frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 17 April 2025
DOI 10.3389/frwa.2025.1376943

OPEN ACCESS

EDITED BY
Pablo Garcia-Chevesich,
Colorado School of Mines, United States

REVIEWED BY
Chicgoua Noubactep,
University of Göttingen, Germany
Naushita Sharma,
Oak Ridge National Laboratory (DOE),
United States

*CORRESPONDENCE
Gbenga Abayomi Afuye
✉ afuyeabayomi@gmail.com

RECEIVED 26 January 2024
ACCEPTED 17 March 2025
PUBLISHED 17 April 2025

CITATION
Kalumba AM, Afuye GA, Mazinyo SP, Zhou L, Adom RK, Simatele MD and Das DK (2025) Spatial assessment of climate change, water resource management, adaptation and governance in South Africa. *Front. Water* 7:1376943. doi: 10.3389/frwa.2025.1376943

Spatial assessment of climate change, water resource management, adaptation and governance in South Africa

Ahmed Mukalazi Kalumba[1,2], Gbenga Abayomi Afuye[1,2]*, Sonwabo Perez Mazinyo[1], Leocadia Zhou[3], Richard Kwame Adom[4], Mulala Danny Simatele[5] and Dillip Kumar Das[6]

[1]Department of Geography and Environmental Science, University of Fort Hare, Alice, South Africa, [2]Geospatial Application, Climate Change and Environmental Sustainability Lab–GACCES, University of Fort Hare, Alice, South Africa, [3]Risk and Vulnerability Science Centre, University of Fort Hare, Alice, South Africa, [4]School of Geography, Archaeology and Environmental Studies, University of Witwatersrand, Johannesburg, South Africa, [5]The Global Change Institute, University of Witwatersrand, Johannesburg, South Africa, [6]School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban, South Africa

The study explored the intellectual domain of climate change, water resource management, adaptation, and governance (CCWRM_AG), identifying research hotspots, and proposing solutions to address water scarcity and environmental impacts in South Africa. In total, 1,117 original published studies in BibTeX format were obtained using Web of Science and Scopus databases from 1997 to 2022. The data analyzed on CCWRM_AG includes top-cited articles and the distribution of author keywords, most-cited journals, word cloud, thematic evolution and top author affiliations. The National Integrated Water Information System (NIWIS) database was utilized to monitor and assess the potential for water shortages in South Africa. The study employed geobibliometrics, an integrated approach that combines bibliometric analysis and remote sensing data, to evaluate research trends and monitor dam water levels. The CCWRM_AG field in South Africa is experiencing an 18.98% annual growth in citations per article, with the University of Kwazulu-Natal and the University of Cape Town ranking first with the highest total number of published top articles, indicating their significant influence and associated research centers. Based on the top keyword, climate change and water resource scarcity are central to issues related to drought and water shortage, indicating a hint of the relatedness for further studies. The spatial analysis reveals severe water shortages in the Western Cape province, adversely affecting water quality, agriculture, and livelihoods due to critically low dam levels. The Northern Cape faces water scarcity in its arid lands, while other provinces show relatively stable water availability. The findings of this study can enhance the multifaceted approach that integrates robust water governance infrastructure, regulatory policies, and economic incentives to mitigate water scarcity and environmental impacts.

KEYWORDS

climate change adaptation, institutional water governance, water policy, water resource management, water scarcity

1 Introduction

The global climate change scenario is significantly increasing water scarcity, leading to a high ratio of water scarcity (UNESCO, 2021; Bianucci et al., 2024). Water resources are a crucial environmental component and a valuable natural resource for agricultural, industrial, and domestic purposes (Afuye et al., 2018; Yildiz et al., 2022). Climate change is predicted to disrupt global hydrological systems, increase water cycle variability, reduce availability, and threaten sustainable development, affecting vulnerable communities through land-use change, soil health issues, biodiversity loss, and environmental degradation (Leal Filho et al., 2022; Afuye et al., 2024a). The Global Climate Model (GCM) and Regional Climate Models (RCM) predict a continued rise in global temperatures, leading to increased wetter and drier regions, thereby worsening various disasters such as droughts, floods, heat waves, and storms (Huang et al., 2022; Fabian et al., 2023; Sibandze et al., 2024). The European Union is implementing an agent-based model to manage water resource conflicts, with the African Ministers Council on Water (AMCOW) overseeing the Pan-African Groundwater Program (APAGroP), aiming to promote sustainable groundwater use and improve African lives (Ozano et al., 2022; Thamaga et al., 2024). Certain regions experience increased droughts, leading to a significant reduction in vegetation health, subsequently impacting people's health and productivity (Chatanga and Seleteng-Kose, 2021; Afuye et al., 2022; Mbuqwa et al., 2024). Reports show agriculture uses 72% of water withdrawals, 16% used by households and services, and 12% by industries, with 2.3 billion people in water-stressed counties and 733 million in extremely high-water vulnerability (FAO, 2020). Human activities and population growth in developing nations are causing water shortages, especially for lower-income populations, due to decreased groundwater levels, deteriorating water quality, and increasing commercial and agricultural demand (Ozano et al., 2022; Izah et al., 2024).

