Past, present, and future of the Hurst-Kolmogorov dynamics in Stochastics: A bibliometric analysis of the last 50 years in water resources

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Abstract

Hurst's paper on the Nile's flow variability marked a pivotal moment in hydrology and beyond by introducing what was called the Hurst phenomenon. Independently, Kolmogorov developed a mathematical model describing this behaviour a decade earlier. The Hurst-Kolmogorov dynamics (HKd) is used to express this phenomenon physically and mathematically, which is characterised by high uncertainty and persistence (across spatial and temporal scales) and challenges traditional analytical frameworks, particularly in water resources-related topics and implications in engineering designs. Given the importance of HKd, a bibliometric analysis of it in water resources is helpful to trace its historical development, current state, and (possible) future trajectories. The latter intends to offer a comprehensive perspective on HKd, serving as a guide for new readers seeking an entry point into this field. Using the Web of Science database, 617 publications from 1974 to 2023 are analysed, revealing a consistent growth trend in research outputs up to 2018. Collaborative efforts among researchers worldwide have been prominent, with the USA and China leading in international collaborations. High-impact journals on topics related to water resources and geosciences are primary outlets for research related to the HKd. Interestingly, only two journals published the 20 most cited papers on this topic. A clear pattern from "groundwater" to "streamflow" to "soil moisture" to "precipitation" was observed from the past to

the present. Overall, this analysis provides a comprehensive overview of the past, present, and future trends in HKd research, and highlights its contribution to the scientific literature of water resources.

Keywords: Bibliometric analysis; Hurst-Kolmogorov dynamics; Stochastics; Water resources.

1. INTRODUCTION

Hydrology underwent a transformative shift with the work of Hurst (1951), who published his paper on the variability of natural processes, including the Nile flow records. Hurst's analysis revealed physical statistical behaviours that challenged prevailing analytical frameworks, laying the groundwork for what would become known as long-term persistence (LTP), long-range dependence (LRD), or Hurst-Kolmogorov dynamics (HKd). The latter name emerged to give credit to the completely independent contributions of Hurst (1951) and Kolmogorov (1940), who established the grounds for its theoretical analysis (Koutsoyiannis, 2010).

Among the many complex dynamics of different phenomena in water resources (and related topics), HKd is directly related to high uncertainty and persistence (McMillan et al., 2018; Westerberg et al., 2022; Westerberg & McMillan, 2015). Even if this topic originated in hydrology-related works, its importance has been recognised across many fields outside hydrology, such as economy, climatology, and statistics (see, e.g., O'Connell et al. (2016) for a recent review paper and Dimitriadis (2017) for a variety of analyses of different hydroclimatic variables). HKd means that the probability of an event occurring again depends strongly on the history of the events before it. As a result, its autocorrelation function decays as a power law. The latter implies that the correlation between observations persists over longer lags than expected (under usually applied modelling frameworks, e.g., Beran et al., 2013; Mandelbrot & Wallis, 1968). HKd implications are significant at research and operational levels since they indicate that traditional modelling approaches (based on the independence principle among observations) may not be appropriate for describing some natural phenomena (see, e.g., Dimitriadis & Koutsoyiannis, 2018; Koutsoyiannis, 2016, 2023, for the stochastic simulation of HKd with an arbitrary marginal distribution and with focus on the extremes of hydroclimatic processes, respectively).

Figure 1 shows different values of the Hurst parameter (H) to help readers visualise how H affects the behaviour of time series data. Such a figure presents synthetic data generated using the Filtered Hurst-Kolmogorov Cauchy-Dagum (FHK-CD) model, with parameter values set as follows: $a_1 = a_2 = b_1 = b_2 = M = 0.5$, and H ranging from 0.5 to 0.9. The synthetic data follows an exponential distribution with $\lambda = 2$, and non-positive values were truncated to zero. Synthetic data was generated at an "annual" scale (in blue) along with the 20-“year” average (in red). The length of the generated time series was 1000 “years”. Some remarks as follows:

- All generated data follows the same probability distribution;
- H = 0.5 represents white noise with no long-term persistence (i.e., past values have no significant influence on future values);
- H > 0.5: Increasing H values indicate a higher degree of persistence, where past values increasingly influence future values. Additionally, variability at higher time scales (in this case, 20 "years" in red) increases with H.

