

# Mapping a Quarter-Century of Fuzzy-Based Models for Groundwater Level Estimation: A Bibliometric Analysis

Sepideh Zeraati Neyshabouri<sup>1</sup>, Abbas Khashei-Siuki<sup>1\*</sup>, and Mohammad Ghasem Akbari<sup>2</sup>

<sup>1</sup> Department of Water Engineering, University of Birjand, Birjand, Iran.

<sup>2</sup> Department of Mathematical Sciences, University of Birjand, Birjand, Iran.

\* Corresponding Author: [abbaskhashei@birjand.ac.ir](mailto:abbaskhashei@birjand.ac.ir)

## ORCID: s

Sepideh Zeraati Neyshabouri (<https://orcid.org/0000-0003-4691-8194>)

Abbas Khashei-Siuki (<https://orcid.org/0000-0002-2863-8482>)

Mohammad Ghasem Akbari (<https://orcid.org/0000-0001-5064-8065>)

## Abstract

Groundwater, the planet's largest freshwater reservoir, faces mounting stress from overuse and climate change, demanding interpretable, uncertainty-aware modeling tools. Fuzzy-based modeling is offered as a unique solution, yet its global research landscape, scientific evolution, intellectual structure, and global diffusion remain unmapped. To address this gap, we present the first focused bibliometric synthesis of fuzzy-based approaches for groundwater level estimation, analyzing 189 Web of Science-indexed articles published between 2000 and 2025 using Bibliometrix and VOSviewer. Our analysis quantifies publication growth, identifies leading countries, institutions, and authors, and maps thematic clusters. Results reveal a 19.8% annual growth rate since 2016, with Iran dominating in publications and the United States achieving the highest citations. Key institutions include Islamic Azad University, University of Tabriz, and University of Tehran, while leading authors such as Kisi, El-Shafie, and Nourani anchor the intellectual structure of the field. Science-mapping demonstrates the dominance of hybrid frameworks, particularly those integrating wavelet transforms, metaheuristics, or adaptive neuro-fuzzy inference systems (ANFIS). Keyword co-occurrence networks (minimum occurrence = 5) and temporal overlay visualizations demonstrate a paradigm shift from standalone fuzzy systems toward climate-aware, physics-informed hybrids. While fuzzy models offer high interpretability and robustness in handling uncertainty, challenges remain regarding spatial scalability and integration with large-scale physical models. This study consolidates a scattered body of knowledge and establishes fuzzy-based groundwater modeling as a maturing sub-discipline. While these models offer distinct strengths such as interpretability and the ability to handle epistemic uncertainty, they also present weaknesses, including challenges in spatial scalability and data dependency. We identify critical frontiers, including explainable AI integration, improved spatial scalability, and applications in data-scarce transboundary aquifers. Future research should prioritize cross-paradigmatic collaboration to bridge data-driven and process-based modeling, enhancing both scientific rigor and policy relevance, particularly in the context of escalating water insecurity driven by climate change.

**Keywords:** Aquifer, Drought, Co-occurrence analysis, Intellectual structure, Scientometrics, VOSviewer.

## 1. Introduction

Groundwater constitutes the largest reservoir of accessible freshwater on Earth, underpinning global food security, sustaining ecosystems, and supporting the livelihoods of billions of people (Zaresefat & Derakhshani, 2023; Scanlon et al., 2023). However, this critical resource is under unprecedented stress from a confluence of anthropogenic pressures and the amplifying effects of climate change, which alter recharge patterns and intensify hydrological extremes (Scanlon et al., 2023; Ali et al., 2024). The Gravity Recovery and Climate Experiment (GRACE) satellite pair reveals that 15 of the planet's 37 largest aquifers are now in a state of severe over-extraction (Liu et al., 2025; Biswas et al., 2025). Given the criticality of this resource, the accurate estimation of Groundwater Level (GWL) is a necessity for effective water resource management, ensuring sustainable abstraction rates and preventing irreversible depletion. To achieve this, various modeling approaches have been developed, generally categorized into physically-based models, which rely on governing hydrogeological equations, and data-driven models, which utilize machine learning and statistical algorithms to learn patterns from historical data. Traditional approaches to GWL modeling, including physically-based numerical models like MODFLOW, remain invaluable for process understanding (Boo et al., 2024), but they often falter when faced with the inherent nonlinearity, non-stationarity, and data scarcity that characterize complex aquifer systems (Rajaei et al., 2019; Zaresefat & Derakhshani, 2023). MODFLOW is a program that utilizes physically mathematical equations based on flow equations in a porous medium, which can better represent the interrelation of processes such as recharge, discharge, evapotranspiration, and flow between aquifers. Over the past quarter-century, machine learning (ML) has revolutionized

the field by providing powerful, data-driven alternatives capable of learning intricate, hidden patterns from historical observations without requiring a complete understanding of the underlying physics (Hou et al., 2025; Boo et al., 2024). A vast body of literature now confirms the efficacy of models ranging from foundational techniques like Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) to more advanced deep learning (DL) architectures such as Long Short-Term Memory (LSTM) networks (Liu et al., 2025; Boo et al., 2024; Zaresefat & Derakhshani, 2023).

Fuzzy-based models, however, occupy a unique niche within the broader ML ecosystem. By embedding linguistic rules and membership functions, they explicitly encode the epistemic uncertainty that typifies hydrogeological datasets (i.e., piezometer sparsity, measurement error, and subjective expert knowledge) while remaining interpretable to water managers (Zaresefat & Derakhshani, 2023; Lozano Hernández et al., 2024). Techniques such as the adaptive neuro-fuzzy inference system (ANFIS), type-2 fuzzy logic, and hybrid fuzzy-metaheuristic architectures have repeatedly outperformed crisp ML analogues in GWL forecasting tasks across various aquifers (Osman et al., 2022; Zaresefat & Derakhshani, 2023). These successes are scattered across disparate case studies, consistently report that hybridizing fuzzy-based models with optimization algorithms (e.g., Genetic Algorithm, Particle Swarm Optimization) or signal processing techniques (e.g., Wavelet Transform) significantly enhances predictive accuracy and robustness (Zaresefat & Derakhshani, 2023; Boo et al., 2024).

Several reviews (i.e., Hou et al., 2025; Boo et al., 2024; Zaresefat & Derakhshani, 2023) have examined the application of ML and hybrid models in GWL prediction. In these reviews, fuzzy-based models are discussed as one component within a broader set of ML and hybrid models. Therefore, those studies represent narrative reviews that mainly summarize methodological development and applications rather than systematically analyzing the structure and evolution of the research field.

However, despite the existence of these reviews, no study has quantitatively investigated how research on fuzzy-based models for groundwater-level estimation has evolved, diffused geographically, or formed distinct thematic research clusters. Unlike previous narrative reviews, the present study adopts a bibliometric and scientometric approach to systematically map the global research landscape of fuzzy-based GWL modeling.

To the best of our knowledge, there is currently no dedicated bibliometric analysis that exclusively delineates the scientific landscape, research evolution, and thematic structure of fuzzy-based models in GWL prediction. Existing reviews are often either too broad, covering all AI methods for groundwater, or too narrow and narrative, failing to provide a comprehensive assessment of the research landscape for fuzzy logic specifically (e.g., Hou et al., 2025; Boo et al., 2024; Zaresefat & Derakhshani, 2023; Osman et al., 2022). This gap is critical because, without a systematic, bibliometric analysis, the research community lacks a clear map of the most impactful contributions, the central research themes, the leading institutions and nations, the most effective hybrid strategies, and the persistent methodological challenges within this specific sub-domain.