South Africa is among other developed countries implementing initiatives to sustain water resources across various sectors, promoting a broader implementation of water resource management for sustainable development (García et al., 2016; Sheffield et al., 2018). The South African Government's National Water Resource Strategies (NWRS) for 2003, 2013, and 2020, under the National Water Act (NWA) of 1998, gained significance in 1998 with incorporation the of critical components (Pahl-Wostl, 2019). However, the NWA prioritizes water as a public resource, ensuring two components of Basic Human Needs Reserve and Ecological Reserve, through legally established priority allocation for water policy and governance regime (Makaya et al., 2020). The Reserve's inclusion in South Africa's NWA has made strides in improving water management and addressing past injustices, but lacks preparedness for future climate and resource challenges, (Pahl-Wostl, 2019; Adom and Simatele, 2021), highlighting the need for further adaptation and sustainable practices amid rising water scarcity and drought conditions. The 2020 NWRS in South Africa lacks integrated strategies for strengthening water governance, infrastructure, incentives, and policies to mitigate climate and environmental impacts, despite increasing awareness of climate change impacts on water resources management (Pahl-Wostl, 2019; Edokpayi et al., 2020; Mathetsa et al., 2022). South Africa's water resource management, adaptation, and governance are understudied, primarily focusing on adaptation and socio-economic development (Meissner and Meissner, 2017; Makaya et al., 2020; Mathetsa et al., 2022; Shiriyedete et al., 2024), despite their crucial role in promoting sustainability and water quality. For instance, Siphambe et al. (2024a) argue that conventional Integrated Water Resources Management (IWRM) overlooks water mass balance, where total rainfall is 100% available water. They emphasize that true IWRM requires rainwater harvesting and that conventional IWRM, like low-impact development strategies like sponge cities, focuses on managing stormwater rather than directing it to rivers. In contrast, Siphambe et al., 2024b advocate for the complete prohibition of stormwater generation, promoting the concept of "zero runoff" as the most effective solution to mitigate climate change. Moreover, South Africa's adoption of IWRM, while aligning with global best practices faces challenges like resource limitations, governance, and climate resilience (Eslamian et al., 2017; Awuah, 2020), necessitating effective implementation to overcome these obstacles. The semi-arid region, with an average annual rainfall of 500 mm, is a water-stress region with less than 200 mm and 500 mm rainfall, respectively, and low rainfall levels in the interior and western areas, accounting for 60% of the global average (Du Preez and Van Huyssteen, 2020; Strauss et al., 2021). Seasonal rainfall variability impacts natural water sources, causing low stream flow, increased run-off, and evaporation rates, posing threats to various economic sectors, including agriculture, fishing, and tourism (Munyai et al., 2021), while achieving "zero runoff" is a solution (Siphambe et al., 2024b).

South Africa is facing severe water scarcity due to climate change, resulting in temperature changes, wind patterns, decreased precipitation, soil moisture, and wildfires, with limited research on water governance implementation (Makaya et al., 2020; Olabanji et al., 2020; Du Preez and Van Huyssteen, 2020; Shinga et al., 2024). The severe water crises are exacerbated by a semi-arid climate, urbanization, and poor water management, limiting rural community resilience, and causing significant environmental damage and water-related issues (Tapela, 2015; Du Plessis and Du Plessis, 2017; Shiriyedete et al., 2024; Thakur, 2024). As such, effective water management strategies are crucial for efficient national and local resource management, ensuring a better understanding of the spatial distribution and impacts of water shortage risk. This study examines the intricate link between climate change, water resource management, adaptation, and governance (CCWRM_AG) studies to address water stress, analyzing top-cited articles, author keywords, most cited journals, word cloud, thematic evolution, and top author affiliations. The study used bibliometric and spatially based information assessment for statistical data visualization and mapping (Zyoud and Zyoud, 2021; Idris et al., 2022), enhancing comprehension of interconnected studies within the research domain. However, other statistical, mathematical, and geospatial data mapping techniques were used to enhance the robustness and accuracy of this study. The National Integrated Water Information System (NIWIS) database was utilized to monitor and assess the potential for water shortages in South Africa (Sambo et al., 2015). Hence, this study aimed to assess CCWRM_AG studies in South Africa, identifying research hotspots and proposing solutions to address water scarcity and environmental impacts. To the best of our knowledge, this is the first of its kind in South Africa to systematically evaluate CCWRM_AG research, mapping existing studies, identifying research gaps, and providing

practical recommendations to enhance sustainable water management in the agricultural sector. This study seeks to answer two specific objectives: (i) to assess the evolution of dominant themes that significantly contribute to the intellectual domain of CCWRM_AG research and future direction. (ii) to analyze the spatial distribution of water shortage risk and its impacts, considering the region's transitional attributes. This study identifies research gaps in CCWRM_AG studies, which are crucial for assessing and managing regional water scarcity in drought-prone areas, enhancing adaptive management and climate policy intervention.

2 Materials and methods

2.1 Study area

South Africa is an emerging country situated between 30.5595° S and 22.9375° E, with an elevation of 3,367 m (11,047 ft) above sea level and a population of 60,604,992 as shown in Figure 1 (StatsSSA, 2021). It covers 1,221,037 km^2 (471,445 sq. mi) and has 2,798 km of coastline along the South Atlantic and Indian Oceans (Sanbi, 2020). The country is bordered by Namibia, Botswana, Zimbabwe, Mozambique, Eswatini, and Lesotho. It comprises nine provinces, including the Western Cape, Northern Cape, Northwest, Free State, Gauteng, Limpopo, Mpumalanga, KwaZulu-Natal, and the Eastern Cape Province (Forssman, 2022). South Africa's climate is divided into three zones: arid (desert), subtropical wet (humid and dry winters), and subtropical dry (hot summers) regions. South Africa experiences average monthly temperatures ranging from 22°C to 11°C, with an annual precipitation of 469.9 mm, with the wettest months being November through March and the least rainfall months June through August (Mbokodo et al., 2023). The region's climate varies, with the eastern part experiencing a subtropical wet climate with mild winters and high humidity, and the northern part experiencing a subtropical dry climate with warm summers (Mahlalela et al., 2020).

2.2 Data identification, methodology and validation

The study employed geobibliometrics, an integrated approach that combines bibliometric analysis and remote sensing data, to evaluate research trends and monitor dam water levels (Zyoud and Zyoud, 2021; Idris et al., 2022), enhancing understanding of interconnected studies in the niche area. This study used keywords: ("Climate Change AND Water Resource Management") OR TITLE ("Water Scarcity") OR TITLE ("Climate Change Adaptation") OR TITLE ("Water Governance") OR ("Water Policy") OR TITLE ("Institutional Water Governance") AND PUBYEAR >1997 AND PUBYEAR <2022 in the titles, abstracts, and keywords (author keywords and keywords plus) of the articles published between January 1997 and December 2022 (Figure 2). In addition, the retrieved articles were country-specific, specifically South Africa, encompassing articles, proceeding papers, review articles, book chapters, editorial materials, and book reviews and books written in English language. Literature indicates that using a specific topic and title in a database search ensures minimal loss, significant recovery, and increased sensitivity compared to other searches (Afuye et al., 2021b; Serame and Afuye, 2024). This study obtained published research articles on CCWRM_AG studies from