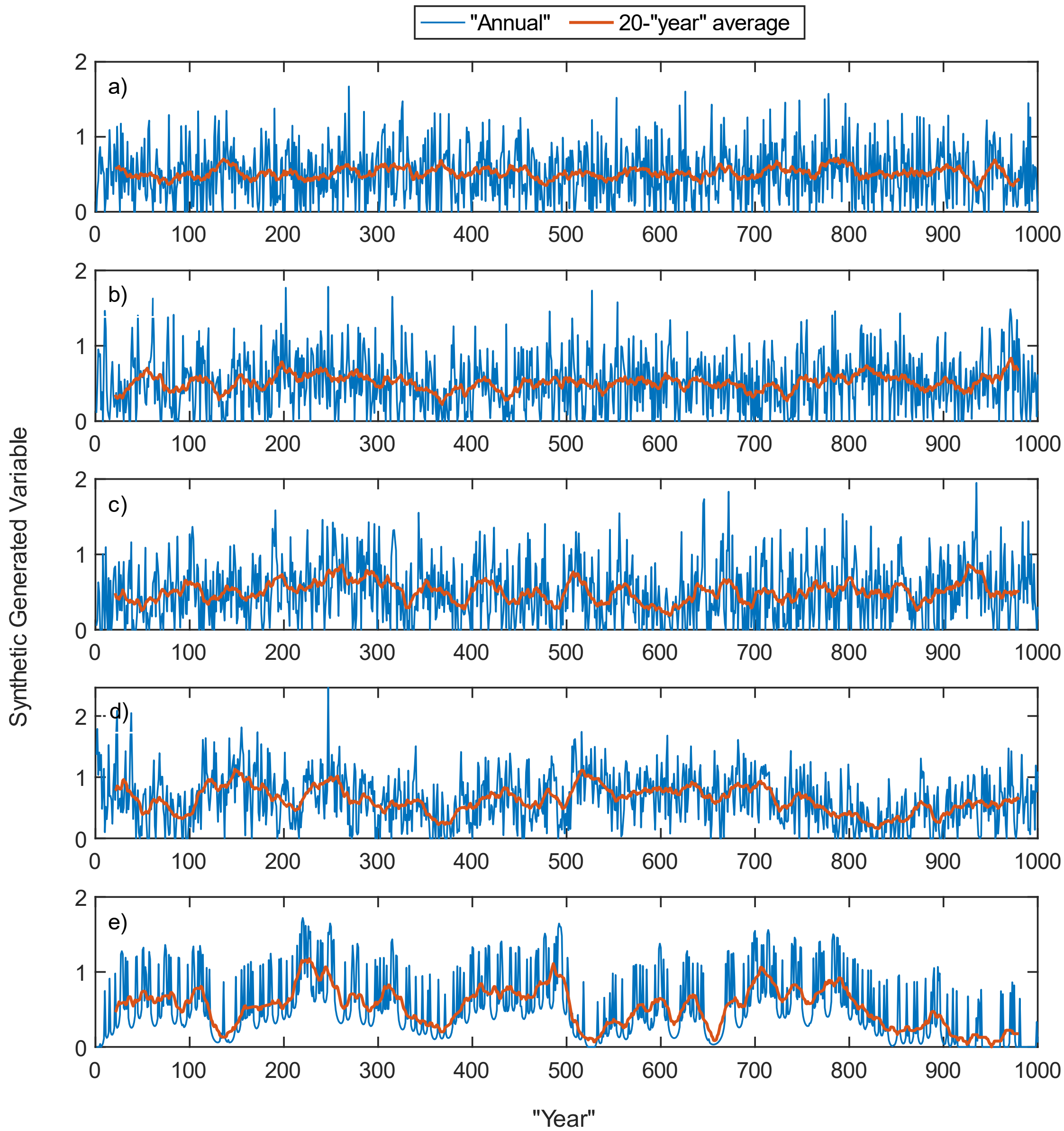

Figure 1. Synthetically generated data (blue colour, "annual" scale) and 20-"year" average (red colour) with different values of the Hurst parameter (H): a) H = 0.5; b) H = 0.6; c) H = 0.7; d) H = 0.8; and, e) H = 0.9.

Since the HK behaviour was discovered, several works have been published in hydroclimatic processes evidencing, quantifying, and simulating it. Table 1 summarises some examples in terms of the research topic/variable of interest and its respective reference.

Table 1. Recent works evidencing, quantifying, and simulating HKd in terms of research topic or variable of interest.

Research Topic or Variable	**References**
Hydroclimatic processes	Dimitriadis & Koutsoyiannis (2018)
Temperature	(Glynis et al., 2021; Koutsoyiannis, 2003; Pelletier, 1998)
Rainfall	(Fraedrich & Larnder, 1993; Pelletier & Turcotte, 1997; Iliopoulou et al. 2018; Iliopoulou and Koutsoyiannis, 2019)
Wind power	(Haslett & Raftery, 1989; Katikas et al., 2021; Koutsoyiannis et al., 2018)
North-Atlantic Oscillation index	(Stephenson et al., 2000)
Streamflow	(Aguilar et al., 2017; Graves et al., 2017, pp. 1951–1980; Koutsoyiannis, 2011; Montanari, 2012; O’Connell et al., 2016; Pizarro et al., 2022; Vavoulogiannis et al., 2021)
Rock formation	(Dimitriadis et al., 2019)
Groundwater	(Varouchakis et al., 2012)
Solar radiation	(Koudouris et al., 2018)
Evapotranspiration	(Dimitriadis, Tegos, et al., 2021)
Water-energy nexus	(Mamassis et al., 2021; Sargentis, 2022)
revised tools and methodologies for key water-cycle hydrological processes	(Dimitriadis, Koutsoyiannis, et al., 2021; Koutsoyiannis, 2020a)
History and relevance of HK behaviour	O’Connell et al. (2016)
Quantification of HK behaviour through autocovariance, power-spectrum, and climacogram	Dimitriadis & Koutsoyiannis (2015)
Simulation of HKd	Dimitriadis, Iliopoulou, et al. (2021); Koutsoyiannis (2020b)
Stochastic investigation of hydrological extremes	(Iliopoulou, 2020; Koutsoyiannis, 2023)

Recognising the dissemination of Hurst's physical evidence and Kolmogorov’s mathematical description in the subsequent developments in the last decades, this bibliometric analysis aims to uncover the multifaceted aspects of HKd in water resources, shedding light on its historical development, current state, and possible future trajectories. This study offers a panoramic view of the research status by examining key metrics such as publication growth, authorship patterns, international collaboration, journal impacts, and the frequency of used keywords. Furthermore, it seeks to identify authors with significant contributions to HKd research, influential publications, and emerging trends within this field. Through this bibliometric analysis, we aim to offer new readers a detailed and accessible introduction to this subject.

2. METHODOLOGY AND METHODS

2.1 Search strategy and data extraction

A comprehensive search for publications on HKd in water resources was conducted in the Web of Science (WoS) database on the 12th of March 2024. We utilised the WoS Core Collection, known for its rigorous selection and evaluation process of academic information, to ensure the reliability and accuracy of our findings. The WoS database provided content coverage and detailed citation analysis information, making it an ideal resource for this study. The search strategy involved the use of a carefully designed equation that incorporated relevant terms. Such an equation, in the WoS nomenclature, is explicitly presented as follows (TS means a topic search): *(TS=(Hurst-Kolmogorov) OR TS=(Hurst parameter) OR TS=(Hurst phenomenon) OR TS=(Hurst coefficient) OR TS=(Hurst exponent) OR TS=(Hurst effect) OR TS=(long-term persistence) OR TS=(long-*

range dependence)). These terms were searched within the water resources topic field (WoS categories), encompassing titles, abstracts, author keywords, and keyword-plus terms. All references indexed and published from the 1st of January 1974 to the 31st of December 2023 were included to provide a comprehensive analysis of the last 50 complete years (i.e., a filter was applied to consider full years, and therefore, documents published in 2024 were not considered within the analysis). Early-access papers were excluded from the bibliometric analysis. Including only fully published papers allows for a more stable and comparable dataset, ensuring that the bibliometric indicators reflect finalized research outputs. Additionally, early-access papers will eventually be incorporated into the normal publication cycle and can be included in future analyses once they are fully published. Only documents written in English were considered. The WoS extraction tool was employed to extract the raw data from the WoS database, generating data in BibTeX format available to download. The following information was extracted from each document: title, journal, article type, author names, affiliations, keywords, publication date, research area, abstract, cited references, language, and open access information. These data formed the foundation for the bibliometric analysis. Figure 2 shows the core steps of the bibliometric analysis.