To address this gap, this study conducts a bibliometric analysis of the global research on fuzzy-based modeling and its applications in GWL forecasting. Bibliometric science-mapping offers an objective lens through which to trace such intellectual trajectories (Bayhan et al., 2025; Öztürk et al., 2024). Our central hypothesis is that the field, while productive, is fragmented, with a significant skew toward specific geographical regions. The primary aim of this research is: (i) to quantify publication growth, leading countries, institutions, and journals; (ii) to delineate thematic clusters and their temporal evolution; and (iii) to identify frontier topics that signal future research directions. By providing this comprehensive and scientometric overview, our study not only consolidates a vast and scattered body of knowledge but also offers a clear, evidence-based research agenda to enhance the scientific rigor, practical applicability, and global equity of fuzzy-based groundwater modeling in support of water security under climate change.

## **2. Materials and Methods**

### **2.1. Research Design and Scope**

This study employed a structured bibliometric research design to systematically map the scientific landscape, intellectual structure, and global research trends related to the application of fuzzy-based models in GWL estimation over a quarter-century period (January 2000–December 2025). This study adheres to established guidelines for bibliometric reviews in the environmental and computational sciences, following methodological frameworks (e.g., Liu et al., 2025). The primary objective is to map the intellectual structure, thematic evolution, and global research dynamics of fuzzy-based modeling approaches applied to GWL estimation over 25 years (January 2000–December 2025). Specifically, the analysis aims to: (i) quantify the temporal evolution of scientific publications addressing fuzzy-based approaches for GWL estimation; (ii) identify the most influential authors, journals, institutions, and countries contributing to this research domain; and (iii) uncover major thematic clusters and methodological trends within fuzzy modeling applications.

The analysis focused exclusively on peer-reviewed journal articles published in English and addressing GWL estimation, prediction, or modeling using fuzzy logic or related fuzzy-based techniques.

## 2.2. Dataset and Search Strategy

The Web of Science Core Collection (WoSCC) was selected as the sole bibliographic data source for this study due to its high academic reliability, rigorous indexing standards, and widespread acceptance as a benchmark database for bibliometric and citation-based analyses (Pranckutė et al., 2021). WoSCC provides high-quality, standardized metadata, including titles, abstracts, author keywords, affiliations, citation counts, and source information, essential for robust and reproducible bibliometric investigations (Öztürk et al., 2024).

A comprehensive literature search was conducted on 28 December 2025 using the TOPIC field (covering title, abstract, author keywords, and Keywords Plus) to maximize retrieval sensitivity while maintaining thematic specificity. The search strategy was designed around two conceptual blocks: (1) Fuzzy-based modeling approaches (“fuzzy logic” OR “fuzzy model” OR “fuzzy inference” OR “fuzzy set” OR “hybrid-fuzzy” OR “ANFIS” OR “adaptive neuro-fuzzy” OR “fuzzy rule” OR “fuzzy-based” OR “fuzzy system\*” OR “fuzzy regression\*” OR “fuzzy clustering”); and (2) Groundwater level estimation (“groundwater level” OR “water table” OR “water level” OR “groundwater head” OR “phreatic level” OR “groundwater fluctuation”)

The final search query applied in WoSCC was:

TS = (“fuzzy logic” OR “fuzzy model” OR “fuzzy inference” OR “fuzzy set” OR “hybrid-fuzzy” OR “ANFIS” OR “adaptive neuro-fuzzy” OR “fuzzy rule” OR “fuzzy-based” OR “fuzzy system” OR “fuzzy regression” OR “fuzzy clustering”) AND (“groundwater level” OR “water table” OR “water level” OR “groundwater head” OR “phreatic level” OR “groundwater fluctuation”) AND PY = (2000–2025) AND DT = (Article OR Review) AND LA = (English)

This strategy balances precision (by targeting specific fuzzy methodologies) and recall (by including synonymous hydrological terms). Only peer-reviewed articles and review papers were retained to ensure academic rigor and exclude non-validated outputs (e.g., conference abstracts, book chapters), consistent with best practices in scientometric research. The final dataset was exported in plain text and CSV formats for reproducibility. Before analysis, records underwent rigorous preprocessing.

## 2.3. Data Screening and Preprocessing

The initial dataset underwent a multistep preprocessing procedure to ensure accuracy and analytical robustness. First, duplicate records were identified and removed using metadata cross-checking (title, DOI, and author information). Second, relevance screening was performed based on titles and abstracts to exclude studies not directly related to fuzzy-based modeling of GWL estimation.

Metadata normalization was subsequently conducted to harmonize variations in institutional affiliations, country names, and keywords (e.g., abbreviations, alternative spellings, and naming conventions). Synonymous terms related to fuzzy modeling techniques (e.g., “adaptive neuro-fuzzy inference system” and “ANFIS”) and groundwater-related terminology were unified using a custom thesaurus file to improve the reliability of keyword co-occurrence and thematic analyses.

## 2.4. Bibliometric Analysis and Visualization

Bibliometric and scientometric analyses were conducted using Bibliometrix (R package) and VOS viewer (version 1.6.20), which provide complementary analytical and visualization capabilities widely recognized in the bibliometric literature.

The analyses were structured into two main categories: performance analysis and scientific mapping. Performance analysis was used to quantify: (1) annual publication trends; and (2) productivity and impact of authors, journals, institutions, and countries. Scientific mapping techniques were employed to explore the intellectual and conceptual structure of the research field, including: (1) Keyword co-occurrence analysis to identify thematic clusters and dominant research topics (minimum occurrence = 5); (2) Co-authorship analysis at country and institutional levels to visualize global collaboration networks (minimum documents = 5); (3) Co-citation analysis to identify influential references and foundational studies within fuzzy-based groundwater modeling (minimum citations = 10); (4) Overlay visualization, in which the average publication year was mapped onto keyword and network structures to illustrate the temporal evolution of research themes and emerging frontiers.

In VOSviewer, the association strength normalization method was applied, and clusters were generated using the VOS clustering algorithm with a resolution parameter of 1.0 to ensure stable cluster formation, consistent with recent groundwater bibliometric studies (Xue et al., 2024).

## 3. Results and Discussion

### 3.1. General Publication Trends

Figure 1 illustrates the temporal distribution of publications and citation metrics in fuzzy-based GWL modeling from 2000 to 2025. The 25-year trajectory of fuzzy-based GWL estimation research can be segmented into three distinct phases: (i) an incubation period (2000–2011) with low output ( $\leq 8$  publications/year); (ii) a take-off phase (2012–2018) marked by steady growth (8–16 publications/year); and (iii) a surge phase (2019–2024) characterized by accelerated publication rates ( $\geq 10$  publications/year), peaking at 30 in 2021. This sudden inflection coincides with the post-2020 global policy push for explainable AI and the incorporation of fuzzy logic into various hybrid models. Citation ratio follows a different rhythm. This inflection point coincides with the post-2020 global policy emphasis on explainable AI (XAI) and the integration of fuzzy logic into hybrid modeling frameworks (e.g., ANFIS, wavelet-fuzzy). Citation ratio follows a different pattern: while annual publications peaked in 2021, the average citations per publication reached its highest point in 2024 ( $\approx 12$  citations/paper), reflecting the lag between publication and scholarly impact. The compound annual growth rate (CAGR) of 19.8% since 2016 significantly exceeds the 12% CAGR reported for the broader groundwater-machine learning literature (Liu et al., 2025), underscoring the rapid maturation of fuzzy-based GWL modeling as a distinct sub-discipline. This growth trajectory signals a transition from a niche methodological curiosity to a mainstream research frontier within hydroinformatics.

