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A Bibliometric Analysis of Artificial Intelligence (AI) Applications in Hydrological Modeling

Dewi Ayu Sofia[1*], *Naufal Ariq Pratama*[2]
[1]Building Engineering Education, Universitas Pendidikan Indonesia, Bandung, Indonesia
[2]Civil Engineering, Universitas Pendidikan Indonesia, Bandung, Indonesia
[1*]dewiayusofia@upi.edu, [2]naufalariqp@upi.edu

ABSTRACT

The rapid advancement of artificial intelligence (AI) has opened new opportunities for developing hydrological models that are more adaptive, accurate, and efficient. This study aims to examine the research trends and directions concerning the application of AI in hydrological modeling using bibliometric analysis. A total of 136 relevant articles published between 2015 and 2025 were retrieved from the Semantic Scholar database using the Publish or Perish software. These records were then analyzed with VOSviewer to map keyword relationships and identify current research focuses. The results reveal a consistent upward trend in AI-based hydrological modeling publications, particularly since 2020. Among the top 15 cited articles, a total of 2,316 citations were recorded, averaging 17.03 citations per article. Keywords such as "LSTM," "RNN," "streamflow," and "hydrological forecasting" appeared with the highest frequency and recentness, signifying a shift toward more adaptive and predictive modeling approaches. Furthermore, density visualization highlights a strong focus on deep learning models—particularly LSTM and Support Vector Machines—while showing opportunities for further exploration in hybrid models and climate resilience applications. Although limited to a single database, the study provides a methodologically robust overview of the current research landscape. The findings underscore the transformative role of AI, not merely as a computational tool, but as a key enabler for designing hydrological models that are data-driven, responsive, and capable of supporting sustainable water resource management in the face of environmental uncertaintie.

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1. INTRODUCTION

Hydrology is the science concerned with the properties of water, including its physical and chemical characteristics, as well as its occurrence and distribution (Chow et al., 1988). In the context of infrastructure development and water resource management, hydrological data analysis plays a vital role as the foundation for planning, design, and evaluation processes. The success of understanding and predicting hydrological phenomena relies heavily on the availability of sufficient data in terms of quantity, quality, and continuity (Ginanjar & Yuningsih, 2018). Accurate hydrological forecasting is particularly critical for the design and resilience of infrastructure systems such as drainage networks and roadside barriers (Aldina & Maulana, 2023). Recent studies highlight the need to integrate hydrological considerations into the structural design of road barriers in high-risk areas (Mufhidin & Maksum, 2021).

One of the main challenges in hydrological analysis lies in the stochastic nature of input variables such as rainfall, which are inherently unpredictable and beyond human control. The uncertainty and irregularity of rainfall patterns create difficulties in producing accurate estimations, especially in regions with high climatic variability (McMillan et al., 2018). This condition underscores the urgent need for adaptive predictive methods and models capable of capturing the complex dynamics of hydrological systems. In this regard, artificial intelligence (AI) has emerged in recent years as a promising tool to complement and enhance traditional modeling techniques.

A growing body of research has explored the application of AI in hydrological modeling. One notable approach is the use of Long Short-Term Memory (LSTM) models, which have been implemented at grid scales to generate hydrological projections in glacier-dominated areas such as the Third Pole Asia (Long et al., 2024). These models offer innovative means to better understand water dynamics in complex mountain environments. In addition, (Ley et al., 2024) applied the Explainable Artificial Intelligence (XAI) framework to compare algorithms and elucidate the influence of input data on LSTM simulations. Their study introduced the concept of the "timestep of influence," referring to the number of preceding days with the most significant impact on model outputs. Meanwhile, (Kumanlioglu & Fistikoglu, 2019) successfully integrated Artificial Neural Networks (ANN) with Genetic Algorithms (GA) to build a hybrid rainfall-runoff model, demonstrating substantial improvements over conceptual models. ANN techniques have also been used to predict groundwater levels with high accuracy (Guzman et al., 2019).

Furthermore, Ramzi et al., (2024) compared conceptual and neural network models such as NARX-RNN and RNN-LSTM for rainfall-runoff prediction in non-stationary catchments. Their results confirmed the superior ability of AI-based models to represent the temporal variability of hydrological responses. AI's strength lies in its ability to identify patterns in historical data without explicitly modeling the underlying physical processes (Alhajir et al., 2025), making it a suitable solution to many limitations of conventional hydrological methods. Given these advantages, AI continues to be widely adopted for the development of more responsive and precise hydrological models.