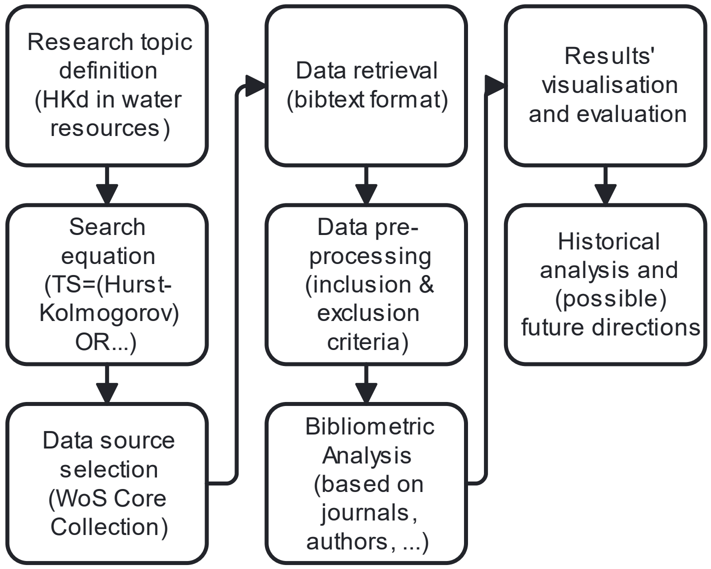

Figure 2. Flowchart of research methodology for the bibliometric analysis applied in this study.

2.2 Data analyses

The bibliometric analysis of the raw data obtained from the WoS database was performed using R software version 4.4.0 (R Foundation for Statistical Computing, Vienna, Austria). Specifically, the analysis was performed using the Bibliometrix R package (Aria & Cuccurullo, 2017. https://www.bibliometrix.org/home/index.php), which encompasses a comprehensive range of bibliometric methods. These methods allow the quantification of time trends, identification of highly cited papers, detection of authors with significant contributions to HKd research, journals, institutions, and countries, as well as the calculation and ranking of research outputs and collaboration. Descriptive bibliometric analysis of the raw data was based on the metrics of sources (journals), authors, and documents. We also analysed two knowledge structures to complete the science mapping of HKd in water-resources research: a) conceptual: e.g., co-occurrence and thematic evolution; and, b) social: e.g., collaboration network among researchers and countries. The conceptual structure was measured by co-word analysis, while a collaboration network analysis measured the social structure. Additionally, to enhance the bibliometric results by measuring the influence of research outputs, the impact factors (IF) of the journals in question were extracted from the latest Journal Citation Reports (JCR, 2023) by Clarivate Analytics.

3. RESULTS

3.1 Publication Analysis Based on Numbers

The search strategy produced 617 publications between 1974 and 2023 (the last 50 years). Figure 3a shows the annual evolution of the research output of HKd in water resources research. From 1974, and on average, the annual growth rate was 6.19%, showing monotonically increasing published papers up to 2018. From 2019 to 2023, a negative trend was observed (see the Discussion section for possible explanations). However, years with lack of publications are available, such as from 1981 to 1987, where no documents were located from the search equation. Figure 3b shows the standardised climacogram – of the time series presented in Figure 3a – alongside a fitted power law to estimate the Hurst coefficient H (H ranges between 0 and 1). H was estimated to have a value of 0.98, which means high persistence. High persistence means that the time series exhibits long-term dependence, where high values are likely to be followed by high values, and low values are likely to be followed by low values over time. This characteristic suggests a strong "memory" effect within the data, implying that past values significantly influence future values. Additionally, a drop at a scale of two years was observed, providing hints about the existence of periodicity at this scale (see, e.g., Koutsoyiannis, 2017, page 43). It is worth mentioning that this periodicity is at the border of the Nyquist frequency; therefore, it is hard to identify it with a usual spectral analysis.

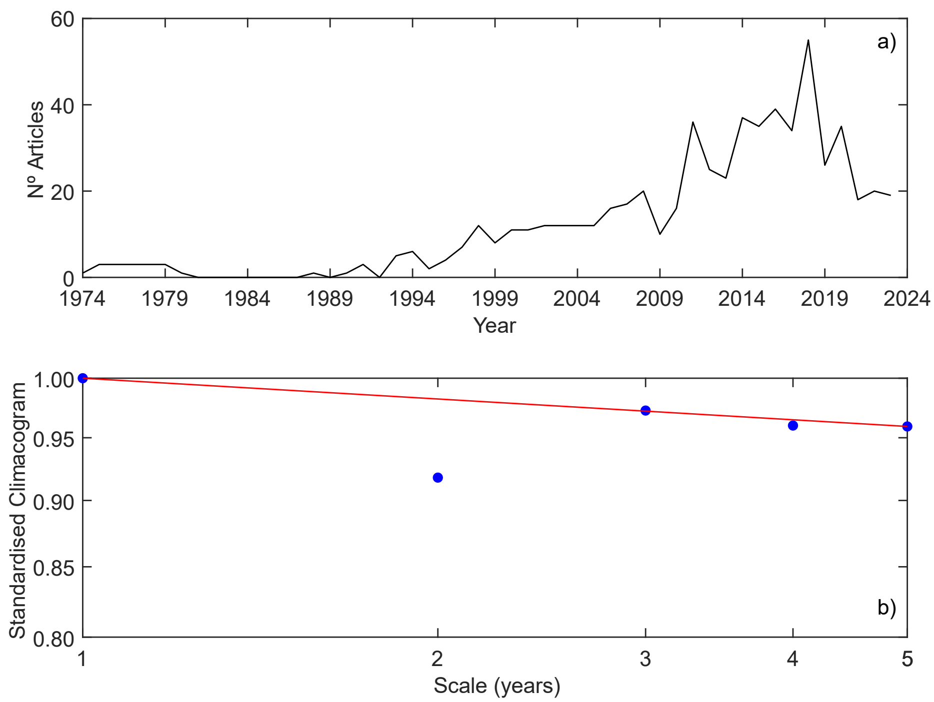

Figure 3. a) Annual publication outputs (from 1974 to 2023) of HKd in water resources. Total references within the published documents were 23,582. b) Standardised climacogram with a fitted power law (red line) from data of the annual publication outputs. The Hurst coefficient was estimated as H = 0.98 (without considering the estimation bias).