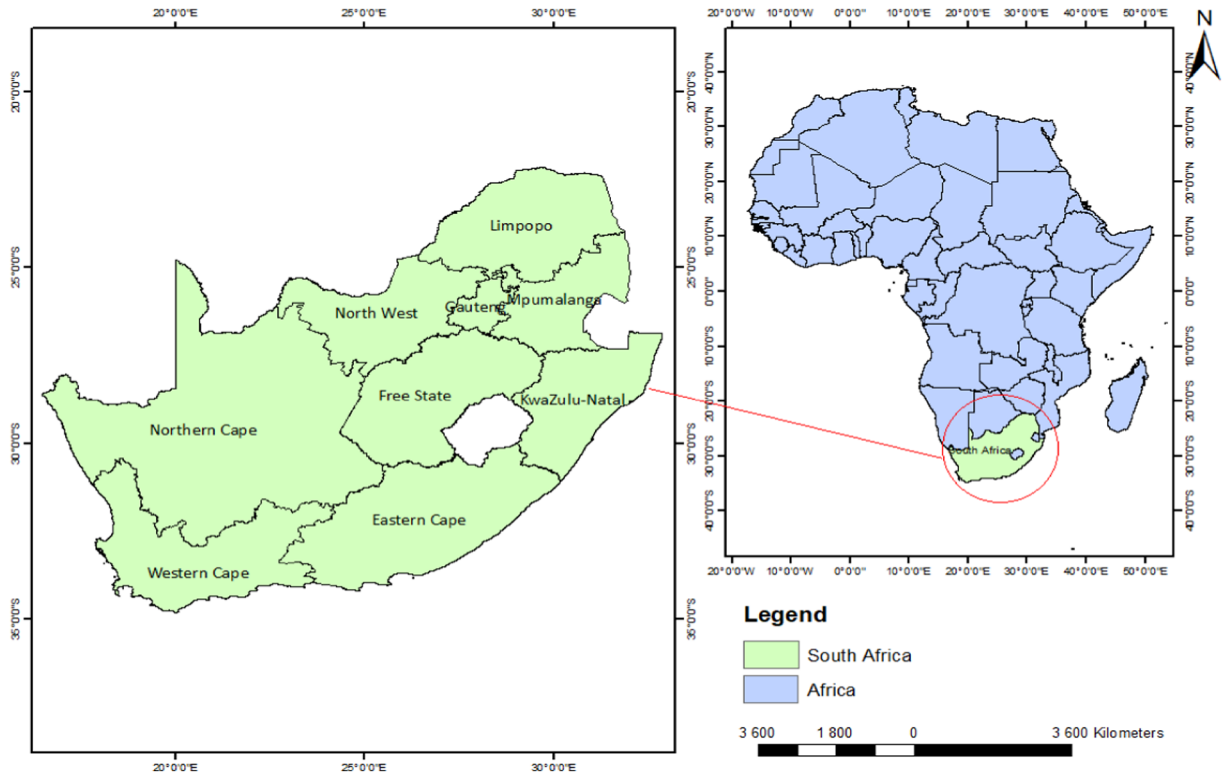


FIGURE 1
Map showing the different provinces in South Africa.

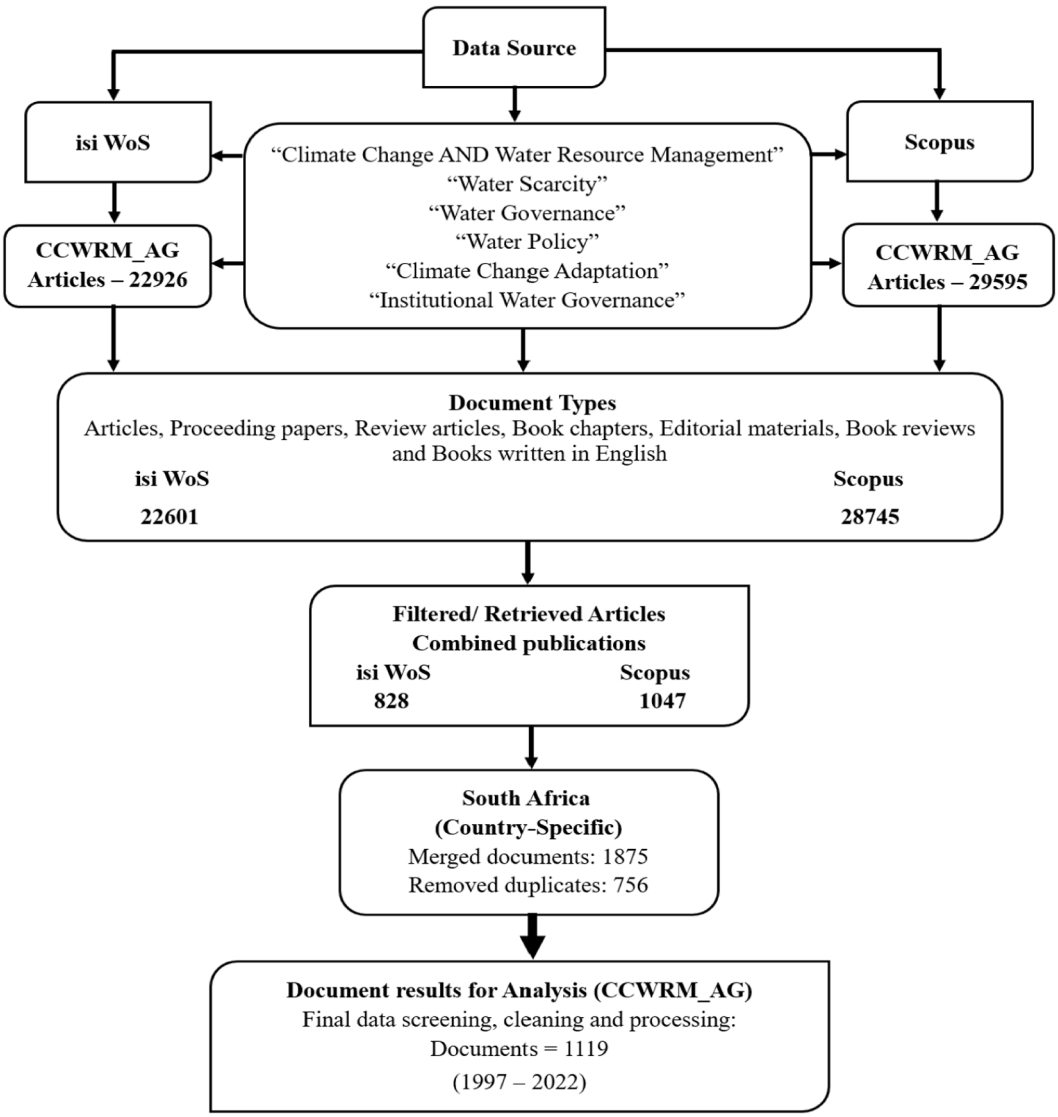


FIGURE 2
Graphical representation showing the criteria for publication selection.