As interest in this topic grows, it becomes increasingly important to assess how AI-based hydrological research has evolved, what methodologies dominate, and where opportunities for further exploration exist. To provide such an overview, bibliometric analysis offers a powerful tool to map scientific trends, emerging topics, and influential works within a research domain (Faruq & Putra, 2024). It enables researchers to evaluate the breadth and depth of existing literature, while also identifying knowledge gaps for future inquiry (Al

Husaeni & Nandiyanto, 2022).

This study offers a distinct contribution by presenting a comprehensive bibliometric analysis of research on the application of artificial intelligence in hydrological modeling over the past decade (2015–2025). In contrast to prior studies that primarily concentrated on algorithm development or model performance evaluation, this research adopts a broader meta-analytical perspective. It systematically identifies prevailing research trends, thematic clusters, methodological evolutions, and prospective directions for future inquiry. The findings are intended to support scholars and practitioners in gaining a deeper understanding of the current research landscape and in formulating strategic responses to the evolving role of AI in hydrological science.

2. METHOD

This study employed a literature review method with a bibliometric approach to explore the topic of artificial intelligence (AI) utilization in hydrological modeling. The literature was sourced from the Semantic Scholar database, which was chosen due to its AI-based search algorithm designed to retrieve relevant information more efficiently than conventional academic search engines. While this study uses Semantic Scholar as the primary database for bibliometric analysis, this choice is justified by its AI-driven indexing capabilities, which are particularly effective in capturing recent and interdisciplinary research developments—especially in artificial intelligence and hydrological modeling. The initial stage involved collecting publications using the Publish or Perish software. Two keyword categories were applied in the search process: the first using English terms ("AI application in hydrological modelling") and the second using equivalent terms in Indonesian ("pemanfaatan AI dalam pemodelan hidrologi"). The search was limited to publications released between 2015 and 2025.

The retrieved data were exported in RIS format and subsequently analyzed using VOSviewer version 1.6.20. This software was used to map term relationships based on the occurrence of keywords in publication titles and abstracts. The analysis generated three types of visualizations: network visualization, overlay visualization, and density visualization. The network visualization presents the interrelationships among keywords using colored, interconnected nodes—where the distance between nodes indicates the strength of the association, and the color represents specific thematic clusters. The overlay visualization illustrates the temporal distribution of keyword occurrences, allowing the identification of emerging or trending topics. Meanwhile, the density visualization depicts the concentration of keyword appearances using color gradients, where brighter areas indicate higher frequencies. These visual bibliometric tools are crucial for identifying patterns, relationships, and shifts within the body of literature. The ability to visualize bibliometric data plays an important role in understanding the broader structure and direction of research development in a particular field (Nandiyanto et al., 2020).

3. RESULT AND DISCUSSION

Based on the results of literature searches conducted using the Publish or Perish software, a total of 136 relevant articles were found in the Semantic Scholar database for the period 2015–2025, using the English keyword "AI application in hydrological modeling." In contrast, when using the Indonesian keyword "pemanfaatan AI dalam pemodelan hidrologi," only one article was retrieved. This stark difference highlights that scientific publications on this topic remain limited and are not yet widely documented in national-level academic literature.

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Table 1 presents the top 15 most-cited articles related to the application of AI in hydrological modeling. The ranking is based on the number of citations, which reflects each article's contribution and influence on the development of knowledge in this field. Collectively, these articles have received a total of 2,316 citations, with an average of 231.60 citations per year and an average of 17.03 citations per article—indicating strong academic interest and growing relevance of this research area.