The 617 documents recovered from the WoS search were based on 125 sources, of which 1722 authors were involved. Single-authored publications represent less than 15% of the sample (n=77, 12.48% of all publications), which implies most of the publications were done by several authors, out of which 27.71% represent international co-authorship. According to the type of document, the most relevant source of the publication outputs was derived from research articles (n=524, 84.93%). The remaining documents were proceeding papers (n=64, 10.37%) and reviews (n=11, 1.78%). Additionally, editorial material (n=2, 0.32%), discussion paper (n=2, 0.32%), and book chapter (n=9, 1.46%) represented less than 3% (all together) of the documents.

3.2 Publication Analysis Based on Journals

Table 2 presents the general characteristics of the 20 journals with significant contributions to HKd research in water resources within the last 50 years. These journals published 432 articles, which accounted for 70.02% of all recovered publications. The journals with significant contributions to HKd research (with an arbitrarily imposed number of 20 or more published articles) were: Water Resources Research (n=96), Journal of Hydrology (n=70), Water (n=35), Hydrological Processes (n=25), and Hydrological Sciences Journal (n=25). These five journals published 40.68% (251 articles) of the total production.

Table 2. Top 20 journals with significant contributions to HKd research in water resources research within the last 50 years.

Rank	Sources	Nº of Articles (%[b])	Categories (Rank)	IF (JCR) [a]
1st	Water resources research	96 (15.56%)	Water Resources; Environmental Sciences (18/127; 98/358)	4.6
2nd	Journal of Hydrology	70 (11.35%)	Geosciences, Multidisciplinary; Water Resources (19/253; 8/127)	5.9
3rd	Water	35 (5.67%)	Environmental Sciences; Water Resources (169/358; 40/127)	3.0
4th	Hydrological processes	25 (4.05%)	Water Resources (45/127)	2.8
5th	Hydrological sciences journal	25 (4.05%)	Water Resources (45/127)	2.8
6th	Hydrology and Earth System Sciences	19 (3.08%)	Geosciences, Multidisciplinary; Water Resources (21/253; 10/127)	5.7
7th	Stochastic environmental research and risk assessment	19 (3.08%)	Water Resources; Statistics & Probability (28/127; 8/168)	3.9
8th	Water research	18 (2.92%)	Water Resources; Environmental Sciences (1/127; 13/358)	11.4
9th	Advances in water resources	16 (2.59%)	Water Resources (27/127)	4.0
10th	Journal of contaminant hydrology	16 (2.59%)	Water Resources; Environmental Sciences (32/127; 146/358)	3.5

Continued table 2

Rank	Sources	N of Articles (%)	Categories (Rank)	IF (JCR)
11th	Water air and soil pollution	15 (2.43%)	Water Resources; Environmental Sciences (30/127; 129/358)	3.8
12th	Environmental earth sciences	11 (1.78%)	Geosciences, Multidisciplinary; Water Resources (84/253; 45/127)	2.8
13th	Journal of hydrologic engineering	10 (1.62%)	Water Resources; Environmental Sciences (67/127; 239/358)	2.2
14th	Natural hazards and earth system sciences	10 (1.62%)	Geosciences, Multidisciplinary; Water Resources (34/253; 25/127)	4.2
15th	Aquatic conservation-marine and freshwater ecosystems	9 (1.46%)	Water Resources; Environmental Sciences (54/127; 209/358)	2.5
16th	Journal of the American water resources association	8 (1.30%)	Geosciences, Multidisciplinary; Water Resources (98/253; 51/127)	2.6
17th	Natural hazards	8 (1.30%)	Geosciences, Multidisciplinary; Water Resources (65/253; 35/127)	3.3
18th	Physics and chemistry of the earth	8 (1.30%)	Geosciences, Multidisciplinary; Water Resources (76/253; 40/127)	3.0
19th	Ecohydrology	7 (1.13%)	Water Resources; Environmental Sciences (54/127; 209/358)	2.5
20th	Environmental modelling & software	7 (1.13%)	Water Resources; Computer Science, Interdisciplinary Applications (14/127; 32/169)	4.8

[a] IF (JCR), impact factor (Journal Citations Reports); Impact factor obtained from the Journal Citation Reports (2023).
[b] Percentage calculated out of the retrieved 617 documents.

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3.3 Publication Analysis Based on Authors

Between 1974 and 2023, the topic in question accumulated 617 documents involving 1722 authors. Most authors published multi-authored documents (single authored-documents: 77; whereas authors of single-authored documents: 58). The authors with significant contributions to HKd research (with an arbitrarily imposed number of 10 or more published articles) were: Koutsoyiannis, D. (n=41); Dimitriadis, P. (n=11); and, Montanari, A. (n=10). Collaboration analysis showed an average co-authorship of 3.45 co-authors per document and (on average) a percentual international co-authorship of 27.71%.

3.4 Publication Analysis Based on Countries/Regions and Institutions

Country publication outputs were measured using the number of author appearances by country affiliation (corresponding author only). The results showed that the research output of HKd in water resources research was geographically located in 57 countries worldwide. Table 3 shows the main features of the top 20 most productive corresponding authors' countries in publishing research on this topic. The USA, China, Canada, and Greece were the most productive countries (in terms of corresponding authors), accumulating around half of the total production (n=326, 52.83%). The intra-country collaboration analysis (i.e., all authors from the same country) showed that these countries also had the highest number of articles published by authors from their own countries (USA=92; China=32; Canada=22; Greece=17). The USA was at the forefront of the inter-country collaboration, registering 31 documents that included authors from other countries. China (n=23) and Canada (n=15) were the second and third most significant contributors. However, in relative terms, South Africa (multiple country publication (MCP) ratio=0.75, total documents=4), Switzerland (MCP ratio=0.67, total documents=15), and Poland (MCP ratio=0.60, total documents=5) were the countries collaborating more actively.

