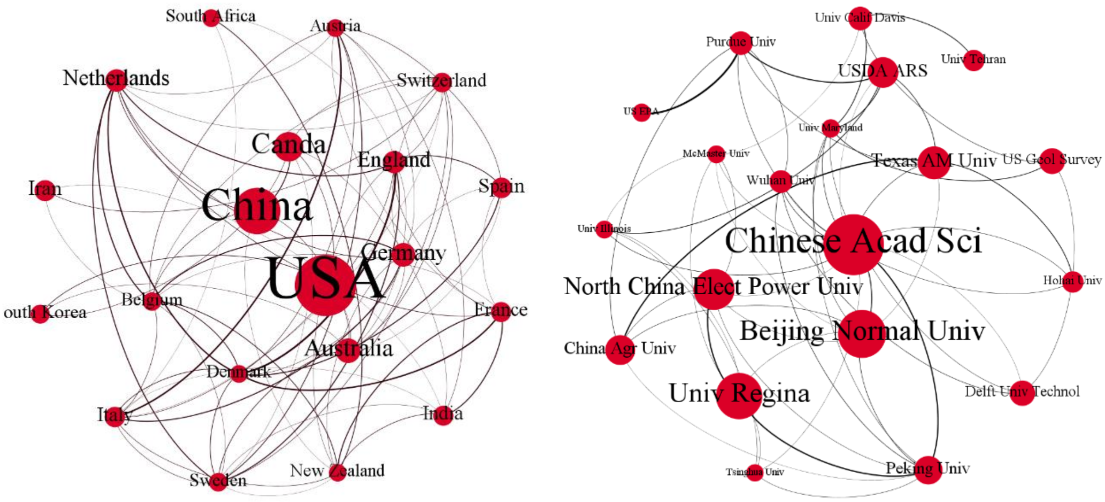
3.3. Country/Territory and Institution Cooperation Analysis

The global spotlight on research addressing the uncertainties in hydrologic simulation and water resources management is evident in the attention garnered by this field. Detailed insights into the top ten productive countries/territories and institutions are provided in Table 2, shedding light on the geographical distribution of research contributions. The results highlight the USA as the foremost contributor, hosting the maximum number of journals dedicated to the field. Following closely are China, Canada, and Australia, with China standing out as the only developing country among the selected nations and territories. Notably, the cumulative output from the top 10 organizations constitutes a significant portion, contributing to 29.2% of the total publications. Delving into institutional contributions, the Chinese Academy of Sciences emerges as the frontrunner, making a substantial impact with 113 publications. Following closely are Beijing Normal University (China) and the University of Regina (Canada), thereby further exemplifying the global collaborative nature inherent in research on hydrologic simulation and water resource management. These findings underscore the diverse and impactful efforts made by institutions across the globe, with each playing a crucial role in advancing our understanding of uncertainties in hydrology and water resource systems.

Table 2. Top 10 most productive countries based on total publications during 1991–2018.

Rank	Country/Region	Number	Institution	Number
1	USA	759	Chinese Acad Sci	113
2	China	507	Beijing Normal Univ	84
3	Canada	220	Univ Regina	80
4	Australia	139	North China Elect Power Univ	68
5	Germany	123	Texas A&M Univ	50
6	The Netherlands	101	USDA ARS	45
7	UK	100	China Agr Univ	43
8	Iran	79	Peking Univ	40
9	Spain	70	US Geol Survey	34
10	Italy	66	Delft Univ Technol	33

To obtain more collaboration information about countries and institutions, a detailed presentation of the first 20 co–country/territory and co–institution networks are presented in detail in Figure 2. The United States and China emerge as pivotal players in global cooperation, exerting significant influence, particularly on countries like Canada and Australia. Noteworthy relationships are highlighted, such as the impactful collaboration between China and Canada, underscoring the interconnectedness of research efforts on a global scale. And the symbiotic ties between the Chinese Academy of Sciences and Beijing Normal University underscore the importance of institutional collaboration. Additionally, the analysis also illustrates areas for potential enhancement in international influence. For instance, India and Tsinghua University are identified as entities that could amplify their impact either by increasing their publication output or fostering closer collaborations in the relevant domain. This insight serves as valuable guidance for countries and institutions seeking to strengthen their global presence and contribute meaningfully to advancements in hydrological research and water resource management. As the interconnected landscape of global collaboration unfolds, fostering strategic partnerships and bolstering international influence emerge as key considerations for the continued progress and innovation in the field.