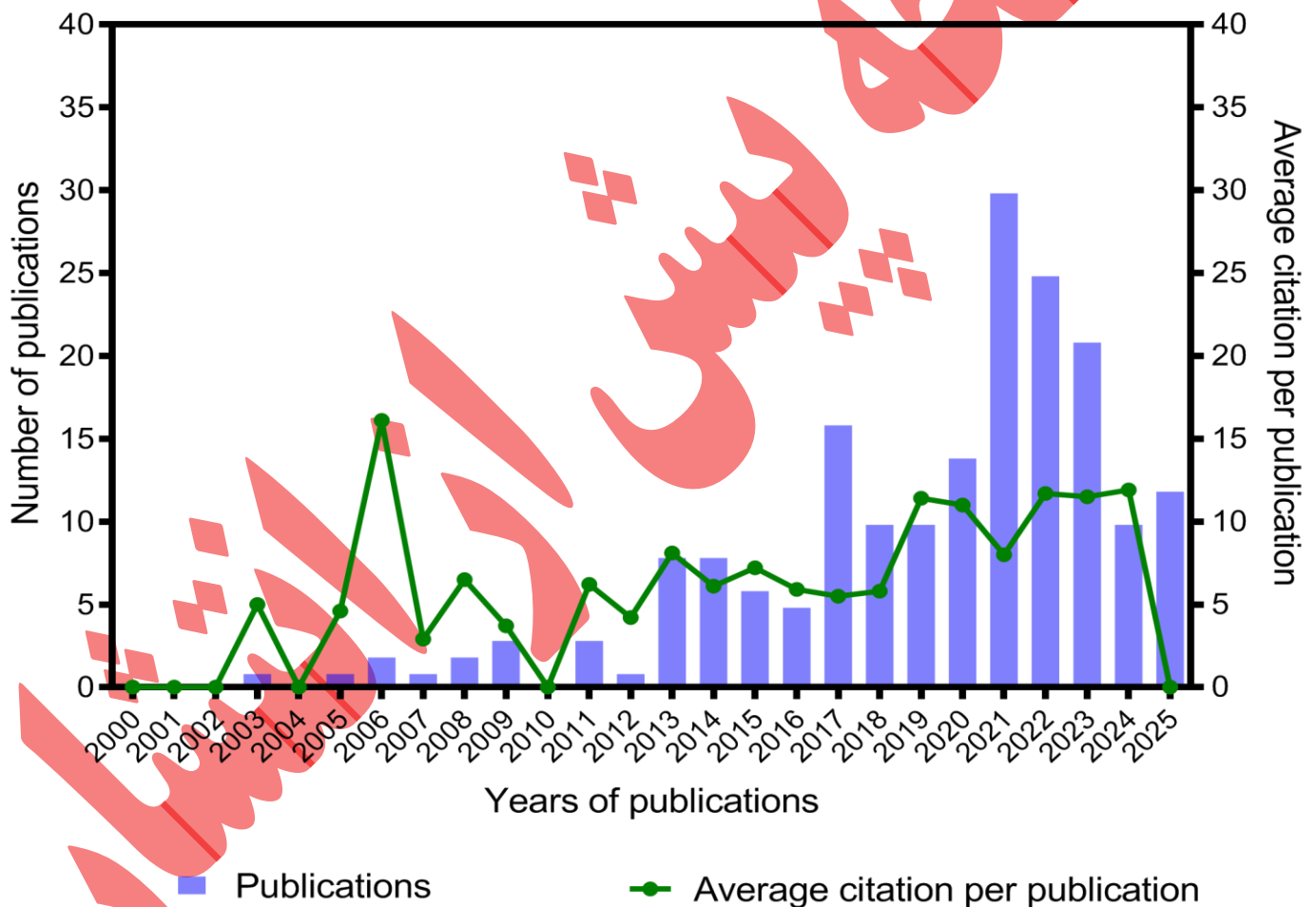


Fig 1. Temporal distribution of publications and citation metrics in fuzzy-based groundwater level modeling (2000–2025).

### 3.2. Core Journals and Publication Sources

Table 1 presents the top 10 journals by publication output and citation impact in fuzzy-based GWL modeling between 2000 and 2025. The publication landscape is shaped by ten journals that together account for 41% of the corpus and 45% of total citations. Water Resources Management leads in publication volume (13 articles), whereas the Journal of Hydrology stands out for scholarly impact (1398 citations), reflecting a superior citation-per-article ratio (116.5 versus 70.2) and reinforcing its role as the discipline’s “gold standard” (Liu et al., 2025). The bifurcation between Water (MDPI) and Journal of Hydrology (Elsevier) is instructive: both published 12 articles, but the latter accrued nearly fivefold more citations, highlighting the distinction between quantity and quality in journal impact and signaling quality-weighted

prestige that is valued by editors and tenure committees. Specifically, Earth Science Informatics and Groundwater for Sustainable Development are identified as niche outlets, publishing 8 and 7 articles, respectively, suggesting a methodological tilt toward computational innovation and policy-relevant applications. This concentration in high-impact, specialized water journals, rather than broad-scope environmental periodicals, indicates that fuzzy-based GWL research has matured into a legitimate sub-discipline, yet its footprint remains narrow, with three journals publishing fewer than five articles each. The absence of flagship multidisciplinary outlets (i.e., Nature Water, Science Advances, and Scientific Reports) implies that the field has yet to capture mainstream attention, a strategic gap for future submissions aiming to broaden visibility and cross-disciplinary fertilization.

**Table 1. Top 10 journals by publication output and citation impact in fuzzy-based groundwater level modeling (2000–2025).**

Rank	Journal	Number of Publications	Total Citations	Total Link Strength
1	Water Resources Management	13	912	70.2
2	Journal Of Hydrology	12	1398	116.5
3	Water	12	293	24.4
4	Environmental Earth Sciences	10	395	39.5
5	Earth Science Informatics	8	167	20.9
6	Groundwater For Sustainable Development	7	260	37.1
7	Applied Water Science	4	61	15.3
8	Arabian Journal Of Geosciences	4	90	22.5
9	Environmental Monitoring And Assessment	4	125	31.3
10	Journal Of Hydrologic Engineering	4	169	42.3

TLS represents the connectivity in co-citation networks, serving as an indicator of intellectual centrality.

Figure 2 illustrates the publisher-wise distribution of all reviewed papers, revealing a pronounced concentration within a small number of major academic publishers. Springer (39.15%) and Elsevier (22.75%) together account for more than half of the total publications, reflecting their long-standing dominance in hydrology, earth sciences, and environmental modeling journals. This pattern is consistent with previous bibliometric studies in groundwater and AI-related research, which report a similar concentration of outputs in large, multidisciplinary publishing platforms due to their broad journal portfolios and high indexing visibility (e.g., Bayhan et al., 2025; Xu et al., 2024). The notable contribution of MDPI highlights the growing role of open-access publishers in accelerating dissemination, while the presence of specialized publishers underscores the methodological and applied diversity of fuzzy-based groundwater research.