Figure 4 illustrates the network mapping of international collaboration among the countries. The USA led the most significant number of international collaborations (n=156). The following most significant collaborators were China (n=79), Greece (n=46), and Canada (n=45). Table 4 presents a general description of the top 20 most productive research institutions/universities in publishing research on HKd in water resources. These institutions produced 541 documents (87.68%) out of 617 recovered publications. Worthy mentioning is that the first institution in Table 4 (National Technical University of Athens, Greece) published more than three times the number of papers of the second institution in the ranking in question (Hohai University, China).

Table 3. Top 20 productive corresponding authors' countries in publishing papers on HKd in water resources (1974-2023).

Countries	N of documents	% [a]	SCP	MCP	MCP Ratio[b]
USA	156	25.28%	128	28	0.18
China	79	12.80%	56	23	0.29
Greece	46	7.46%	37	9	0.20
Canada	45	7.29%	33	12	0.27
Australia	34	5.51%	25	9	0.27
Italy	31	5.02%	18	13	0.42
United Kingdom	23	3.73%	12	11	0.48
Germany	22	3.57%	16	6	0.27
India	18	2.92%	18	0	0.00
France	16	2.59%	11	5	0.31
Spain	14	2.27%	7	7	0.50
Iran	9	1.46%	7	2	0.22
Poland	8	1.30%	6	2	0.25
Brazil	7	1.13%	7	0	0.00
Austria	6	0.97%	5	1	0.17
Netherlands	6	0.97%	1	5	0.83
Switzerland	6	0.97%	1	5	0.83
Czech Republic	5	0.81%	4	1	0.20
Japan	5	0.81%	2	3	0.60
Mexico	5	0.81%	4	1	0.20

Abbreviations: SCP, single country publications; MCP, multiple country publications.

[a] Percentage calculated out of the retrieved 617 documents.

[b] We calculated the Multiple country publication ratio as MCP divided by the total published documents per country.

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Table 4. Top 20 most productive research institutes/universities in publishing papers on HKd in water resources (1974 to 2023), sorted by the total number of articles.

University/Research Institute	**Country**	**N of articles**	**% [a]**
National Technical University of Athens	Greece	80	12.97%
Hohai University	China	26	4.21%
University of Arizona	USA	24	3.89%
Colorado State University	USA	21	3.40%
University of Padua	Italy	20	3.24%
Beijing Normal University	China	19	3.08%
Newcastle University	UK	19	3.08%
University of Bologna	Italy	18	2.92%
Purdue University	USA	17	2.76%
University of California, Davis	USA	17	2.76%
University of Saskatchewan	Canada	17	2.76%
Vienna University of Technology	Austria	16	2.59%
University of Iowa	USA	15	2.43%
University of Newcastle	Australia	15	2.43%
Northwest A&F University	China	14	2.27%
University of Granada	Spain	14	2.27%
University of Waterloo	Canada	14	2.27%
Texas A&M University	USA	13	2.11%
University of Nevada	USA	13	2.11%
University of Tennessee	USA	12	1.94%

[a] Percentage calculated out of the retrieved 617 documents.

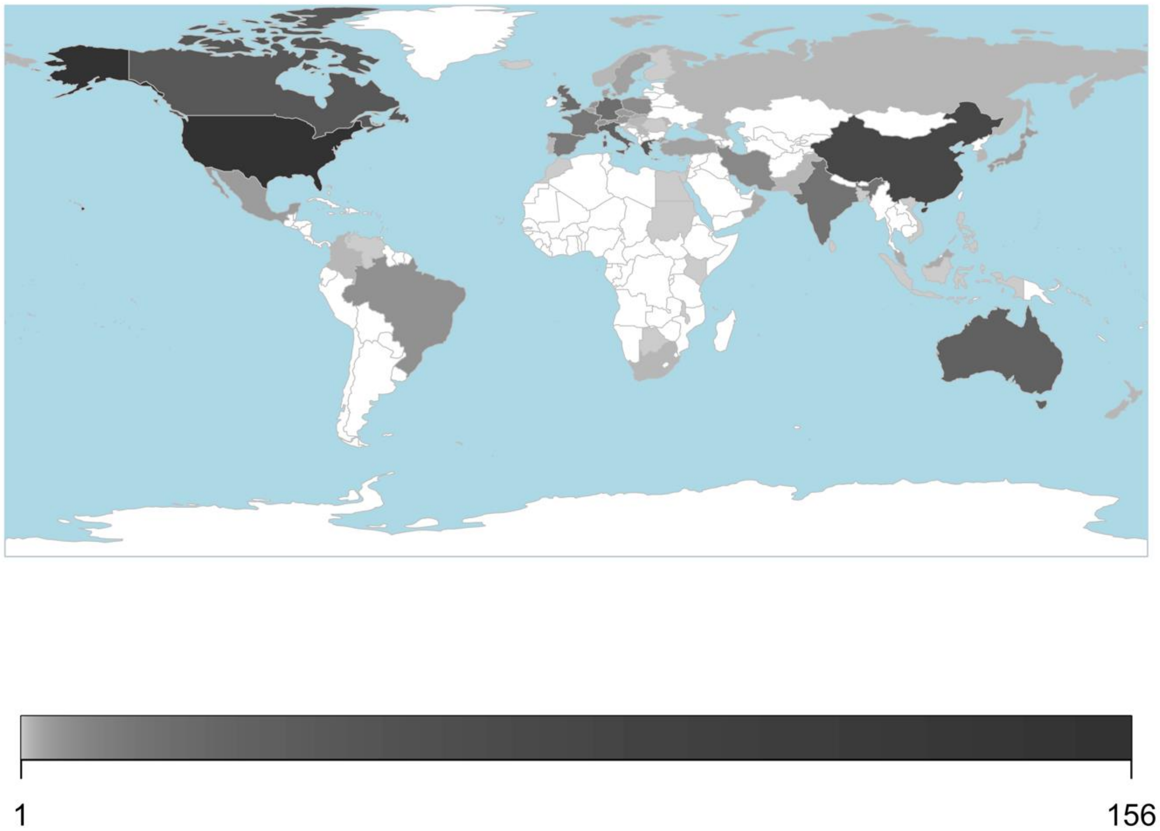

Figure 4. Geographical distribution map of countries' research output in publishing papers on HKd in water resources from 1974 to 2023. The number of articles is represented by colours in grayscale, where white and black mean the minimum and maximum number of articles, respectively. Notice there are countries in white (i.e., without publications) in Latin America, Africa, and Asia.