(**a**) (**b**)

Figure 2. The cooperation network of the top 20 countries/territories and institutions: (**a**) network map of countries/territories; (**b**) network map of institutions.

3.4. Author Co–Citation Analysis

In Figure 3, an item density visualization unveils the most influential authors shaping the landscape of uncertainty in hydrological systems. Notably, the preeminent figure in hydrological modeling is Arnold from the United States Department of Agriculture, whose impactful contributions have garnered widespread recognition, reflected in an impressive citation frequency of 354 [38]. Arnold's seminal research serves as a cornerstone in the field, evidenced by its broad incorporation and acknowledgment by peers. Following closely is Beven from Lancaster University, England, occupying the second position as an influential researcher. Subsequent noteworthy contributors include Wilby from the University of Derby, England, Huang from the University of Regina, Canada, and Bergstrom from the Karolinska Institution, Sweden. These scholars, prominently featured in the item density visualization, have collectively played pivotal roles in advancing our understanding of uncertainty in hydrological systems. It is discernible from the results that these influential figures share interconnected research threads, underscoring a collaboration in their significant contributions to the field.

3.5. Reference Citation Bursts Analysis

The identification of citation bursts in a publication is a strong indicator of its widespread recognition within its scientific domain. Moreover, it serves as a tool for discovering emerging research fields, often characterized by clusters with citation bursts [39]. In Table 3, where the top ten references are presented, the time horizon spans from 1991 to 2018, with the red line denoting the citation bursts. Notably, the first significant milestone paper in this field, dating back to 1991, focused on model evaluation in simulations and exhibited a substantial burst strength of 24.61 [10]. Following closely, the second highest burst–ranking reference delves into the calibration and validation of the SWAT model, boasting a burst strength of 18.6 [40]. Remarkably, eight references within this study are closely linked to the SWAT model, suggesting its prominence as possibly the most widely adopted model in hydrological modeling and water resources management. The visual representation of citation bursts not only highlights pivotal contributions but also offers valuable insights into the temporal dynamics and evolving emphases within this research domain.

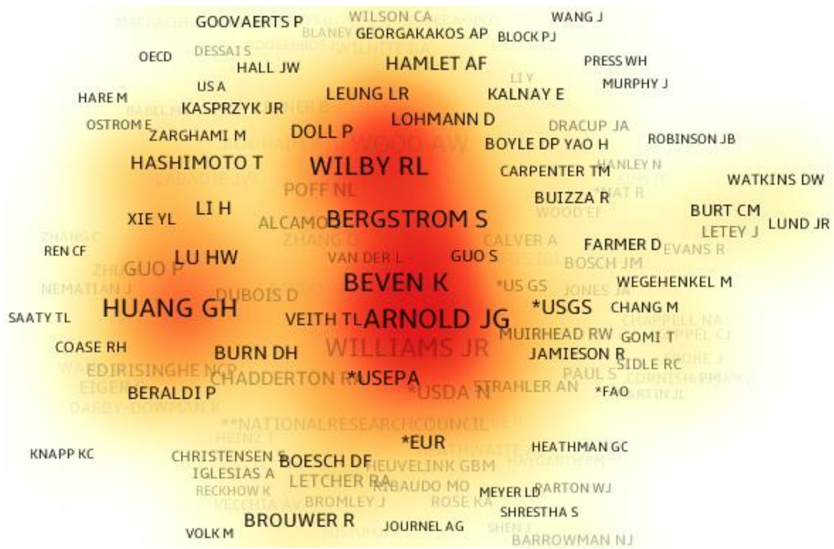


Figure 3. Main co–cited authors contributing to publications (* and ** represent agencies. *USEPA: United States Environmental Protection Agency; *EUR: European Research Council; *USGS: European Research Council; National Research Council: National Research Council of United States).

Table 3. Top 10 references with the strongest citation bursts (Red bars: Indicate periods of citation bursts where a reference is cited significantly more frequently compared to other times. Blue or light blue bars: The citation frequency of the reference is at a normal or baseline level, without significant peaks).