Scopus and Web of Science (WOS) databases on March 19, 2023. These databases were chosen for their reliable research coverage, efficiency, and high-impact scientific research due to their reliability and impact (Visser et al., 2021; Nduku et al., 2023). Furthermore, the National Integrated Water Information System (NIWIS) database was utilized to monitor and assess South Africa's dam water levels and trends from 2018 to 2022.[1] The dataset is a crucial tool for monitoring and assessing water-related issues, highlighting the need to raise awareness about water scarcity and develop mitigation strategies (Sambo et al., 2015). The search results were filtered from original articles and reviews to eliminate non-traceable papers, remove duplicates and irrelevant documents, and reduce the vocabulary dimension through data screening, cleaning, and processing (Gagolewski, 2011). Zotero software v6.0.7 and Citation analysis package (CITAN) in the R repository were used to filter non-informative words and gather all retrieved published documents (Busayo et al., 2020; Nduku et al., 2021). The chosen variables are often considered to make a distinctive contribution to the existing knowledge (Orimoloye et al., 2021; Afuye et al., 2024a). Figure 2 shows a graphical representation of the criteria for publication selection.

2.3 Data collection and analysis

The study analyzed 1,119 BibTeX original articles, assessing author information, titles, citations, keywords, journal citation trends, and institutional collaboration, among other data. The articles are region-specific, representing CCWRM_AG publications conducted within South Africa, as they are geographically selected within the country, referring to a single nation (Bonilla et al., 2015; Qureshi et al., 2020). Open-source software like bibliometrix R-package (Rstudio v4.0.4) and

1 https://www.dws.gov.za/niwis2

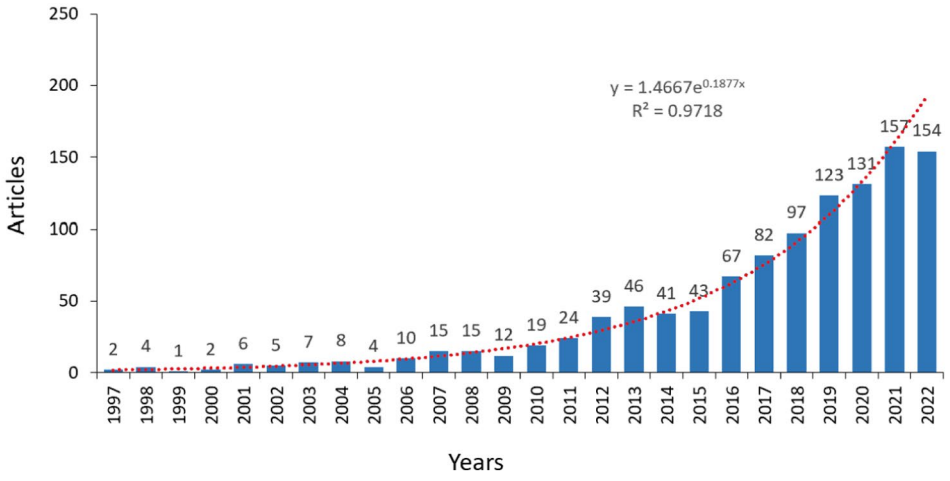


FIGURE 3
Annual scientific production on CCWRM_AG studies in South Africa.

biblioshiny software (v1.6.16) offer tools and an interactive bibliometric web interface for bibliometric analysis (Aria and Cuccurullo, 2017). The data was imported into the R environment, translated into a bibliographic data frame, and structured for duplication, limiting duplicated articles to one record (Gusenbauer and Haddaway, 2020). The spelling errors, variant names, and associations in each collection were thoroughly reviewed and checked for any potential issues. A density visualization map for top author's names, keywords, citations, and keyword-plus was retrieved using a built-in formula on the R package repository. The annual research on CCWRM_AG from 1997 to 2022 was analyzed for keywords and keyword-plus phrases, presenting a two-category collection, as depicted in Figure 3. The average growth rate, the difference between the previous and current year, and the number of publications in annual scientific production growth were evaluated. From 2016 to 2022, South Africa's exceptional research output demonstrates its strong support for research capabilities, with local affiliations actively participating in the niche area. The availability of research grants could have increased the productivity of CCWRM_AG studies, facilitated the expansion of funding initiatives, attracted top scholars, and supported other developing institutions (Saygitov, 2018). The high research output from top universities suggests effective funding for research capacity, potentially increasing productivity and motivation. Nevertheless, this connotes a possible link between increased funding from co-authors' nationality or the organization's domicile and research centers.

3 Results

3.1 Analysis of top-cited articles

The study analyzed 1,119 articles from Scopus and WOS databases, presenting the annual scientific output of CCWRM_AG research over time, as shown in Figure 3. The review reveals an annual growth rate of 18.98%, indicating an increase in the research horizons of CCWRM_AG over time. From 1997 to 2015, CCWRM_AG studies experienced a decline in scientific production, except for 2012 and 2013, possibly due to factors impacting the field's scientific output. For instance, the keywords used in studies on CCWRM_AG have their origins, with synonyms and alternatives used such as "Water Scarcity," "Climate Change AND Water Resource Management," "Water Policy," "Climate Change Adaptation," "Water Governance" and "Institutional Water Governance" became the standard phrases. Recent studies on the human dimensions of climate change, sustainable water resource use, and societal awareness have been influenced by climate change response policies and adaptation to water management (Aznar-Sánchez et al., 2018; Madondo and Nkwana, 2021). From 2016 to 2021, CCWRM_AG studies experienced exponential growth, with more researchers publishing in niche areas, but related journals were not producing as much as expected. South Africa reached its highest number of publications in CCWRM_AG in 2021, a significant peak in the research field, reflecting the region's progressively increasing publications between 2020 and 2021 (Figure 3). Consequently, the CCWRM_AG studies experienced significant growth in 2021, but progress decreased in 2022 possibly due to increased research on climate change influences, including rising greenhouse gas concentrations.