3.5 Publication Analysis Based on Citations

The 617 documents included in the present bibliometric analysis had 23,582 citations, with an average of 38.22 citations per document (considering all years) and an average of 0.76 citations per document annually. There were 42 (6.81%) documents with no citations, 193 (31.28%) were cited between one and ten times, 123 (19.94%) received between 11 and 20 citations, 130 (21.07%) were cited between 20 and 50 citations, 81 (13.13%) between 50 and 100 citations, and 50 (8.10%) were cited over 100 times. The most relevant authors (in terms of number of published articles) were Koutsoyiannis, D. (n=41); Dimitriadis, P. (n=11); and, Montanari, A. (n=10). Additionally, the most locally cited authors were Koutsoyiannis, D. (n=169); Montanari, A. (n=125); and Klemes, V. (n=61). Local citations are the number of citations a document received from other articles in the analysed database (n=617 articles in total).

The top 20 most cited articles are presented in Table 5. These articles were published in only 2 scientific journals, namely: i) Water Resources Research; and, ii) Journal of Hydrology. Regarding citations, Klemeš (1974) was the most locally cited article, while Hamed (2008) was the most globally cited one. In relative terms, Koutsoyiannis & Montanari (2007) and Hamed (2008) were the most cited documents, locally and globally, respectively.

Table 5. Top 20 most-cited research papers from 1974 to 2023, sorted by the number of citations (Local cited documents)

Rank	Authors	Year	Journal	DOI	LC	LCy	GC	GCy
1st	Klemeš	1974	Water Resources Research	https://doi.org/10.1029/WR010i004p00675	59	1.18	234	4.68
2nd	Koutsoyiannis & Montanari	2007	Water Resources Research	https://doi.org/10.1029/2006WR005592	58	3.41	221	13.00
3rd	Montanari et al.	1997	Water Resources Research	https://doi.org/10.1029/97WR00043	41	1.52	196	7.26
4th	Hamed	2008	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2007.11.009	39	2.44	877	54.81
5th	Koutsoyiannis	2000	Water Resources Research	https://doi.org/10.1029/2000WR900044	26	1.08	115	4.79
6th	Kumar et al.	2009	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2009.06.012	26	1.73	297	19.80
7th	Koutsoyiannis	2006	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2005.09.022	24	1.33	156	8.67
8th	Koscielny-Bunde et al.	2006	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2005.03.004	23	1.28	236	13.11
9th	Potter	1976	Water Resources Research	https://doi.org/10.1029/WR012i005p01047	22	0.46	78	1.63
10th	Mudelsee	2007	Water Resources Research	https://doi.org/10.1029/2006WR005721	22	1.29	84	4.94
11th	Thyer & Kuczera	2003	Journal of Hydrology	https://doi.org/10.1016/S0022-1694(02)00412-2	18	0.86	44	2.10
12th	Sagarika et al.	2014	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2014.05.002	18	1.80	148	14.80
13th	Thyer & Kuczera	2000	Water Resources Research	https://doi.org/10.1029/2000WR900157	17	0.71	70	2.92
14th	Montanari et al.	2000	Water Resources Research	https://doi.org/10.1029/2000WR900012	17	0.71	134	5.58

15th	Thyer & Kuczera	2003	Journal of Hydrology	https://doi.org/10.1016/S0022-1694(02)00411-0	16	0.76	38	1.81
16th	Vogel et al.	1998	Water Resources Research	https://doi.org/10.1029/98WR02523	15	0.58	61	2.35
17th	Salas et al.	1979	Journal of Hydrology	https://doi.org/10.1016/0022-1694(79)90143-4	14	0.31	35	0.78
18th	Eltahir	1996	Water Resources Research	https://doi.org/10.1029/95WR02968	14	0.50	155	5.54
19th	Boes & Salas	1978	Water Resources Research	https://doi.org/10.1029/WR014i001p00135	13	0.28	58	1.26
20th	Khaliq et al.	2009	Journal of Hydrology	https://doi.org/10.1016/j.jhydrol.2009.02.045	13	0.87	104	6.93

Abbreviations: LC, local citations; LC_Y, local citations per year; GC, global citations; GC_Y, global citations per year.

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4. DISCUSSION AND INTERPRETATION OF RESULTS

The results of this study contribute to a better understanding of the state of research on HKd in water resources research. In particular, the last 50 years were analysed, focusing on applications in water resources. Understanding HKd provides insights not only at scientific levels but also for practitioners and policymakers operating in engineering praxis, hydrological modelling, and flood risk management, among others. The implications of HKd are substantial, suggesting that conventional modelling methods, which usually rely on the assumption of independence among observations, might not accurately capture certain natural phenomena. This bibliometric analysis is not intended to be a usually understood review but to extract and analyse critical information from the database investigated. It aligns to give a holistic view of the HKd topic, fostering and paving the path for new readers who do not know where to start (for instance, reading all the papers in Table 6 and Table 6).

Table 6. Top-cited papers with reference to Hurst’s work beyond water resources (adapted from O’Connell et al., 2016). Citations were retrieved from Google Scholar – the 4th of June 2024. Notice that some journal papers in this table were published before 1974 (the starting year of the bibliometric analysis), and they were not found by the search equation.