Table 1. Publication data on the application of AI in hydrological modeling

No	Title	Authors	Year	Citations	Reference
1	Application of soft computing based hybrid models in hydrological variables modeling: a comprehensive review	F. Fahimi, Z.M. Yasen, A. El-Shafie	2017	139	(Fahimi et al., 2017)
2	Temperature-based modeling of reference evapotranspiration using several artificial intelligence models: application of different modeling scenarios	H. Sanikhani, O. Kisi, E. Maroufpoor, Z.M. Yaseen	2018	122	(Sanikhani et al., 2018)
3	Deep learning and machine learning in hydrological processes climate change and earth systems a systematic review	S. Ardabili, A. Mosavi, M. Dehghani, A.R. Varkonyi-Koczy	2019	109	(Ardabili et al., 2019)
4	Non-tuned machine learning approach for hydrological time series forecasting	Z.M. Yaseen, M.F. Allawi, A. Yousif, O. Jaafar, F. Hamzah, A. El-Shafie	2018	94	(Yaseen et al., 2018)
5	Recent advances in evapotranspiration estimation using artificial intelligence approaches with a focus on hybridization techniques—a review	M.Y. Chia, Y.F. Huang, C. Koo, K.F. Fung	2020	84	(Chia et al., 2020)
6	Forecasting of Multi-Step Ahead Reference Evapotranspiration Using Wavelet- Gaussian Process Regression Model	M. Karbasi	2018	82	(Karbasi, 2018)
7	Neural network modeling of hydrological systems: A review of implementation techniques	O. Oyebode, D. Stretch	2018	74	(Oyebode & Stretch, 2019)
8	Review on applications of artificial intelligence methods for dam and reservoir-hydro-environment models	M.F. Allawi, O. Jaafar, F.M. Hamzah, S. Abdullah, A. El-Shafie	2018	64	(Allawi et al., 2018)
9	Application of Artificial Neural Network in Hydrology- A Review	R. Tanty, T.S. Desmukh	2015	60	(Tanty & Desmukh,

No	Title	Authors	Year	Citations	Reference
					2015)
10	Application of artificial intelligence to estimate the reference evapotranspiration in sub-humid Doon valley	M. Nema, D. Khare, S. Chandniha	2017	59	(Nema et al., 2017)
11	Identifying capabilities and potentials of system dynamics in hydrology and water resources as a promising modeling approach for water management	A.F. Mashaly, A. Fernald	2020	54	(Mashaly & Fernald, 2020)
12	River/stream water temperature forecasting using artificial intelligence models: a systematic review	S. Zhu, A. Piotrowski	2020	52	(Zhu & Piotrowski, 2020)
13	Hybridized Extreme Learning Machine Model with Salp Swarm Algorithm: A Novel Predictive Model for Hydrological Application	Z.M. Yaseen, H. Faris, N. Al-Ansari	2020	52	(Yaseen et al., 2020)
14	Application of the Artificial Neural Network and Neuro-fuzzy System for assessment of groundwater quality	M. Khaki, I. Yusoff, N. Islami	2015	50	(Khaki et al., 2014)
15	Annual rainfall forecasting using hybrid Artificial Intelligence Model: integration of multilayer perceptron with Whale Optimization Algorithm	L. Diop, S. Samandianfard, A. Bodian, Z.M. Yaseen, M. Ghorbani, H. Salimi	2020	48	(Diop et al., 2020)

The bibliometric analysis revealed a notable increase in the number of publications related to the application of artificial intelligence in hydrological modeling over the past decade. As shown in **Figure 1**, the trend has risen significantly, particularly since 2020. While fluctuations occurred in the number of articles published annually, a clear upward trajectory can be observed, as indicated by the linear regression trend line. This growth coincides with the rapid development of AI technologies—especially machine learning and deep learning—which has stimulated scholarly interest in more advanced and responsive modeling techniques. The steady increase in research output reflects growing confidence in AI's capability to address the complexities of hydrological systems, especially under the pressures of climate variability and extreme weather events.