References	Strength	Begin	End	1991–2018
Moriasi et al., 2007 [10]	24.61	2013	2015	
Arnold et al., 2012 [40]	18.60	2015	2018	
Abbaspour et al., 2015 [41]	14.80	2016	2018	
Abbaspour et al., 2007 [42]	13.88	2013	2015	
Yang et al., 2008 [43]	12.72	2013	2016	
Gassman et al., 2007 [44]	12.64	2013	2015	
Taylor et al., 2012 [45]	11.29	2015	2018	
Beven et al., 2001 [14]	8.61	2004	2009	
Huang et al., 2012 [46]	7.98	2016	2018	
Harou et al., 2009 [47]	7.94	2015	2018	

3.6. Subject Categories Co–Occurrence Analysis

The dual–map overlays offer a comprehensive view of the intricate landscape of scientific journals, incorporating data from over 10,000 journals sourced from WOS [48]. In Figure 4, the visualization of publications spanning the years 1991 to 2018 pertaining to the topic of uncertainty in hydrological systems is presented, revealing a dynamic and multifaceted network. The colored curves in the figure delineate the process from left to right, showcasing the evolution of research fields and their interconnections. The distinct separation of citing and cited maps across various research fields is evident in the visualization. Each color cluster is indicative of a specific field, providing a visual representation of the interdisciplinary nature of uncertainty in hydrological systems research. Notably, three primary domains stand out in the landscape of publications on uncertainty in hydrologic modeling and water resource management: the blue cluster corresponds to Ecology/Earth/Marine, the yellow to Veterinary/Animal/Science, and the red to Mathematics/Systems/Mathematical. The blue cluster forms a significant portion of publications and citation links, suggesting a robust foundation in environmental science. Intriguingly, the yellow cluster demonstrates a unique intersection between hydrological systems and veterinary sciences. Meanwhile, the red cluster highlights the quantitative and mathematical aspects inherent in uncertainty analyses. Furthermore, the spatial distribution of citation links originating from the upper right corner of the map indicates a broad interdisciplinary approach. Publications on the uncertainty in hydrological systems draw from diverse disciplines, including environmental science, ecology, geology, mathematics, and chemistry. This interdisciplinary nature underscores the complex and multifaceted character of uncertainty in hydrological modeling and water resource management, emphasizing the need for a holistic and integrated approach to address the challenges posed by uncertainties in this critical field of study.

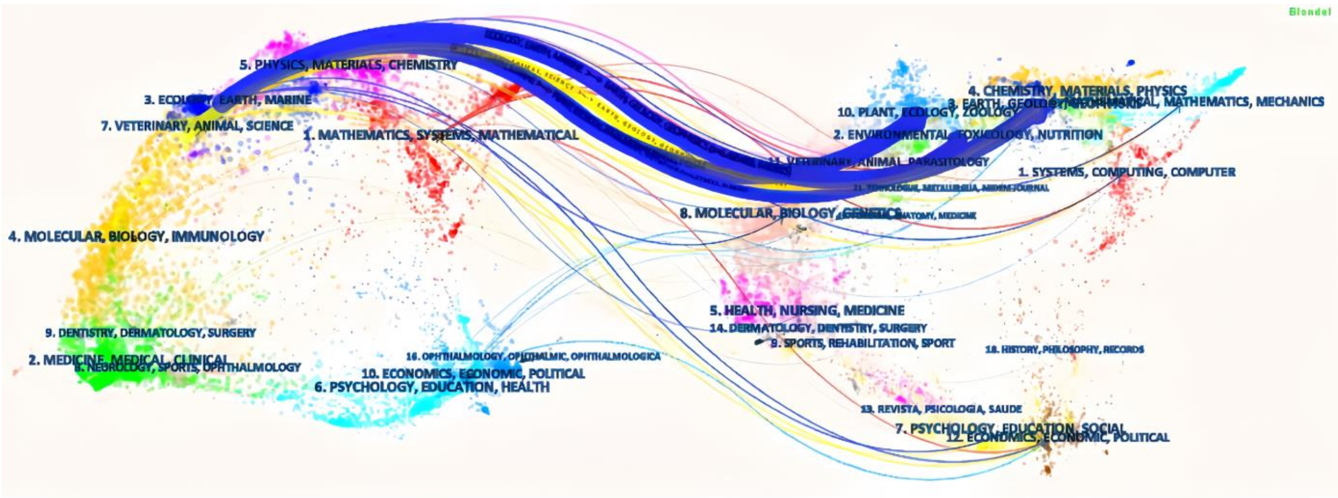


Figure 4. A dual–map overlay of the science mapping literature between 1991 and 2018.