South Africa is enhancing its water management and control capacity to ensure sustainable and equitable use for humanity, addressing water scarcity and streamlining the water sector for equitable use (Meissner and Funke, 2014; Eslamian et al., 2017). The shifts have prioritized climate change adaptation and sustainable development, requiring data-driven research and policy priorities for communal and government stakeholders. Therefore, the responsibility to adapt lies with multiple stakeholders at different societal levels, requiring collaborative engagement to ensure the success of the adaptation process. The impacts of climate change on water resources necessitate collective action from government, industries, communities, and individuals to ensure the sustainability and resilience of water systems. The European Union Assembly and the United Nations are collaborating to tackle water shortages globally and regionally (Booth et al., 2020), thereby enhancing water efficiency and contributing to the observed growth trend. The temporal growth in scholarly output since 1997 ($y = 1.4667e^{0.19x}$), is depicted by publications on CCWRM_AG as shown in Figure 3. The Intergovernmental Panel on Climate Change (IPCC) predicts a significant increase in temperatures and sea levels, potentially leading to severe food and water shortages, droughts, and significant human migration in coastal areas by 2050 (Chao and Feng, 2018). The scholarly interest in CCWRM_AG studies surged in 2021

and 2022 due to projections about water scarcity, droughts, and storm's potential impacts on water resource management and sustainability (Al-Hemoud et al., 2020).

Table 1 provides a comprehensive overview of 1,119 articles, 123 book chapters, 769 articles, 38 conference papers, 7 editorials, 118 review papers, 525 journal sources, and 13 books assessed. The publication developments on CCWRM_AG research have been strengthened by 2,965 author appearances, 6.89 articles per author, 3.87 authors per document, and 5.719 co-authors per document. 183 single-authored and 123 multi-authored authors, with a collaboration index of 5.719, were involved in all appraised articles. The study, involving 183 single-authored and 123 multi-authored authors, revealed that CCWRM_AG studies have experienced a significant increase in monitoring and assessment, with an average annual growth rate of 18.98% and citation rate of 17.71% from 1997 to 2022.

Figure 4 shows the author's keyword usage from 1997 to 2022, revealing peak and fall trends based on hot topics, and providing a comprehensive overview of their dynamic keyword usage patterns. The most frequently used keywords after 2003 show a consistent increase in terms of climate change, South Africa, water scarcity, and adaptation. In 2022, there was a significant rise in climate change research, with 342 published articles, largely due to ongoing discussions on global impacts on water resources and agriculture (Fróna et al., 2019). Since 2015, climate change and agriculture have become the most prominent topics in the study field, indicating a significant increase in discourse on this subject. The United Nations has recorded 2023 as the second warmest year on record, tied with 2022, largely due to high global temperatures (United Nations, 2023; Kaba, 2024), potentially impacting early studies on CCWRM_AG in regions like South Africa.

The keywords related to South Africa are used in an Overarching Implementation Plan and Strategic Framework for CCWRM_AG studies, aiming to enhance sectoral synergies and coordinate adaptation efforts at all levels (Adom et al., 2022). Consequently, this study highlights the growth trend in water, climate change adaptation, food security, governance, adaptive management, Africa, and water resources between 2005 and 2009 as mankind seeks a sustainable economy. The 2015 and 2016 drought in South Africa significantly impacted the hydrological cycle, leading to a surge in topics such as resilience, sustainability, vulnerability, water governance, and water policy (Meza et al., 2021). After 2016, research on climate change-induced water scarcity and drought in the country has been accelerated due to this development. More research should focus on key terms to identify significant, recent, and future issues in the niche area of nature-based solutions (NBS) for climate change adaptation, defining recent and future challenges. Consequently, the keyword terms reveal the relationship between the co-word network and high-frequency author's keywords, aiding in understanding the topics and themes covered by the CCWRM_AG research area.

TABLE 1 Focal information about data retrieved from CCWRM_AG studies in South Africa.

Documents	Time-period
Timespan	1997–2022
Sources (Journals, Review Articles, Books, etc.)	525
Documents	1,119
Annual growth rate %	18.98
Document average age	6.89
Average citations per document	17.71
References	56,631
Document contents	
Keywords plus (ID)	4,181
Author's keywords (DE)	2,827
Authors	
Authors appearances	2,965
Authors of multiple-authored documents	123
Authors collaboration	
Single-authored documents	183
Co-authors per document	3.87
International co-authorships %	5.719
Document types	
Article	769
Article, book chapter	20
Article, early access	5
Article, publication with expression of concern	1
Book	13
Book chapter	123
Conference paper	38
Data paper	2
Editorial	7
Editorial material	1
Editorial material, book chapter	5
Letter	1
Meeting abstract	1
Note	3
Proceeding paper	6
Retracted	1
Review	118
Review, book chapter	1
Short survey	4

3.2 The distribution of top author's keywords and most cited journals

Table 2 shows the annual topmost cited articles and total citations in the CCWRM_AG research field, indicating growth trends in citations over the years. The influence of an author in a specific research field is typically measured by the average total citations per year and the number of publications in that field. The annual growth trend of citations and publications by academic scholars indicates their research strength and the quality of their research output (Wang et al., 2018). The annual citation trends in CCWRM_AG show a peak in 2011 and 2015, followed by a high peak in 2014, and a decline in 1998, 2021, and 2022, indicating a significantly low average article citation in the field (Figure 3). From 1997 to 2005, South Africa experienced a significant shortage of water resource management and climate change publications, with four without citations in 1998 due