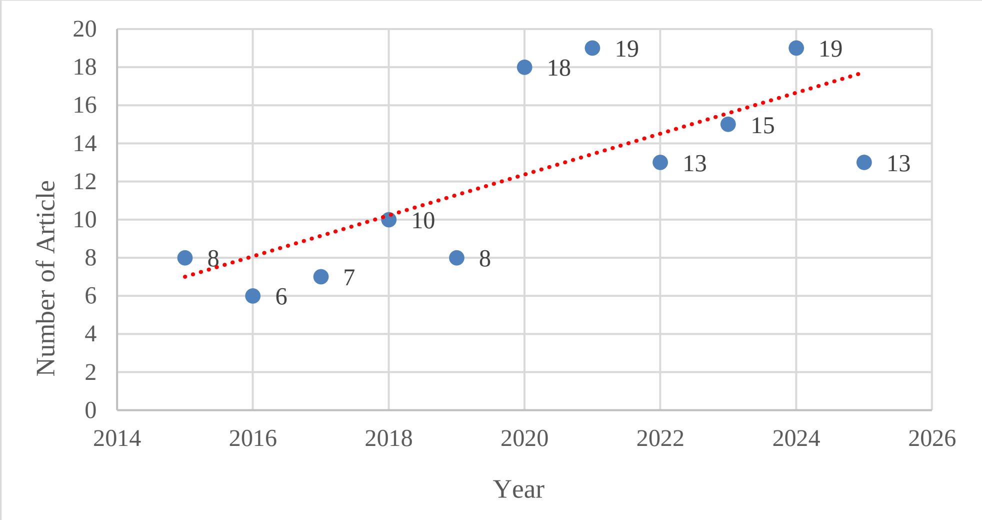

Figure 1. Annual trend of publications related to the application of AI in hydrological modeling (2015–2025)

To further examine the structure of research within this field, keyword co-occurrence mapping was conducted using VOSviewer. The results are visualized in **Figure 2**, which shows the network of thematic clusters formed by frequently appearing keywords in AI-related hydrological research.

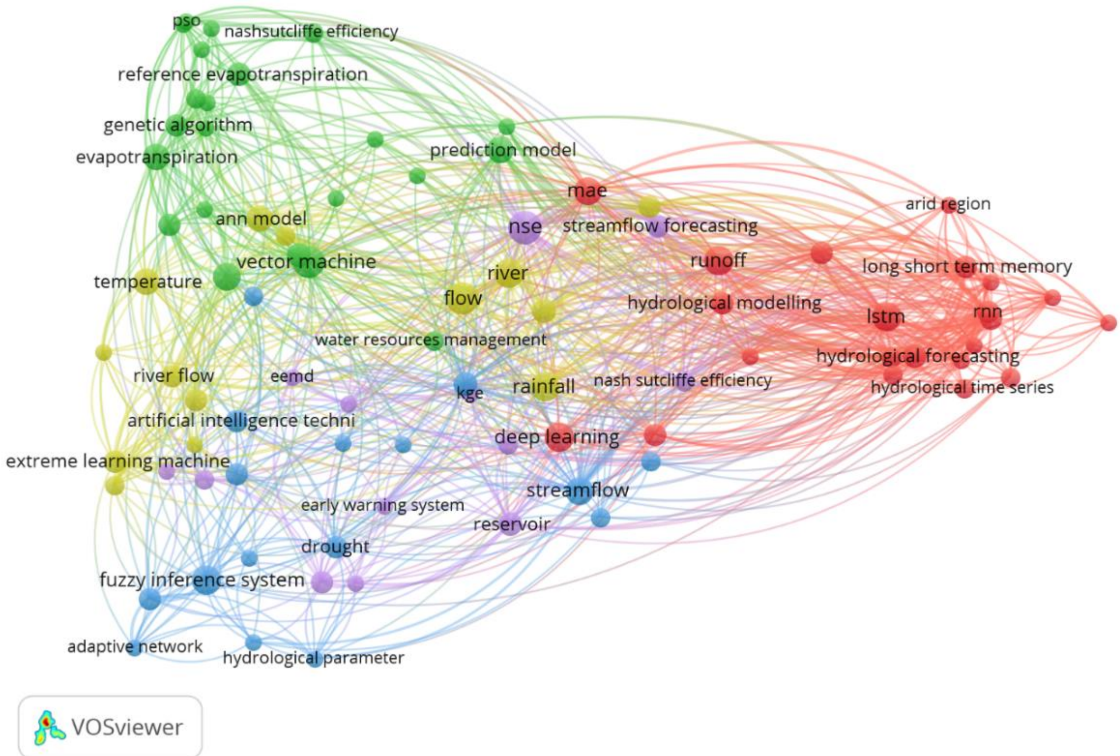

Figure 2. Network visualization showing thematic clusters based on keyword co-occurrence in AI-based hydrological modeling publications (2015-2025**)**