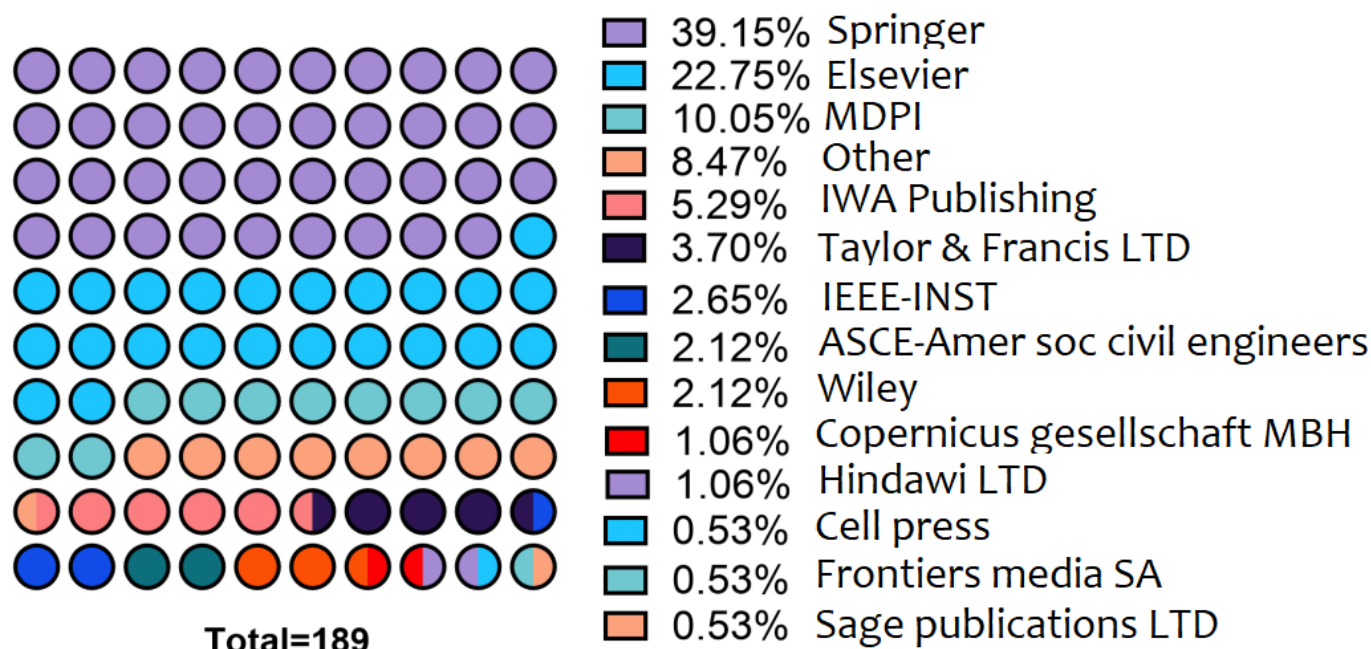


Fig 2. Distribution of the 189 reviewed papers by publisher, presented as a proportional dot plot. The data illustrates the relative contribution of each publisher to the total corpus.

### 3.2. Leading Countries

Table 2 and Figure 3 depict the top ten contributing countries and country collaborative networks in fuzzy-based GWL modeling, revealing a geographically heterogeneous yet highly concentrated global research landscape. Iran ranks first by a substantial margin, accounting for the highest number of publications (NP = 81) and Total Citations (TC = 3991), alongside a strong collaboration profile (Total Link Strength (TLS)= 74). This dominance reflects Iran's sustained scientific focus on groundwater modeling driven by acute water scarcity challenges and national investment in data-driven and soft-computing approaches, a pattern widely reported in groundwater bibliometric studies (Afrifa et al., 2022).

Total Link Strength (TLS) serves as a quantitative indicator of a country's integration into the global research network, defined as the cumulative strength of co-authorship ties with all international partner countries (Yan & Zhiping, 2023). Unlike simple collaboration counts, TLS accounts for the frequency and weight of joint publications, thereby capturing not only the breadth but also the depth of scientific partnerships. Consequently, higher TLS values signify more sustained, intensive, and structurally embedded international collaboration, reflecting a nation's capacity to engage in cross-border knowledge co-production within the fuzzy-based groundwater modeling community.

While the United States publishes fewer articles (23), its superior citation-per-paper ratio (63.7 vs. Iran's 49.3) and strong collaborative integration (TLS = 41) signal greater cross-border scientific influence, aligning with bibliometric evidence that U.S.-led research "has the highest academic impact" through robust international partnerships (Xue et al., 2024). China and India exhibit moderate-to-high productivity but comparatively lower citation efficiency, consistent with prior findings indicating strong domestic research capacity coupled with more localized collaboration structures. European countries such as Germany and Australia display balanced performance across NP, TC, and TLS, reflecting their emphasis on interdisciplinary research and international collaboration frameworks. Notably, countries like Malaysia and Saudi Arabia underscore the growing participation of emerging research economies in fuzzy-based groundwater studies.

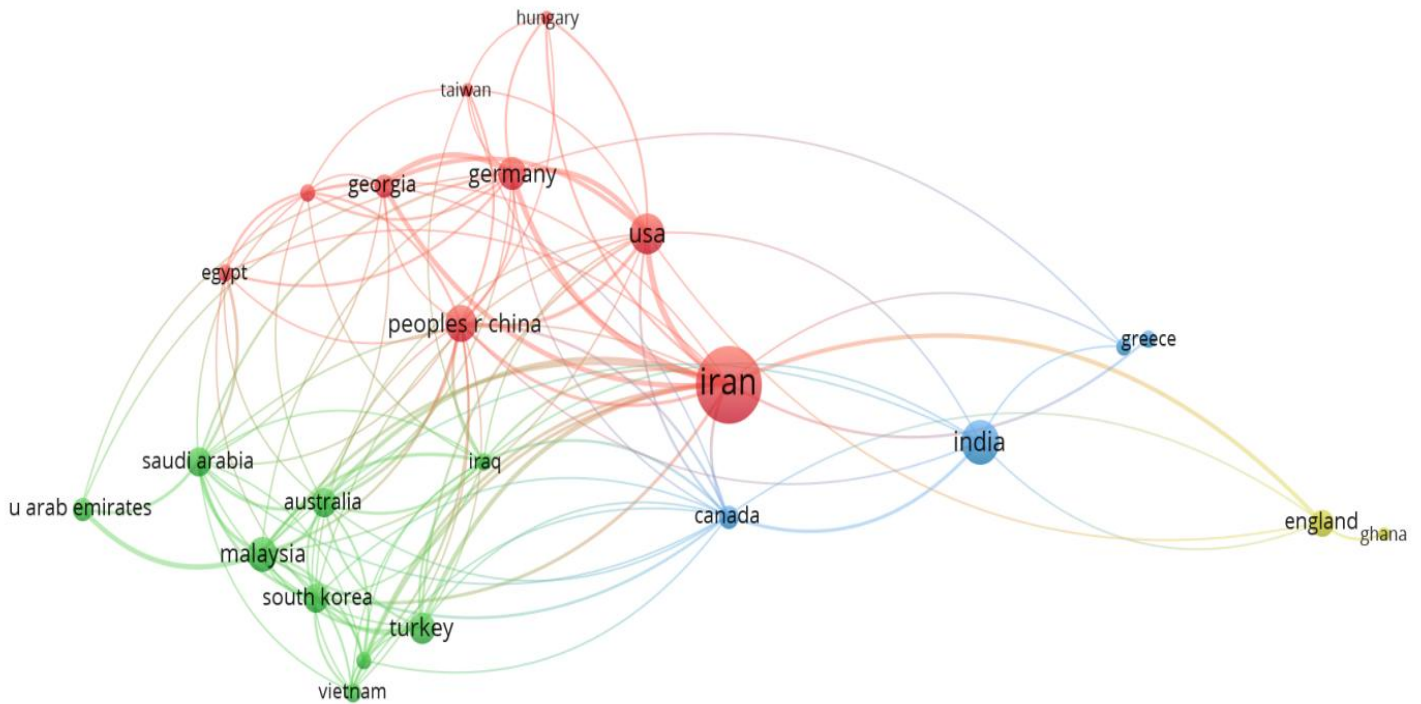
Overall, the country-level patterns indicate that scientific leadership in this field is driven not only by publication volume but also by sustained citation impact and collaborative connectivity, signaling a mature and internationally interconnected research domain. As visualized in Figure 3, Iran's central position and dense network of collaborations are reflected in its high TLS score, while the United States exhibits broader but less intensive ties across multiple regions.

Table 2. Top 10 Countries by publication output and citation impact in fuzzy-based groundwater level modeling (2000–2025).

Rank	Country	Number of Publications	Total Citations	Total Link Strength
1	Iran	81	3991	74
2	India	28	936	9

3	USA	23	1465	41
4	China	18	926	33
5	Malaysia	17	897	35
6	Germany	15	755	41
7	Turkey	14	1525	22
8	Australia	11	675	28
9	Saudi Arabia	11	517	27
10	South Korea	11	861	20

TLS represents the connectivity in co-citation networks, serving as an indicator of intellectual centrality.