Field	Reference	DOI	Subject	Citations
Statistics and stochastics	Mandelbrot & Van Ness (1968	https://doi.org/10.1137/1010093	Fractional Brownian motion	10158
	Hosking (1981)	http://dx.doi.org/10.1093/biomet/68.1.165	FARIMA model	4973
Geophysical sciences	Mandelbrot & Wallis (1969)	http://dx.doi.org/10.1029/WR005i002p00321	Geophysical records	1410
	Sadler (1981)	http://dx.doi.org/10.1086/628623	Sediment accumulation rate	1369
Physics	Voss & Clarke (1975)	http://dx.doi.org/10.1038/258317a0	Acoustics	839
	Borland (1998)	http://dx.doi.org/10.1103/PhysRevE.57.6634	Diffusion	413
Economics and finance	Greene & Fielitz (1977)	http://dx.doi.org/10.1016/0304-405X(77)90006-X	Stock market prices	664
	Baillie (1996)	http://dx.doi.org/10.1016/0304-4076(95)01732-1	Econometrics	2651
Medical sciences	Ellaway (1978)	http://dx.doi.org/10.1016/0013-4694(78)90017-2	Neurophysiology	528
	Kobayashi & Musha (1982)	http://dx.doi.org/10.1109/TBME.1982.324972	Heartbeat period	1026
Biology	Peng et al. (1992)	http://dx.doi.org/10.1038/356168a0	Nucleotide sequences	1809
	Arneodo et al. (1996)	http://dx.doi.org/10.1016/016	DNA sequences	223

		7-2789(96)00029-2		
Information sciences	Leland et al. (1994)	http://dx.doi.org/10.1109/90.282603	Ethernet traffic	8336
	Frost & Melamed (1994)	https://doi.org/10.1109/35.267444	Traffic in telecommunication networks	1025
Climate science	Koutsoyiannis (2003)	http://dx.doi.org/10.1623/hysj.48.1.3.43481	Climatic variability	500
	Cohn & Lins (2005)	http://dx.doi.org/10.1029/2005GL024476	Trends in climate	454

In terms of research outputs, this bibliometric analysis revealed an increasing trend up to 2018. After that year, the number of published papers was decreasing. The latter is probably due to the COVID-19 outbreak's impacts on researchers and the population worldwide (see, e.g., Riccaboni & Verginer (2022), whose findings established a dropping trend for research outputs in unrelated medical subject papers). Another possible explanation might be that in the past decades, the research focus in the hydrologic literature has progressively shifted towards the identification of trends under nonstationarity, i.e. adopting a deterministic perspective on natural variability and seeking to identify deterministic signals of change (cf. Appendix I in Iliopoulou & Koutsoyiannis, 2020, and relevant discussion). Additionally, machine learning (and also other) methodologies to capture LRD might have attracted the attention of researchers recently (see, e.g., (Rozos et al., 2021)).

Thematic evolution through time can be helpful in identifying the past, present, and future of stochastics in water resources. Figure 5 shows four different periods: a) from 1974 to 2003 (i.e., the first 30 years); b) from 2004 to 2010; c) from 2011 to 2017; and, d) from 2018 to 2023. Grey bands connect the research topics, expressing how those topics relate through time. Interestingly, "groundwater" has been a topic for several decades, while there has been a line of thought from "climate change" to "climate variability" (passing through "change" and "climate change" again). We hypothesise that this line of thought will be intensified in the future, changing the paradigm from climate change to climate variability.

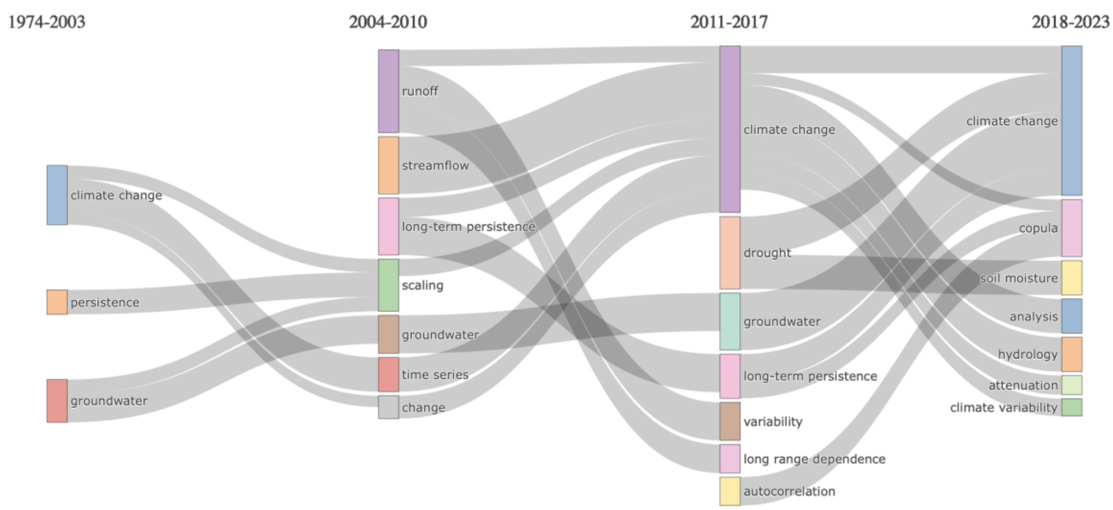

Figure 5. Thematic evolution of HKd in water resources. 50 years of analysis through the author's keywords. Connecting keywords are determined through the inclusion index weighted by word occurrences and the walktrap clustering algorithm (minimum cluster frequency per thousand docs = 14; minimum weight index = 0.1).

Zooming in on the last two decades and in terms of trending topics, Figure 6 shows different authors' keywords with their boxplots (ranging in years). The location of the dots represents the median, and the dot's size is the number of times the keyword in question has been used in different documents. Interestingly, there is a visible pattern – of research interests as a function of hydroclimatic variables – of migration from "groundwater" to "streamflow" to "soil moisture" to "precipitation". Current research is more focused on "droughts", "trend analysis", and "stochastic models". "Groundwater", "forecasting", and "time-series analyses" have been persistent through almost the entire analysed period.