The first cluster, shown in red, consists of 22 keyword items, including LSTM, RNN, Long Short-Term Memory, hydrological forecasting, and hydrological time series. This cluster represents deep learning-based approaches, particularly Recurrent Neural Networks (RNN), used for time-series prediction tasks such as river flow and rainfall modeling. The second cluster, colored green, also includes 22 keywords such as Genetic Algorithm, Support Vector Machine, hydrological cycle, and evapotranspiration. This cluster focuses on classical AI techniques for optimization and parameter modeling in hydrology. The third cluster, in blue, comprises 16 keyword items such as streamflow, drought, and groundwater level. These terms reflect the real-world applications of AI in core components of hydrological systems, highlighting its practical value. The fourth cluster, represented in yellow, includes 14 keywords like flow, river, river flow, temperature, and discharge. This group contains more general terms that serve as connectors across clusters, indicating interdisciplinary overlap. Lastly, the fifth cluster, displayed in purple, consists of 13 keywords such as climate variability, early warning system, and extreme weather event. This cluster reflects the use of AI in early warning systems and climate-related applications, emphasizing AI's role in addressing environmental uncertainty and risk prediction.

The visualization indicates that deep learning—particularly the Long Short-Term Memory (LSTM) model—has become one of the primary focal points in AI-based hydrological modeling research. The interconnections between clusters suggest that various AI approaches complement one another, collectively contributing to the development of hydrological modeling systems that are adaptive and responsive to the challenges of climate change and the complexity of water resource management.

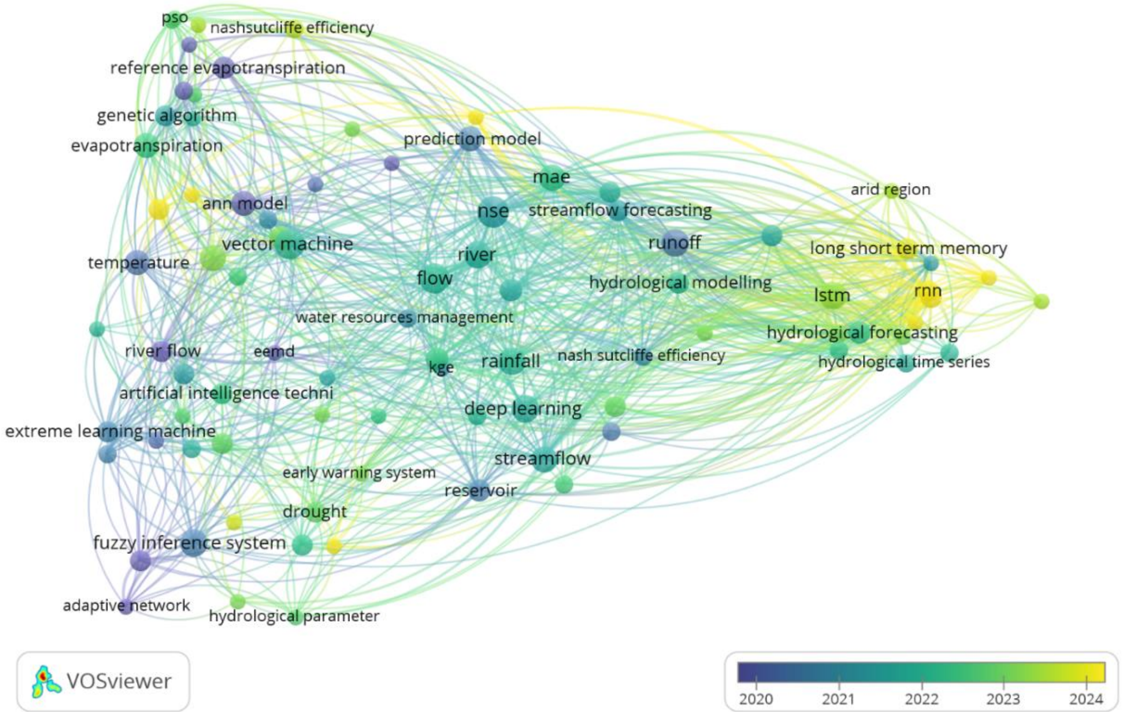

Figure 3. Overlay visualization illustrating the temporal dynamics of frequently occurring keywords in AI-based hydrological modeling research

Figure 3 presents the overlay visualization illustrating the temporal dynamics of frequently occurring keywords in scientific publications related to the application of AI in hydrological modeling. Each node is color-coded to reflect the average year in which the keyword

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appeared, ranging from dark blue (earlier years, around 2020) to bright yellow (more recent years, around 2023–2024).