**Fig 3. Visualization of national cooperative networks in fuzzy-based groundwater level modeling (2000–2025) (Created in VOSviewer). Node size indicates publication output, while link thickness represents the strength of collaboration.**

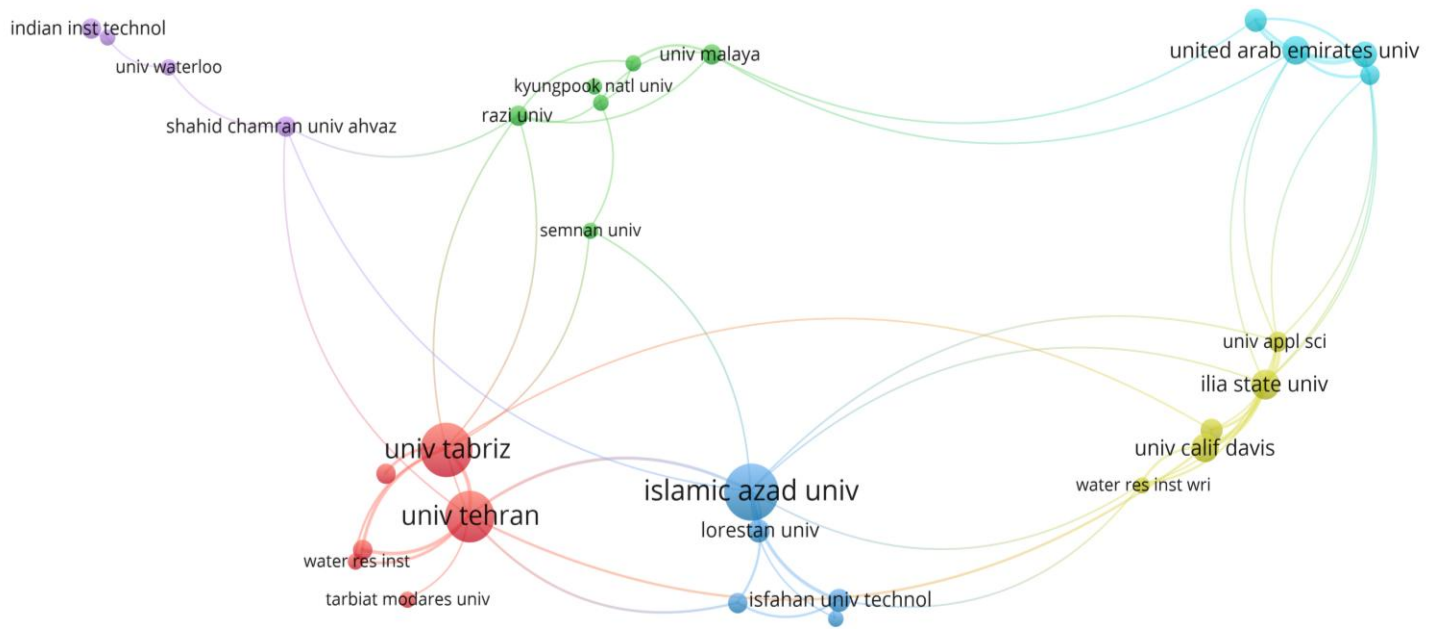
### 3.3. Institutional Productivity

Table 3 and Figure 4 illustrate the research output and institutional concentration, with Iranian universities occupying six of the top 10 positions (Table 3; Figure 4), underscoring Iran's strategic and sustained investment in data-driven groundwater research to address chronic water scarcity and aquifer depletion challenges. Islamic Azad University leads in publication volume (NP = 22), while the University of Tabriz demonstrates the highest citation impact (TC = 1537), indicating that research influence is not strictly proportional to output quantity. The University of Tehran exhibits the highest collaboration strength (TLS = 22) among Iranian institutions, reflecting its central role in national and international research networks. This pattern aligns with prior bibliometric findings highlighting Iranian institutions as key contributors to groundwater modeling using machine learning and soft-computing techniques. Beyond Iran, institutions such as Ilia State University (Georgia), United Arab Emirates University, and the University of California, Davis illustrate the geographically diverse yet selective global engagement in this research area. Notably, the presence of UC Davis highlights the influence of U.S. institutions in advancing methodologically robust and internationally visible research, particularly in drought-prone regions such as California. Malaysian institutions further reflect the growing role of emerging research hubs in Southeast Asia. Overall, the institutional landscape indicates that scientific leadership in fuzzy-based groundwater modeling is shaped by both region-specific water challenges and the capacity to integrate computational innovation with collaborative research frameworks.

**Table 3. Top 10 institutional research leadership and collaborative connectivity in fuzzy-based groundwater level modeling (2000–2025).**

Rank	Institutions	Country	Number of Publications	Total Citations	Total Link Strength
1	Islamic Azad University	Iran	22	546	17
2	University of Tabriz	Iran	21	1537	17
3	University of Tehran	Iran	19	938	22
4	Ilia State University	Georgia	8	236	18
5	United Arab Emirates University	UAE	7	218	16
6	University of California, Davis	United states	7	328	14
7	University Malaya Um	Malaysia	6	199	14
8	University Tenaga Nas	Malaysia	5	187	10
9	Isfahan University of Technology	Iran	5	84	9
10	Kharazmi University	Iran	5	122	8

TLS represents the connectivity in co-citation networks, serving as an indicator of intellectual centrality.



**Fig 4. Visualization of the institutional cooperation network in fuzzy-based groundwater level modeling (2000–2025) (Created in VOSviewer). Node size indicates publication output, while link thickness represents the strength of collaboration.**

### 3.4. Authorship and Citation Impact

Table 4 summarizes the main authorship and citation impact indicators, while Figure 5 visualizes the co-citation network of authors in fuzzy-based GWL modeling. Bibliometric co-citation analysis reveals a distinct structure of scholarly influence within groundwater modeling research (Gaviria-Marin et al., 2019). Ozgur Kisi dominates the field with 12 papers and 790 citations (65.8 cites/paper), positioning him as both the most prolific and most cited scholar. Similarly, Ahmed El-Shafie (10 publications, 467 citations, 46.7 cites/paper) emerges as a leading contributor, demonstrating sustained scholarly impact. Kisi’s co-citation links (TLS = 19) indicate enduring collaborative ties across Iran, Turkey, and the Caucasus, corroborating prior evidence that Kisi “anchors the largest co-citation cluster in soft-computing hydrology” (Xue et al., 2024). Notably, citation intensity does not always correlate linearly with publication volume;