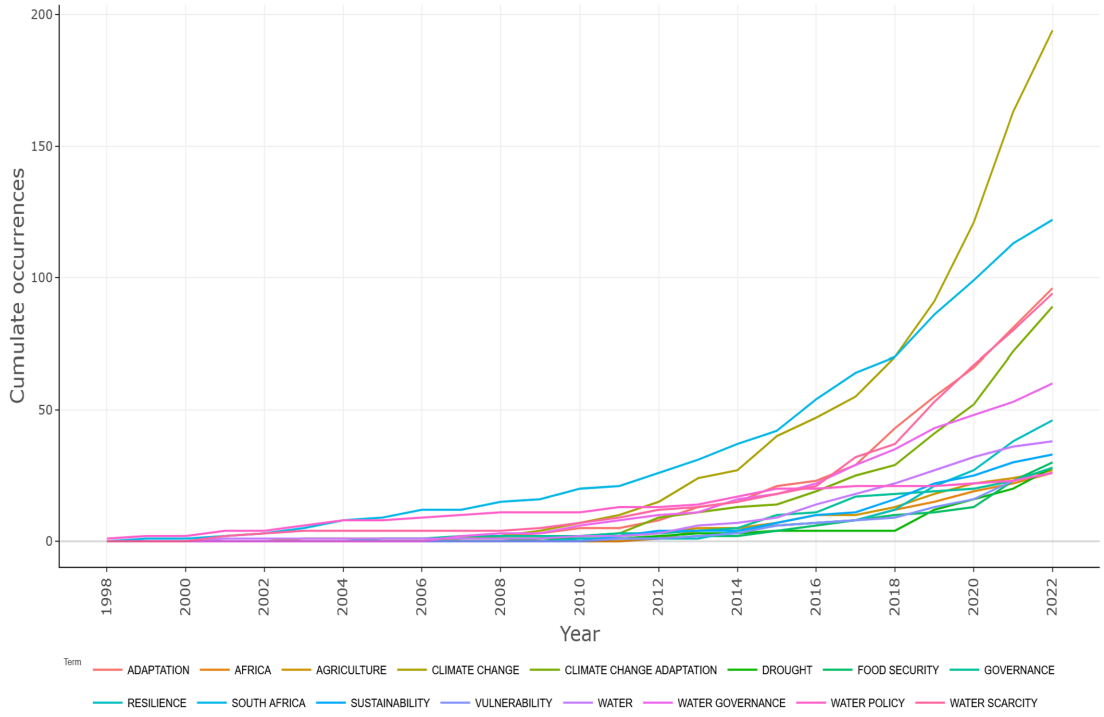


FIGURE 4
Dynamic trends of hot topics on CCWRM_AG studies in South Africa.

to early studies. This trend persisted from 1998 to 2005, highlighting the need for further research and citations in these areas. The overall article citation trend fluctuated between 2006, 2010, 2016, and 2017, with multiple average citations per article, indicating a fluctuating trend that continued to grow and fluctuate over the years. The decline in average citations per article indicates a potential instability in the research field in terms of total citations per article (Ellegaard and Wallin, 2015). Between 2010 and 2011, article citations experienced a swift increase, with an average of 31.11 and 43.08 per article respectively, indicating a rapid and substantial increase (Table 2). Between 2014 and 2015, the highest growth in top-cited articles was observed, with the highest average citations per article being 48.51 and 45.74, respectively, during the survey period.

Figure 5 shows the top 10 most cited journals on CCWRM_AG studies in South Africa. The study ranked 525 journals based on the number of most cited articles and their start year of publication on CCWRM_AG studies during the survey period. In 2022, Water SA surfaced in the top list of journals accounting for (n = 37) followed by Sustainability (32), Physical and Chemistry of the Earth (n = 28), Water Policy (n = 24), and JAMBA: Journal of Disaster Risk Studies (n = 23). Notably, the Water SA journal ranked highest with 3.32% of articles, indicating a wide distribution of research scholarship across various fields in large journals (Zyoud and Fuchs-Hanusch, 2017). In essence, Water SA's high citation rate and impact factor in CCWRM_AG studies demonstrate the quality and applicability of its published articles, indicating their potential for global audience and relevance in the field. CCWRM_AG is recognized for its top-cited articles in various fields such as climate change, water resource management, water scarcity, water policy, remotely sensed water stress, institutional water governance, water sustainability, and hydrological droughts among others.

3.3 Analysis of top authors keywords, word cloud, and thematic evolution

Table 3 shows the top 20 most relevant keywords in the field of CCWRM_AG during the survey period. Author keywords include climate change (n = 194), South Africa (n = 123), adaptation (n = 96), water scarcity (n = 94), climate change adaptation (n = 89), water governance (n = 60), resilience (n = 46), water (n = 39), sustainability (n = 33), and food security (n = 30) among others. The analysis of keywords underscores the significance of addressing climate change, water scarcity, and sustainability in the context of CCWRM_AG studies, emphasizing the need for effective solutions for achieving sustainable development. The study identified significant author keywords and keyword-plus such as "climate change" in 194 (17.3%) and 353 (31.5%), "South Africa" in 123 (11.0%) and 303 (27.1%), "water management" in 21 (1.9%) and 243 (21.7%). Additionally, "Africa" was identified in 26 (2.3%) and 85 (7.6%), "Agriculture" in 27 (2.4%) and 76 (6.8%), "water scarcity" in 94 (8.4%) and 68 (6.1%), "drought" in 28 (2.5%) and 58 (5.2%), "sustainability" in 33 (3.0%) and 53 (4.7%) and "water" in 39 (3.5%) and 51 (1.6%) respectively. The results indicate that CCWRM_AG studies consistently identify climate-related risks, highlighting the process influenced by climate change events, extreme weather events, and variables. CCWRM_AG research hotspots focus on key aspects of water resource management, including water footprint, adaptive management, decision-making, irrigation, and climate change adaptation, which have been utilized in this field over time. The major approaches for data collection and integrating policy, program, and practice are water conservation, sustainable development, and governance, which are essential for promoting sustainable development and governance. Nevertheless,

TABLE 2 Annual top 20 most cited articles and total citations per year in CCWRM_AG research.

Year	NC	Mean TC per article	Mean TC per year	Citable years
1997	2	9.50	0.34	28
1998	4	0.00	0.00	27
1999	1	20.00	0.77	26
2000	2	15.00	0.60	25
2001	6	7.83	0.33	24
2002	5	21.00	0.91	23
2003	7	15.29	0.70	22
2004	8	32.62	1.60	21
2005	4	14.75	0.74	20
2006	10	8.90	0.47	19
2007	15	33.27	1.85	18
2008	15	32.4	1.91	17
2009	12	22.58	1.41	16
2010	19	31.11	2.07	15
2011	24	43.08	3.08	14
2012	39	25.36	1.95	13
2013	46	28.65	2.39	12
2014	41	48.51	4.41	11
2015	43	45.74	4.57	10
2016	67	18.49	2.05	9
2017	82	21.16	2.64	8
2018	97	20.03	2.86	7
2019	123	16.43	2.74	6
2020	131	12.27	2.45	5
2021	157	6.36	1.59	4
2022	154	2.44	0.81	3

NC, Number of cited articles; TC, Total citation.

this study identifies South Africa as a country-specific case, highlighting the connection between keywords and authors from the country and its high usage in the field. The study explores the association between CCWRM_AG studies and management approaches for water scarcity, drought events, resilience, and capacity building for sustainable development, based on the author's ideas and document content.