The visualization shows that keywords such as Fuzzy Inference System, Adaptive Network, and Extreme Learning Machines are predominantly shaded in blue to blue-green, indicating that these approaches were more commonly used during the early phase of the analysis period. These terms represent the earlier generation of AI techniques applied in hydrological studies. In contrast, keywords such as LSTM, RNN, Long Short-Term Memory, and hydrological forecasting appear in bright yellow, signifying a notable rise in popularity over the past few years. This trend suggests a clear shift in research focus toward more advanced and adaptive methods, particularly those capable of handling complex hydrological time series data. Other terms like streamflow forecasting, runoff, and hydrological time series, which also appear in yellow, further support the observation that current research is increasingly centered on AI-based prediction of hydrological parameters using historical data.

Overall, the overlay visualization captures the methodological evolution in this field—from classical models toward modern deep learning techniques. The gradual color shift from blue to yellow not only reflects a change in preferred tools and approaches but also highlights the growing integration of cutting-edge technologies in hydrological research. This shift underscores how the research community is adapting to the demand for more accurate and responsive predictive models, especially in light of ongoing climate variability and challenges in water resource availability.

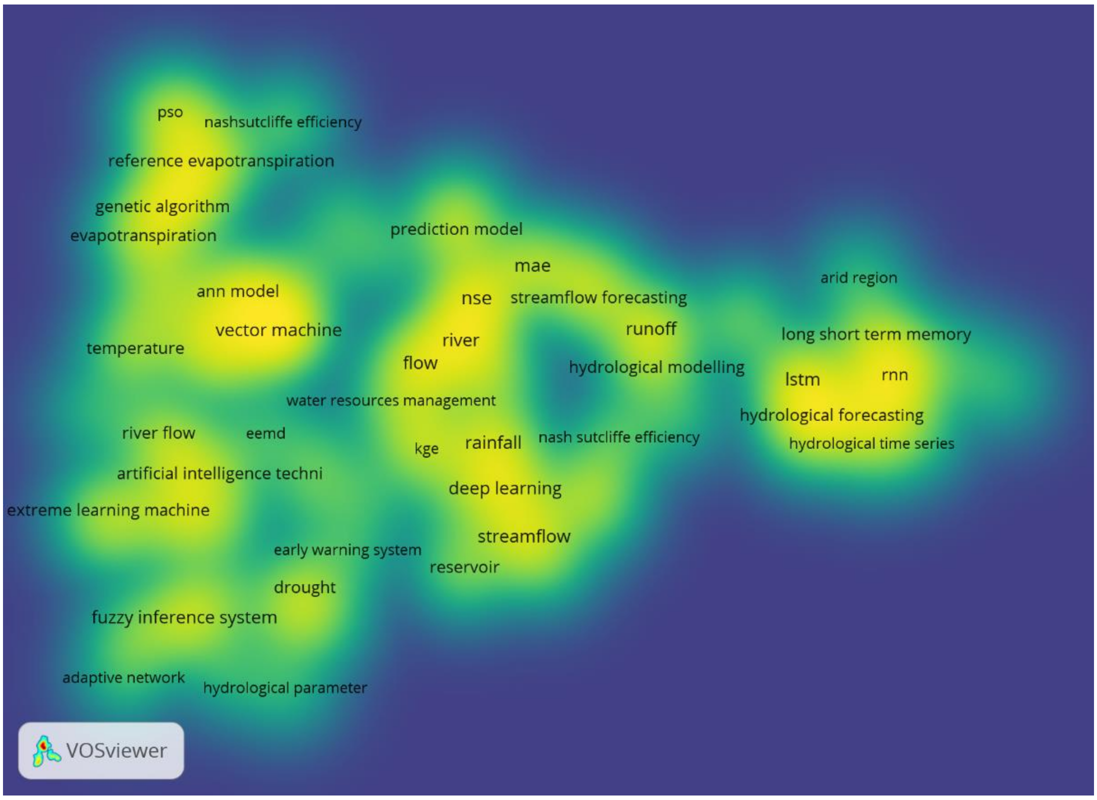

Figure 4. Density visualization displaying the frequency distribution of keywords in AI-related hydrological modeling literature

Figure 4 presents the density visualization of keyword occurrences in publications related to the application of artificial intelligence in hydrological modeling. The color gradient—from dark blue to bright yellow—represents the frequency with which certain keywords appear in the literature. Blue indicates low occurrence, while yellow signifies high frequency. The visualization reveals that keywords such as streamflow, rainfall, deep learning, runoff, Support Vector Machine, LSTM, and hydrological forecasting appear with the highest intensity (bright yellow), indicating that these topics are central to ongoing research in this field. Additionally, terms like NSE, MAE, and Nash-Sutcliffe Efficiency highlight that model performance evaluation remains a crucial component in AI-based hydrological studies.