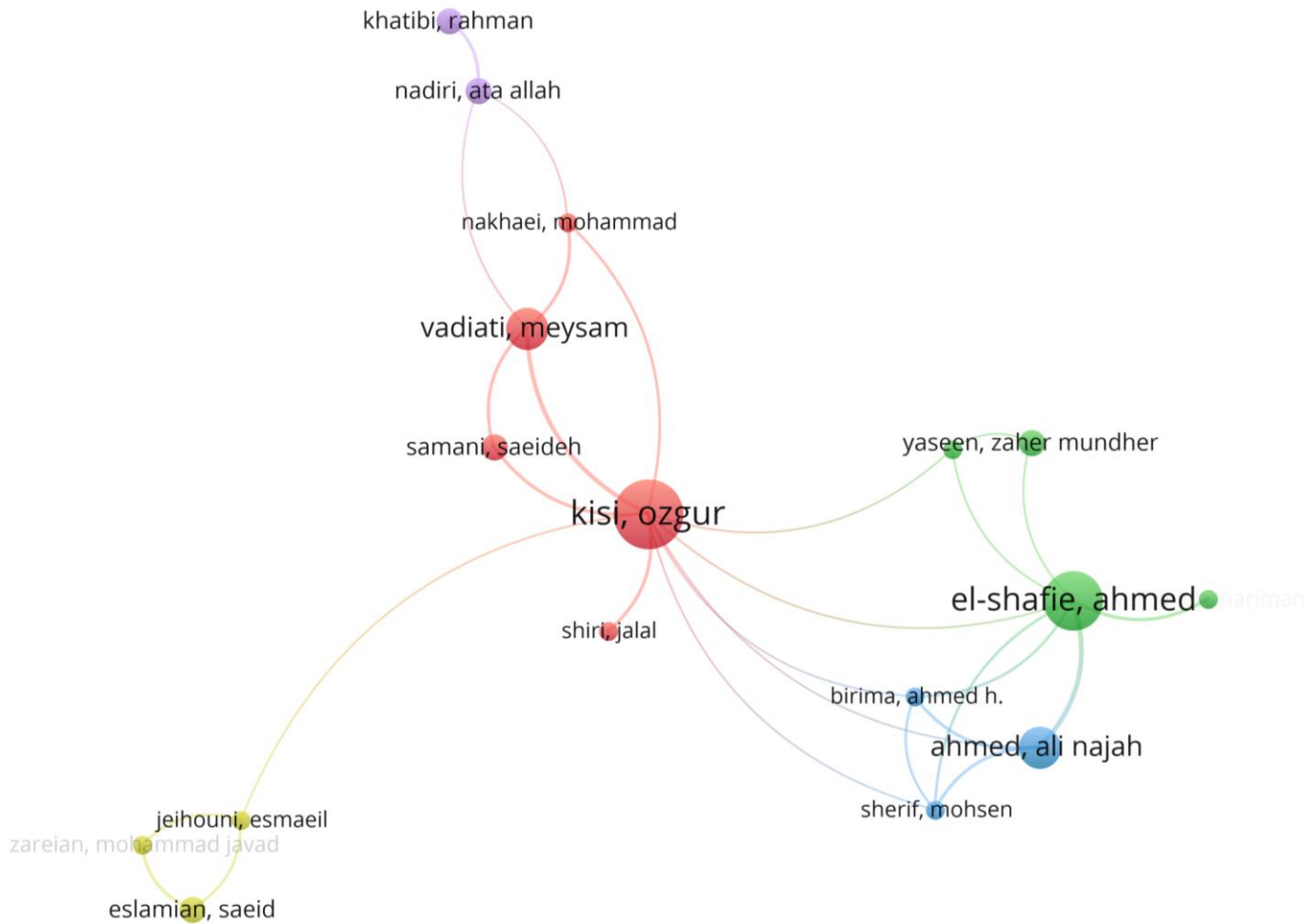
Nourani, for instance, holds 661 citations from only six publications (110.2 cites/paper), indicating quality-over-quantity influence (Liu et al., 2025).

**Table 4. Top 10 leading authors in fuzzy-based groundwater level modeling (2000–2025).**

Rank	Country	Number of Publications	Total Citations	Total Link Strength
1	Kisi, Ozgur	12	790	19
2	El-Shafie, Ahmed	10	467	16
3	Ahmed, Ali Najah	7	218	13
4	Vadiati, Meysam	7	196	12
5	Nourani, Vahid	6	661	0
6	Eslamian, Saeid	4	83	5
7	Kayhomayoon, Zahra	4	122	8
8	Khatibi, Rahman	4	166	3
9	Nadiri, Ata Allah	4	174	5
10	Samani, Saeideh	4	76	6

TLS represents the connectivity in co-citation networks, serving as an indicator of intellectual centrality.

Considering that a total of 618 authors contributed to uncovering the research findings, we specifically focused on a subset of 27 authors who had published more than five papers and established at least one collaborative relationship to construct the co-authorship network diagram depicted in Figure 5. The co-authorship network exhibits four interconnected clusters, each anchored by scholars advancing distinct methodological paradigms—from data-driven modeling to physics-based simulation frameworks. This structure aligns with prior findings that leading researchers often specialize within specific modeling subdomains, forming dense intra-cluster collaboration while maintaining weaker inter-cluster ties (Afrifa et al., 2022). Furthermore, the strong citation performance of authors like Yaseen (547 citations) and Singh (562 citations) underscores the field’s reliance on ensemble and hybrid machine learning techniques. However, a significant number of highly productive authors exhibit low total link strength (e.g., Shabanlou, Neshat), suggesting limited collaborative integration despite substantial output. This pattern indicates a potential fragmentation in the research community, where methodological specialization may inadvertently hinder cross-paradigmatic synthesis. Consequently, while individual contributions have driven technical innovation, the field would benefit from more intentional, cross-cluster collaboration to bridge the gap between data-driven and process-based modeling approaches. Strengthening inter-cluster bridges, especially between the Iranian fuzzy hub and North-American data-driven groups, could accelerate methodological hybridization and elevate the field’s global citation footprint.



**Fig 5. Visualization of a co-citation network of network authors in fuzzy-based groundwater level modeling (2000–2025) (Created in VOSviewer). Node size indicates publication output, while link thickness represents the strength of collaboration.**

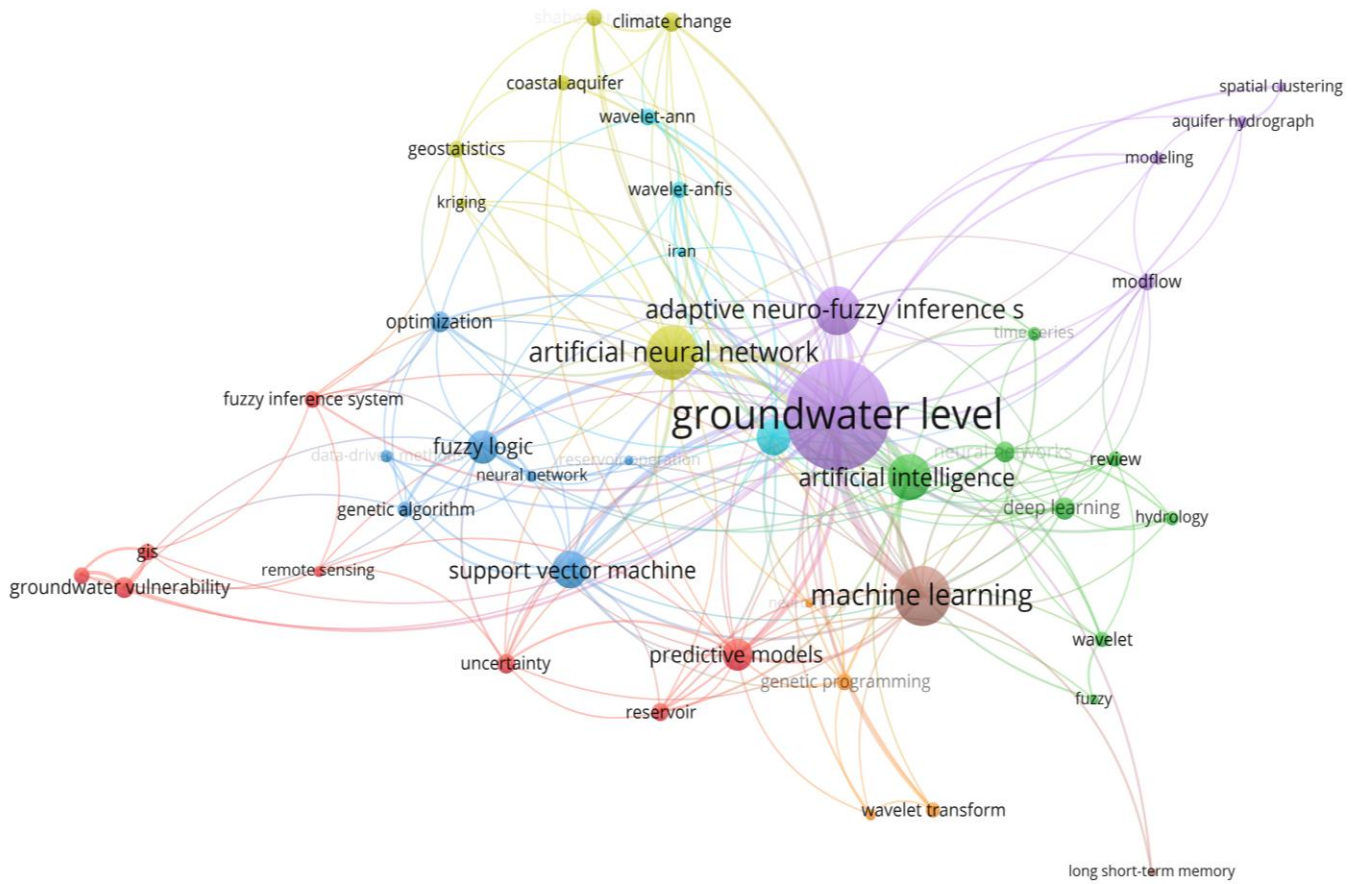
### 3.5. Keyword Co-occurrence and Thematic Clusters