Figure 6 shows the thematic evolution of themes within the CCWRM_AG research field, dividing the period (1997–2018) and (2019–2022) under different time scales. The results reveal that the stable theme used from 1997 to 2018 was linked to climate and environmental change, which evolved into climate-related events from 2019 to 2022, and remained climate-related impacts from 2019–2022, respectively. This section evaluates the evolution of themes and research clusters in South Africa's climate change, water resource management, adaptation, and governance (CCWRM_AG) studies, identifying key terms and sources based on their occurrence. Thematic evolution is a key feature of published articles, indicating the recurring appearance of key research terms or themes over time, influenced by the author's keyword distribution per year. Between 1997 and 2018, flooding was a frequently researched indicator, while between 2019 and 2022, water scarcity emerged as the largest debated issue in South Africa. This may be attributed to South Africa's diverse ecosystem influenced by its bimodal climatic zones, which significantly impacts food systems, water security, human health, and ecological biodiversity due to topographical complexities in semi-arid environments (Muche et al., 2012; Carr et al., 2022; Mndela et al., 2023). The connections between nodes suggest a collaboration between climate change and other landscape-scale indicators, which are still largely unexplored. The stronger the connectivity of each node, the more significant their influence on the environment. The connecting network features a wide indicator-to-indicator node at the edge, with climate change being the most prominent issue in South Africa's independent research articles (Figure 6). Table 3 shows the collective data derived from representative keywords commonly used in the field.

Figure 7 shows a word cloud displaying research outputs and frequently occurring keywords in CCWRM_AG studies, with each keyword size indicating its strength and frequency in the literature. The CCWRM_AG research employs a word cloud to visualize dominant words, identifying areas of focus and stronger literature relationships, aiding in understanding the research effectiveness and relevance during the survey period. For example, climate change adaptation, South Africa, drought, resilience, water scarcity, disaster risk reduction and water governance. Other dominant terms are vulnerability, water footprint, food security, water policy, water management, agriculture, climate variability, irrigation, and sustainability among others. Overall, it is apparent that climate change and water resource scarcity are the major keywords which can be associated with the influence climate change has on water access, water scarcity, drought, adaptation and governance (Kahil et al., 2015; Leal Filho et al., 2022). There is scientific progress or innovation in the study of climate change and water scarcity which should be sustained by leveraging on gaps these keywords have suggested. Therefore, the key themes in South Africa's climate change and water resource management, including adaptation, water scarcity, and governance, should be continuously advanced by addressing identified gaps and effectively utilizing these areas for further research and development. For example, the keywords highlighting the environmental impacts of water scarcity, institutional strengthening of water governance, adaptive management, and sustainable development did not significantly appear, indicating their non-significant association. The study identifies crucial knowledge gaps in the CCWRM_AG domain, especially in Sub-Saharan African countries, thereby advancing the frontier in this field.

3.4 Analysis of top relevant author's affiliations, most-cited authors, and keywords

Figure 8 shows the relationship between the top relevant author's affiliations, most-cited authors, and keywords in the field of CCWRM_AG since 1997. The strength of an author in a specific niche area can be inferred from the influence of articles published by authors, as they exert a significant influence on their work. The researcher's academic impact and output demonstrate their effectiveness and commitment to

10.3389/frwa.2025.1376943

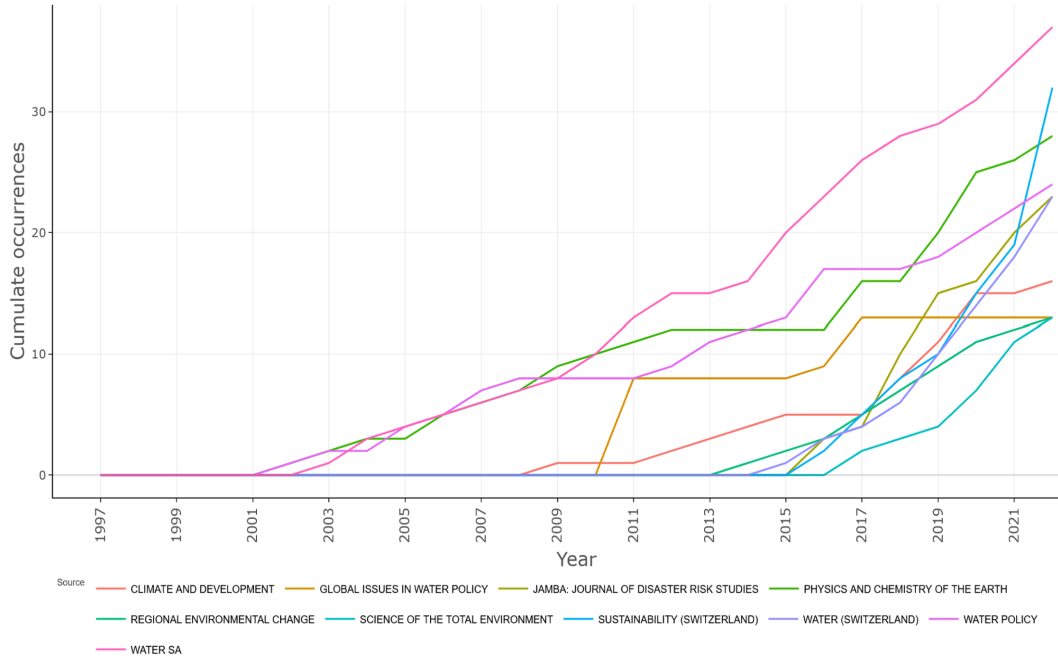


FIGURE 5
Top 10 most cited journals on CCWRM_AG studies.

TABLE 3 Most relevant keywords in CCWRM_AG research.