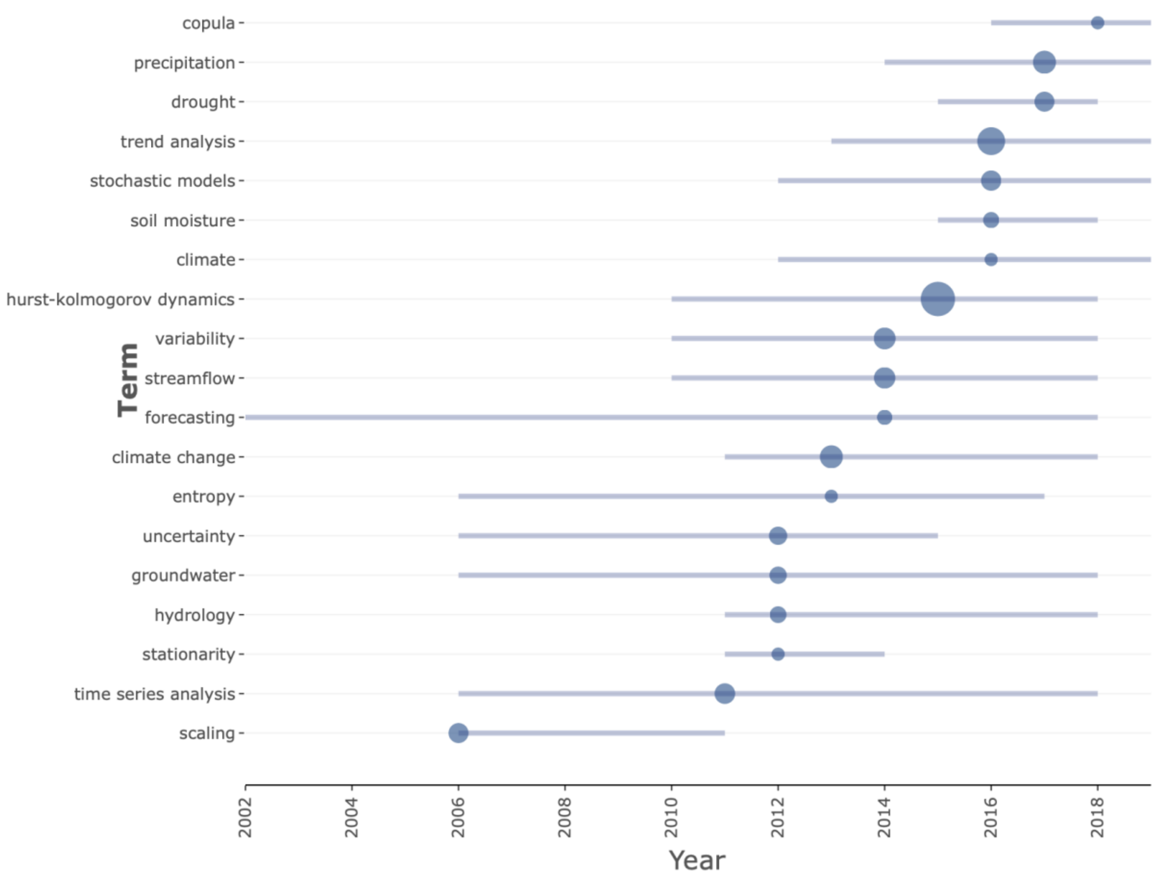

Figure 6. Trending topic author's keywords for the last 20 years. The dots' location is the median of values (years), and the size represents the frequency of used terms.

5. STRENGTHS AND LIMITATIONS

This bibliometric analysis covers the last 50 years of HKd in water resources. Even though the adopted methodology was robust, replicable, and reproducible; there is room for improvement. The following list covers some of them:

a) Database: expanding the source data from WoS to Scopus and other databases with the intention of retrieving the maximum number of articles (even though many of them will be duplicates);
b) Search equation: Sensitivity analysis of the search equation will ensure a comprehensive literature capture alongside possible facets of HKd research;
c) Data pre-processing: Revision of inclusion and exclusion criteria (e.g., period of analysis, language of articles, among others);
d) From bibliometric analysis to a formal systematic review and metanalysis: This bibliometric analysis guides new readers through a first step into HKd research, analysing key aspects from literature. Nevertheless, a formal systematic review will further extract critical information from each article, opening avenues for an HKd research metanalysis.

Currently, progress in HKd needs to be documented to identify the strengths and limitations of methods in different contexts and transfer them to other variables of interest. Establishing standardised approaches represents the critical goal for future developments and collaborative networks.

6. CONCLUSIONS

This bibliometric analysis offers a comprehensive overview of the past, present, and future of the HKd research trends in water resources. The study reveals several key findings:

- **Publications' Growth**: The field has experienced a monotonically increasing growth (up to 2018) with a significant increase in publications. The maximum number of published papers was 55 in 2018. From that year to the present, a decreasing trend has been observed. We hypothesise that this trend is going to be maintained for the near future due to relevant researchers in a transition phase of their lives (e.g., retirement), the global impact of the COVID-19 pandemic, an increasing interest of researchers towards identifying trends under nonstationarity, and trendy methodologies such as machine learning related ones.
- **Global Collaboration**: Researchers from diverse countries actively contribute to this interdisciplinary field. In general terms, the USA, China, Canada, and Greece were the most productive countries, accumulating around half of the total production. Additionally, many countries in Latin America, Africa, and Asia have had zero publications, implying that no research on HKd in water resources is

available. We hypothesise that the latter is due to the lack of accessibility to long time series.

- **Journal Information**: High-impact journals in water resources and geosciences are the primary outlets for HKd research. Only two journals covered the 20 most relevant publications: i) Water Resources Research; and, ii) Journal of Hydrology.
- **Authors**: authors with significant contributions to HKd research from various countries have contributed significantly to this research area, often through multi-authored publications.
- **Citation Impact**: Certain papers have garnered substantial attention and citations, emphasising the field's relevance and impact. Table 5 shows the top 20 most-cited research papers from 1974 to 2023. Klemeš (1974) was the most locally cited article, while Hamed (2008) was the most globally cited one. Additionally, Table 6 shows the top-cited papers with reference to Hurst's work beyond water resources (adapted from O'Connell et al., 2016).
- **Keyword Themes**: Analysing the last 50 years of research revealed a clear pattern of migration of research topics through time. Interest moved from "groundwater" to "streamflow" to "soil moisture" to "precipitation" from the past to the present.

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DATA AND RESULTS AVAILABILITY STATEMENT

The data used in this study, as well as the findings, are available in the following link: http://doi.org/10.17605/OSF.IO/45V3W

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