Figure 6 presents the keyword co-occurrence network, overlay, and density visualizations. Keyword co-occurrence analysis identifies major research themes and their interconnections, with “groundwater level” emerging as the central node (91 occurrences, TLS = 171) (Figure 6a). The network forms distinct clusters reflecting methodological and application-oriented paradigms. A prominent cluster centers on “adaptive neuro-fuzzy inference system” (ANFIS), linked to “artificial neural network”, “optimization”, and “wavelet”, highlighting the dominance of hybrid neuro-fuzzy architectures enhanced by signal decomposition and parameter tuning. Another cluster connects “fuzzy logic” with “support vector machine” and “genetic algorithm”, underscoring foundational ensemble and optimization strategies. Clusters related to “machine learning”, “deep learning”, and “long short-term memory” indicate integration with advanced data-driven techniques, while links to “modflow”, “geostatistics”, and “aquifer hydrograph” reflect emerging hybrid approaches combining fuzzy models with physics-based simulations.

Overlay visualization (Figure 6b) reveals clear thematic evolution over time, with earlier research (purple/blue nodes, ~2016–2018) focused on core concepts such as “fuzzy logic”, “genetic algorithm”, and “support vector machine”, transitioning to more recent topics (green/yellow nodes, ~2020–2022) including “deep learning”, “wavelet transform”, “climate change”, and “long short-term memory” (Figure 6c). This temporal shift evidences progression from standalone fuzzy systems toward climate-aware, hybrid, and interpretable models capable of handling non-stationarity and

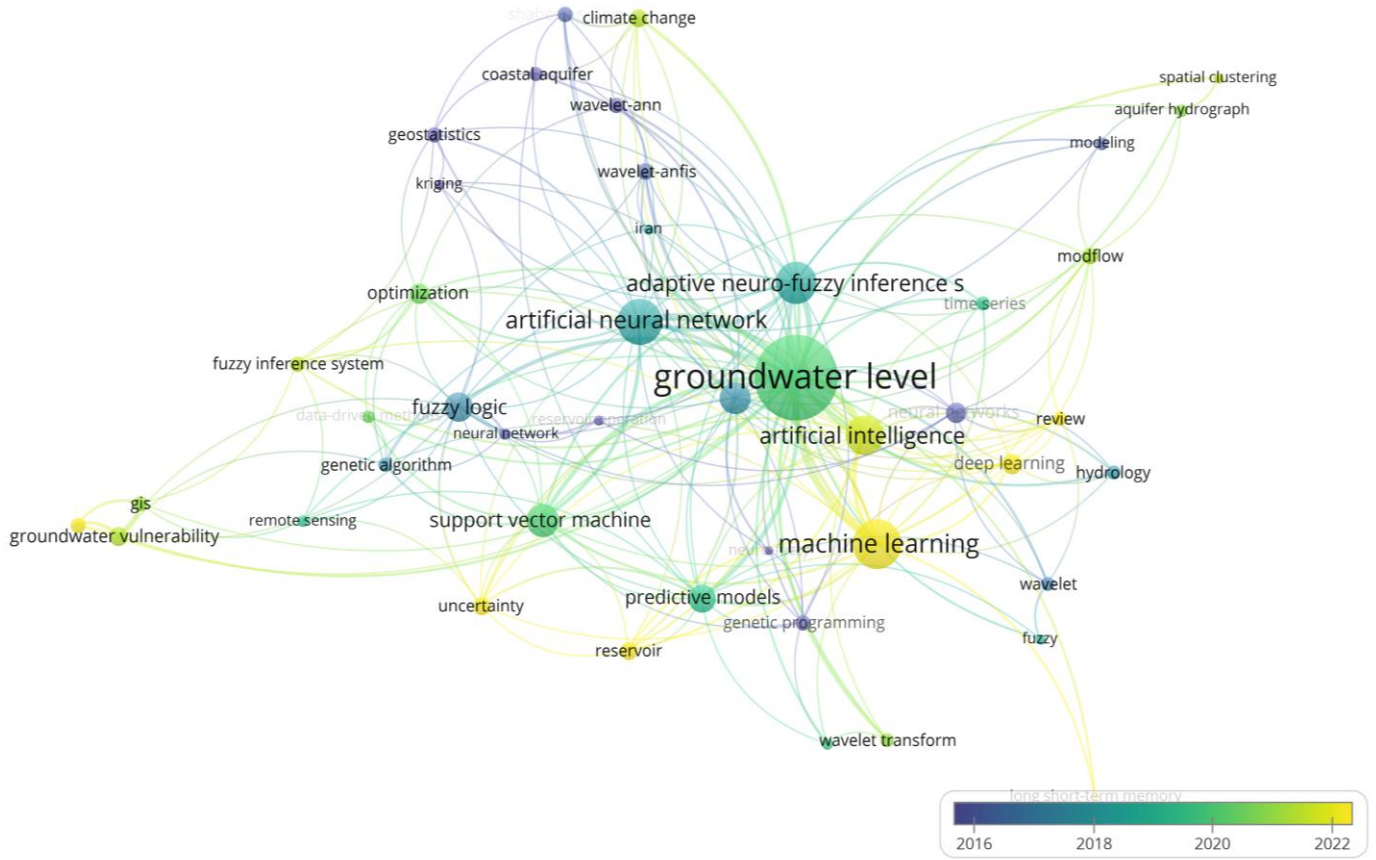
uncertainty. The absence of prominent nodes for “fuzzy-AI” suggests untapped frontiers for future development, consistent with broader trends in groundwater modeling under climate change (Xue et al., 2024; Liu et al., 2025).

(a)