3.7. Keywords Co–Word Analysis

The co–word study performed in this research serves a crucial function in uncovering hotspots and understanding the structure of the relevant scientific domain [36,49]. To construct the co–occurrence network (Figure 5), the first 20 items were selected, each represented by a cross, where the size reflects its frequency—larger sizes indicating higher occurrence rates. In this Figure, "Uncertainty" emerges as the most frequent keyword with 932 occurrences, followed by "basin" (584), "model" (492), "management" (447), and "climate change" (437). "Uncertainty" emerges as the most frequent keyword with 932 occurrences, followed by "basin" (584), "model" (492), "management" (447), and "climate change" (437). The centrality of each node in the network signifies its importance, and among the top 20 keywords, "water quality", "management", and "simulation" stand out with high centrality values, indicating their critical roles in the field of uncertainty in hydrological systems. This underscores the heightened attention towards research on uncertainties associated with water quality, reflecting a significant focus within the broader scope of hydrological modeling and water resources management.

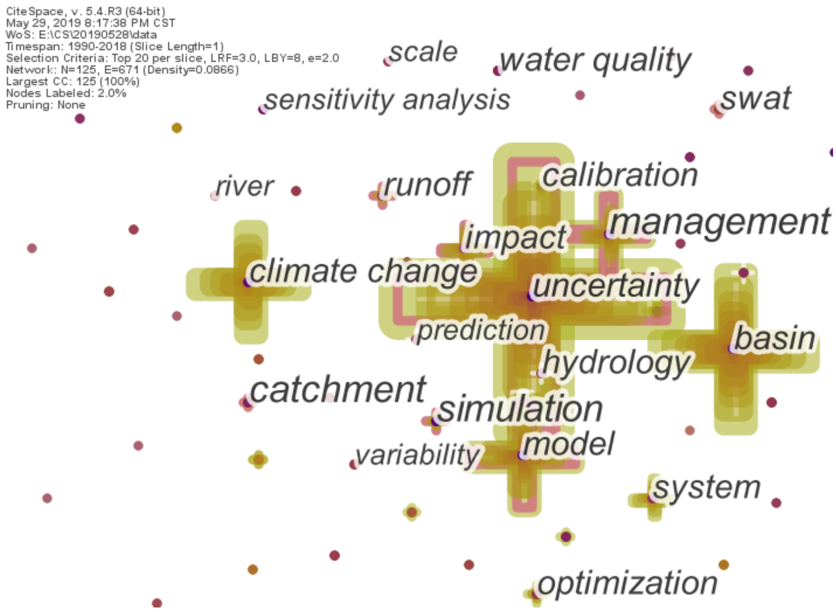


Figure 5. Keyword co–occurrence map of publications.

3.8. Document Co-Citation Analysis

3.8.1. Research Cluster Analysis

The reference relationships within the realm of uncertainty in hydrologic modeling and water resources management not only adhere to the objective law of scientific development but also intricately reflect the intellectual structure of the field [12]. To further determine the distribution rule of references, the top 20 references between 1991 and 2018 were picked out. Figure 6 vividly illustrates the central clusters that define the domain of uncertainty in hydrologic modeling and water resources management. The high modularity value of 0.76 underscores a distinctly defined landscape within the field, providing a clear conceptual framework [38,39,50,51]. Within these references, a granular dissection reveals 96 clusters, with 14 of them appropriately labeled. The study field on uncertainty in hydrologic modeling and water resources management exhibits a multifaceted nature, encompassing diverse aspects such as management objects (water resource and water quality), measures (stochastic programming and statistical learning), simulation techniques (SWAT), technological applications (GIS), and specific study areas (China and Canada). This comprehensive coverage suggests that the study of uncertainty in hydrological modeling and integrated management has evolved into a relatively mature and nuanced area of research in recent years. The multitude of identified clusters and labeled aspects attests to the richness and depth of scholarship within this domain.