The highest keyword densities are found where classical machine learning techniques—such as Support Vector Machine and Artificial Neural Network—intersect with more advanced deep learning models like LSTM and RNN. This suggests an ongoing integration and transition from traditional AI approaches to more sophisticated architectures within hydrological modeling. In contrast, keywords such as Adaptive Network, Fuzzy Inference System, and early warning system appear with moderate to low intensity, indicating that while these topics receive less attention, they represent important areas of specialization and diversification—particularly in early warning and adaptive modeling applications. Overall, the density visualization offers a clear picture of current research concentrations, revealing a strong and growing emphasis on predictive modeling using deep learning. These findings point to a broader shift in hydrological science—from reliance on empirical or purely statistical methods to more adaptive, AI-driven frameworks that can better respond to data complexity and climate variability.

Based on this bibliometric analysis, several implications emerge for the future of research in AI-based hydrological modeling. The growing reliance on deep learning methods—particularly Long Short-Term Memory (LSTM) and Recurrent Neural Networks (RNN)—to address time-series forecasting challenges such as streamflow and rainfall prediction reflects a broader transformation in the field. Conventional techniques are increasingly being complemented or replaced by more flexible, data-driven approaches that can better accommodate complex hydrological dynamics.

This study builds upon and advances previous bibliometric research by offering a more focused lens on AI applications specifically within hydrological modeling, in contrast to broader reviews such as Ardabili et al., (2019) that concentrate on AI in the context of climate and earth systems. Unlike earlier studies that primarily classified AI methods or evaluated model performance, the present analysis incorporates citation data, keyword evolution, and thematic clustering across a decade of research. By utilizing tools like Semantic Scholar and VOSviewer, this study provides a nuanced understanding of methodological convergence and highlights underexplored niches such as AI-driven drought prediction and groundwater quality modeling.

Furthermore, the wide range of AI techniques documented in the literature—from Support Vector Machines to Fuzzy Inference Systems and Genetic Algorithms—demonstrates that no single approach dominates the field. Rather, hybridization and methodological integration are emerging as essential strategies to improve model performance. The combination of trend and density visualizations emphasizes the dynamic and responsive nature of research in this area, particularly in adapting to technological advancements and global environmental challenges such as climate change. Accordingly, the insights presented in this study offer valuable guidance for researchers, practitioners, and policymakers in formulating water resource management strategies that are robust, predictive, and sustainable. Ultimately, this study underscores the evolving role of AI—not merely as a computational tool but as a transformative force in the digital evolution of hydrology and water resource systems.

4. CONCLUSION

The results of this literature review indicate that the application of artificial intelligence (AI) in hydrological modeling has continued to evolve significantly over the past decade. Deep learning models such as Long Short-Term Memory (LSTM) and Recurrent Neural Networks (RNN) have emerged as the dominant approaches, driven by the increasing demand for hydrological predictions that are more responsive to climate variability. Bibliometric analysis reveals a clear shift in research focus—from traditional AI techniques toward more advanced, adaptive, and data-driven methodologies that can be better capture dynamic behavior of hydrological systems. This study also provides an important contribution by offering a structured and thematic overview of existing research through network, overlay, and density visualizations. Five major keyword clusters were identified, reflecting the diversity of applications and methods used in AI-based hydrological modeling. In addition, citation analysis underscores the growing influence and scholarly attention toward this topic. Although the study relies on a single data source (Semantic Scholar), its selection is methodologically justified and effectively captures relevant and high-quality literature within the field. Nevertheless, future studies are encouraged to integrate multiple databases such as Scopus or Web of Science to enrich the bibliometric mapping and enhance coverage. In conclusion, AI is no longer a supplementary tool but has become a transformative force in the field of hydrology. The insights generated from this study can inform future research directions, guide practical applications, and support the development of predictive, resilient, and sustainable water resource management strategies in an era of increasing environmental uncertainty.

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