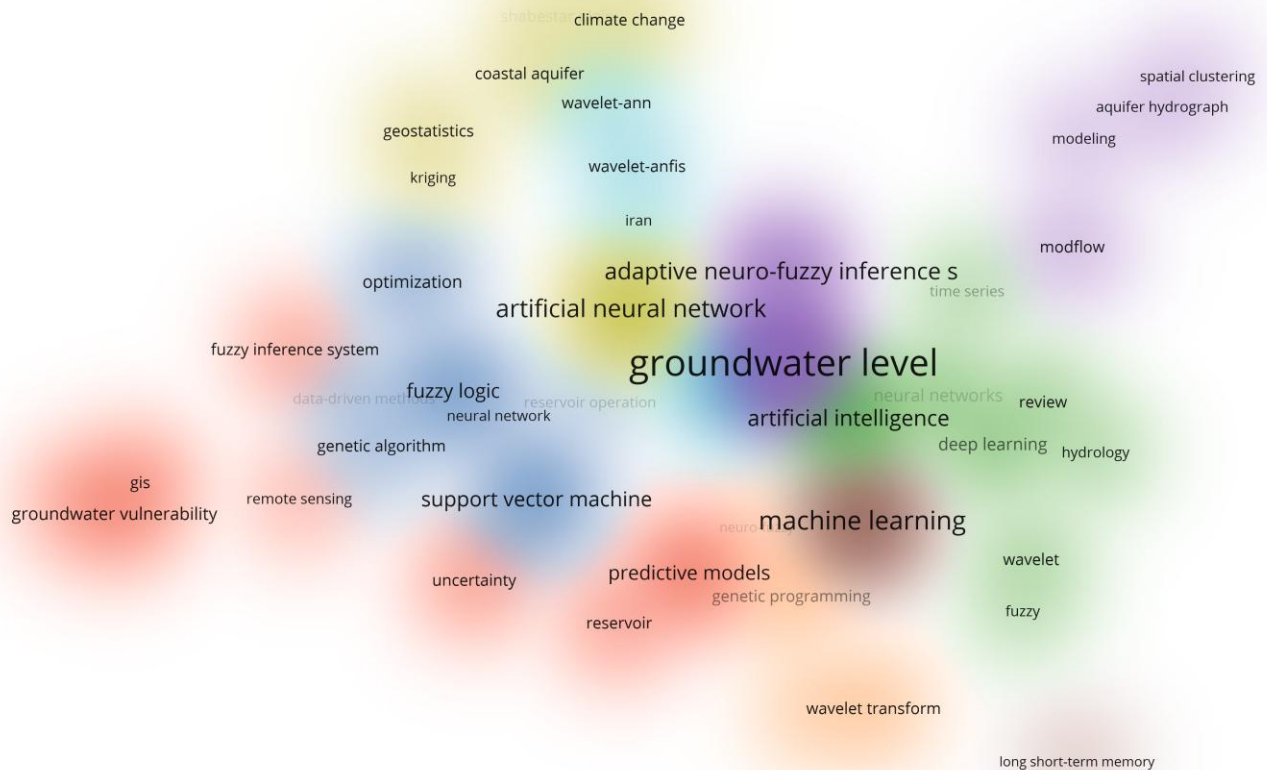


انتشار

(b)



(c)



**Fig 6. Visualisation of keyword co-occurrence network (a), overlay (b), and density (c) in fuzzy-based groundwater level modeling (2000–2025) (Created in VOSviewer). Node size indicates publication output, while link thickness represents the strength of collaboration.**

## Conclusion

This study presents the first dedicated bibliometric analysis of fuzzy-based and hybrid models for GWL estimation (2000–2025), providing a systematic overview of the field's intellectual structure, temporal evolution, and global dynamics. Results indicate steady growth, with a notable acceleration since 2016, surpassing broader groundwater-machine learning trends. Research output is geographically concentrated, led by Iran in productivity and the United States in citation impact and collaboration. Thematic mapping reveals a clear progression from standalone fuzzy systems to hybrid frameworks integrating optimization, wavelet decomposition, and deep learning, increasingly addressing climate-driven uncertainties. Despite progress, persistent gaps include limited explainable AI adoption, spatial scalability challenges, and insufficient cross-regional collaboration. Addressing these through enhanced international and interdisciplinary partnerships will strengthen scientific rigor, interpretability, and policy relevance, particularly amid escalating climate-induced water insecurity. Future research should prioritize transferable, transparent hybrids to support sustainable groundwater management in data-scarce and transboundary contexts.

## Funding

This study was funded by the Iran National Science Foundation (INSF) (Grant No. 4034771).

## Acknowledgments

The authors would like to thank the Iran National Science Foundation (INSF) and the University of Birjand for their support.

## Conflicts of Interest

The authors declare that they have no conflict of interest.

## Data availability statement

All relevant data are included in this published paper.

## References

- Afrifa, S., Zhang, T., Appiahene, P., & Varadarajan, V. (2022). Mathematical and machine learning models for groundwater level changes: a systematic review and bibliographic analysis. *Future Internet*, 14(9), 259. <https://doi.org/10.3390/fi14090259>
- Ali, A. S. A., Jazaici, F., Babakhani, P., Ashiq, M. M., Bakhshae, A., & Waldron, B. (2024). An overview of deep learning applications in groundwater level modeling: Bridging the gap between academic research and industry applications. *Applied Computational Intelligence and Soft Computing*, 2024(1), 9480522. <https://doi.org/10.1155/2024/9480522>
- Bayhan, K., Başakın, E. E., Ekmekcioğlu, Ö., Pham, Q. B., & Chu, H. J. (2025). Overviewing the Machine Learning Utilization on Groundwater Research Using Bibliometric Analysis. *Water*, 17(7), 936. <https://doi.org/10.3390/w17070936>
- Biswas, A., Sarkar, S., Das, S., Dutta, S., Choudhury, M. R., Giri, A., & Paul, D. (2025). Water scarcity: A global hindrance to sustainable development and agricultural production—A critical review of the impacts and adaptation strategies. *Cambridge Prisms: Water*, 3, e4. <https://doi.org/10.1017/wat.2024.16>
- Boo, K. B. W., El-Shafie, A., Othman, F., Khan, M. M. H., Birima, A. H., & Ahmed, A. N. (2024). Groundwater level forecasting with machine learning models: A review. *Water Research*, 252, 121249. <https://doi.org/10.1016/j.watres.2024.121249>
- Gaviria-Marin, M., Merigó, J. M., & Baier-Fuentes, H. (2019). Knowledge management: A global examination based on bibliometric analysis. *Technological Forecasting and Social Change*, 140, 194-220. <https://doi.org/10.1016/j.techfore.2018.07.006>
- Hou, M., Zhou, A., & Huang, P. (2025). Trends, challenges, and opportunities in groundwater level modeling with machine learning. *Environmental Earth Sciences*, 84(21), 615. <https://doi.org/10.1007/s12665-025-12653-y>
- Liu, H., Sun, J., Hu, L., Tang, S., Chen, F., Zhang, J., & Zhu, Z. (2025). Groundwater Storage Changes Derived from GRACE-FO Using In Situ Data for Practical Management. *Water*, 17(24), 3572. <https://doi.org/10.3390/w17243572>

- Lozano Hernández, B. L., Marín Celestino, A. E., Martínez Cruz, D. A., Ramos Leal, J. A., Hernández Pérez, E., García Pazos, J., & Almanza Tovar, O. G. (2024). A systematic review of the current state of numerical groundwater modeling in the United States: Challenges and future research. *Hydrology*, 11(11), 179. <https://doi.org/10.3390/hydrology11110179>
- Osman, A. I. A., Ahmed, A. N., Huang, Y. F., Kumar, P., Birima, A. H., Sherif, M., ... & El-Shafie, A. (2022). Past, present, and perspective methodology for groundwater modeling-based machine learning approaches. *Archives of Computational Methods in Engineering*, 29(6), 3843-3859. <https://doi.org/10.1007/s11831-022-09715-w>
- Öztürk, O., Kocaman, R., & Kanbach, D. K. (2024). How to design bibliometric research: an overview and a framework proposal. *Review of Managerial Science*, 18(11), 3333-3361. <https://doi.org/10.1007/s11846-024-00738-0>
- Pranckutė, R. (2021). Web of Science (WoS) and Scopus: The Titans of Bibliographic Information in Today's Academic World. *Publications*, 9 (1), 12. <https://doi.org/10.3390/publications9010012>
- Rajaei, T., Ebrahimi, H., & Nourani, V. (2019). A review of the artificial intelligence methods in groundwater level modeling. *Journal of Hydrology*, 572, 336-351. <https://doi.org/10.1016/j.jhydrol.2018.12.037>
- Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., & Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, 4(2), 87-101. <https://doi.org/10.1038/s43017-022-00378-6>
- Xue, Y., Niu, Z., Zhang, R., Jia, L., & Guo, S. (2024). Current Status and Future Research of Groundwater Under Climate Change: A Bibliometric Analysis. *Water*, 16(23), 3438. <https://doi.org/10.3390/w16233438>
- Yan, L., & Zhiping, W. (2023). Mapping the literature on academic publishing: A bibliometric analysis on WOS. *Sage Open*, 13(1), 21582440231158562. <https://doi.org/10.1177/21582440231158562>
- Zaresefat, M., & Derakhshani, R. (2023). Revolutionizing groundwater management with hybrid AI models: A practical review. *Water*, 15(9), 1750. <https://doi.org/10.3390/w15091750>