3.8.2. Timeline View of Typical Clusters

The timeline visualization presented in Figure 7 offers a comprehensive overview of the temporal evolution of various clusters, providing valuable insights into the trajectory and longevity of distinct research themes. Ten prominent clusters are delineated along horizontal timelines, each encapsulating a unique set of studies and developments. Figure 7 not only portrays the temporal progress of these clusters but also highlights the three most cited references associated with each timeline. Examining the illustration, it becomes evident that individual clusters exhibit varying temporal spans, with some enduring for approximately 20 years, while others have a more concise duration. For instance, clusters such as #0 and #6, focusing on the SWAT model, demonstrate a prolonged period of significance from 1994 to 2016. Essential achievements within these clusters are notably concentrated between 2005 and 2015, showcasing a concentrated period of impactful research.

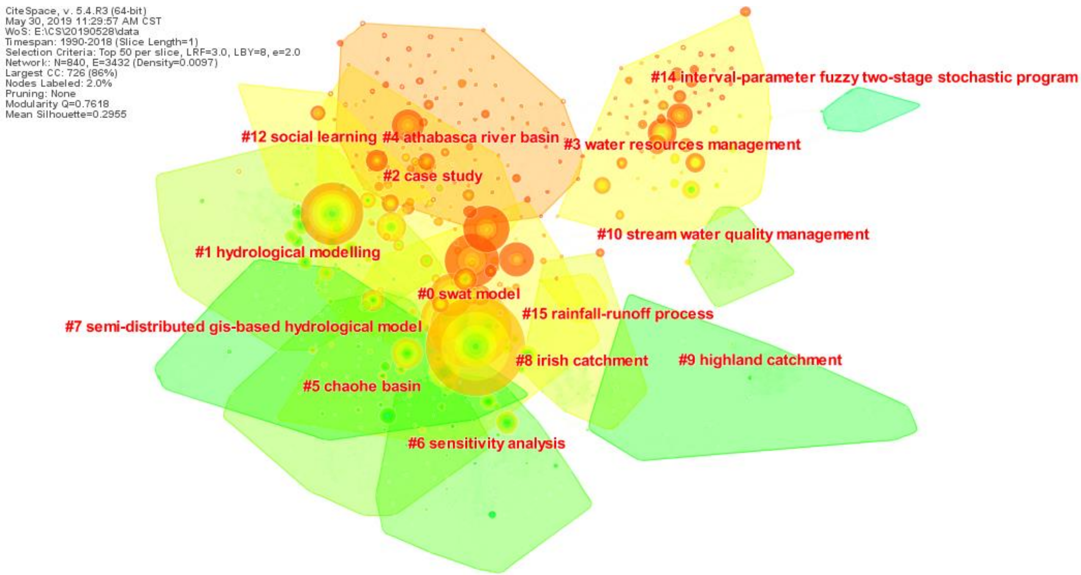


Figure 6. A cluster view of the co–citation network.

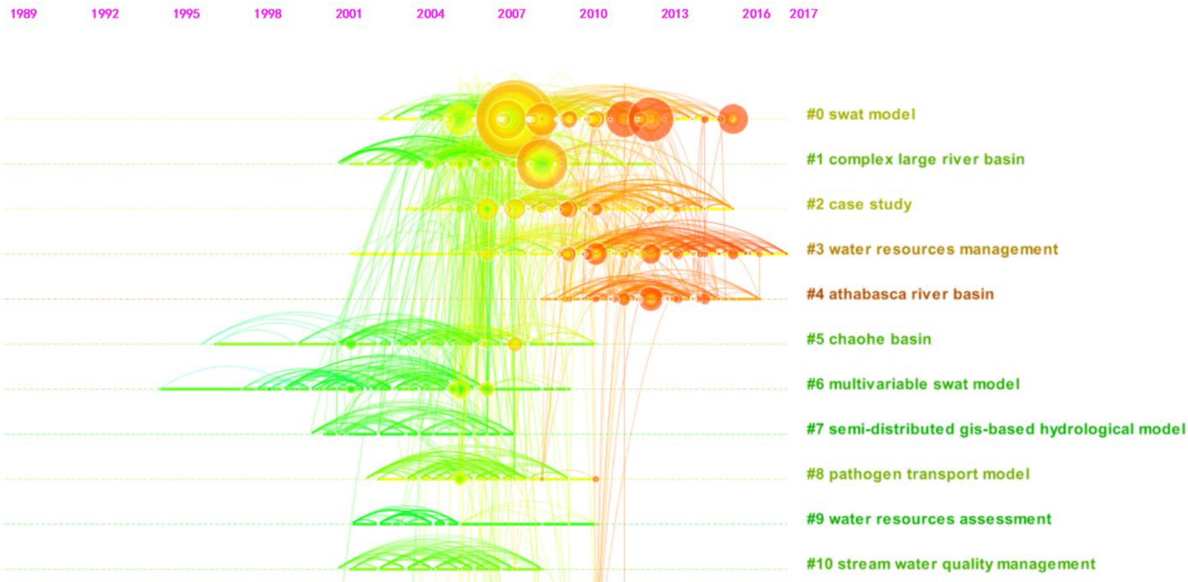


Figure 7. A timeline visualization of the top 10 study clusters.

Cluster #4, centered on uncertain management, stands out with a commendable span of 16 years, underscoring its enduring relevance and continued activity. In contrast, cluster #7, centered on the GIS–based model, concludes in 2007, suggesting a shift in research specialties and the emergence of new directions within the relevant research landscape. The timeline visualization not only serves as a historical record of the longevity of research clusters but also allows for the identification of pivotal periods and transformative shifts in research focus. It provides a dynamic perspective on the evolution of key themes, enabling researchers to trace the development and impact of various clusters over time.

4. Conclusions

This research offers a comprehensive scientometric review that synthesizes the state of uncertainty analysis in hydrologic simulation and water resources systems through a meticulous examination of bibliographic data. The investigation encompasses diverse dimensions, including the characteristics of publications, collaboration among countries/territories and institutions, co–citation of scholars and references, as well as the co–occurrence of topics and keywords. By delving into these multifaceted aspects, the study provides valuable insights into the current state of research in this critical domain.

Over the past three decades, there have been approximately 2020 publications related to the uncertainty in the hydrological system, and the number has increased steadily, which indicates that this field is receiving increasing attention from scholars. Generally, the USA, China, Canada, Australia, and Germany were the first five prolific countries, and at the same time, the Chinese Academy of Sciences, Beijing Normal University, University of Regina, North China Electric Power University, and Texas A&M University were the first five prolific institutions in this related field. The USA contributed greatly to the publications and cooperated with most countries/territories. The Chinese Academy of Sciences was the leading institution and had a relatively intimate relationship with other institutions.

Most studies were published in the representative journals in this field, such as the Journal of Hydrology and Water Resources Research. Arnold, Beven, and Huang were the representative scholars who made outstanding contributions to the field of uncertainty in hydrologic simulation and water resources management. Research on the uncertainty in hydrologic simulation and water resources management covered broad subjects, such as environmental science, ecology, geology, mathematics, and chemistry. Through the keyword analysis, uncertainty, hydrological simulation, climate change, calibration, and optimization were the hotspots in the research domain. Research on water quality and sensitivity analysis have been proven new topics over the years. By evaluating the co–cited network, the primary study field was determined to be hydrological simulations using the SWAT model, and this topic is becoming more and more mature.

In conclusion, this study field for the uncertainty in hydrologic simulation and water resources management is still a research front, and it needs to be further explored and improved in the following aspects. (i) The current uncertainty research mainly concentrates on hydrological models, and further exploration in areas such as structure, parameters, and data collection can enhance the reliability of hydrological predictions and decision–making. (ii) The uncertainty analysis of hydrological systems is insufficient to study the water–transforming pattern within atmospheric water, surface water, and groundwater included in the hydrological cycle, and new methods should be used to explore each link of the eco–hydrological process. (iii) As a single method was unable to meet the study of the uncertainty in the hydrological system, future research will likely focus on the establishment of coupled uncertainty analysis methods for synthetical uncertainty in hydrological model application and management. This research provides a broad perspective for uncertainties in integrated simulation–optimization modeling system. Furthermore, the study contributes to the development of more informed and effective strategies for water system management, especially in addressing challenges such as water scarcity, land use, and climate change. In summary, this research not only advances our understanding of hydrological processes but also provides sustainable adaptive solutions for water resource management.

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Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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