Rank	Author keywords (DE)	Articles frequency (%)	Rank	Keywords-Plus (ID)	Articles frequency (%)
1	Climate change	194 (17.3)	1	Climate change	353 (31.5)
2	South Africa	123 (11.0)	2	South Africa	303 (27.1)
3	Adaptation	96 (8.6)	3	Water management	243 (21.7)
4	Water scarcity	94 (8.4)	4	Water supply	178 (16.0)
5	Climate change adaptation	89 (8.0)	5	Adaptive management	95 (8.5)
6	Water governance	60 (5.4)	6	Africa	85 (7.6)
7	Resilience	46 (4.1)	6	Sustainable development	85 (7.6)
8	Water	39 (3.5)	7	Water resource	79 (7.1)
9	Sustainability	33 (3.0)	8	Agriculture	76 (6.8)
10	Food security	30 (2.7)	9	Decision making	75 (6.7)
11	Governance	29 (2.6)	10	Water scarcity	68 (6.1)
12	Drought	28 (2.5)	11	Governance approach	64 (5.7)
13	Agriculture	27 (2.4)	12	Article	61 (5.5)
14	Africa	26 (2.3)	12	Human	61 (5.5)
14	Vulnerability	26 (2.3)	13	Drought	58 (5.2)
14	Water policy	26 (2.3)	13	Irrigation	58 (5.2)
15	Water footprint	22 (2.0)	14	Water resources	56 (5.0)
15	Water security	22 (2.0)	15	Water conservation	55 (4.9)
16	Water management	21 (1.9)	16	Sustainability	53 (4.7)
17	Disaster risk reduction	20 (1.8)	17	Water	51 (4.6)

conducting quality research, thereby contributing significantly to the field of study (Wang et al., 2018). The most influential author's research outputs were sourced from home affiliations based on CCWRM_AG, according to region-specific results. The University of Kwazulu-Natal ($n = 151$) topped the list of the total number of published articles followed by the University of Cape Town ($n = 150$), the University of

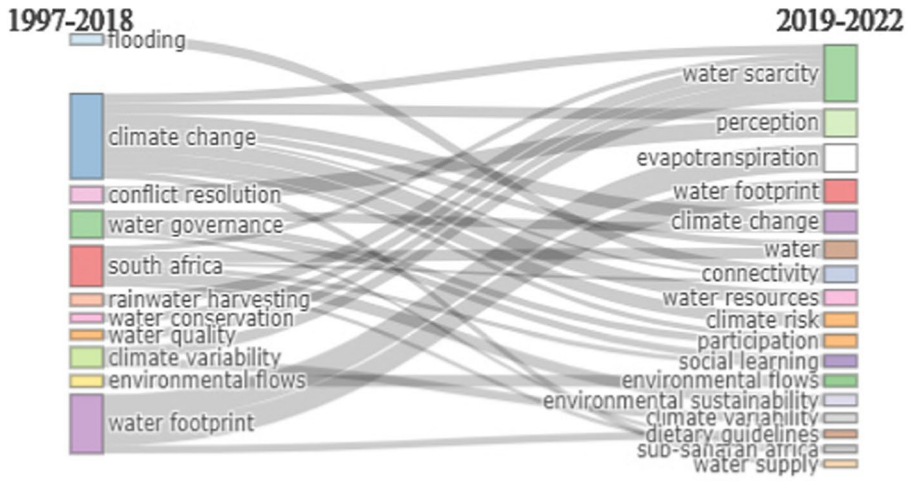


FIGURE 6
Thematic evolution of themes (1997–2018) and (2019–2022) different time scales.

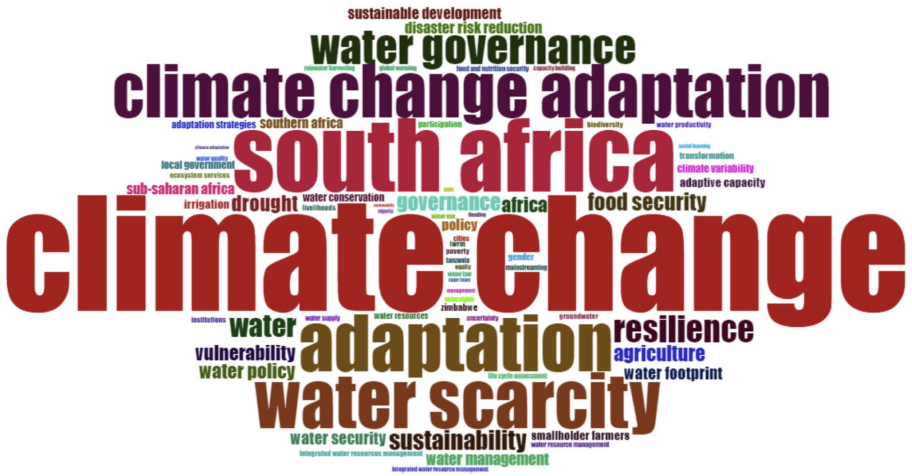


FIGURE 7
Word cloud on CCWRM_AG studies in South Africa.

the Witwatersrand ($n = 88$), the University of the Free State ($n = 82$), and the University of Pretoria ($n = 80$) respectively. The most-cited articles were authored by top authors affiliations including Van Koppen B and Ziervogel G from the International Water Management Institute accounting for 11.34 and 10%, followed by Mabhaudhi T from the University of Kwazulu-Natal accounting for 9.25% and Nhamo L accounting for 7% from Water Research Commission and Modi A T accounting for 6.5% from the University of Cape Town.

South African researchers consistently demonstrate strong research strength and prolific output, highlighting their significance in the field of CCWRM_AG. It is worth noting that Van Koppen B is the most influential author with the highest fractional authorship qualities, accounting for 11.34% of individual author's contributions to published articles. The ratio of fractionalized documents to full counts of publications with external co-authorship ranges from 0 to 1. However, the value 0 indicates exclusive external collaboration without a home university researcher, while the larger value suggests a more collaborative approach (De Moya-Anegon et al., 2018). The results reveal that Van Koppen, Ziervogel G, and Mabhaudhi T are ranked first, second, and third among authors who do not work with external collaborators, as shown in Figure 8. The visualizations were created by selecting three key metadata fields, with each item bar's size proportional to its contribution to the reviewed area. Notably, the University of Kwazulu-Natal (UKZN) and the University of Cape Town (UCT) are frequently mentioned in articles, indicating their significant influence and consistent usage in the field (Figure 8). The survey indicates that publications on CCWRM_AG in South Africa have significantly influenced the field, along with other affiliated institutions, during the survey period. The top two institutions were identified as key contributors to articles on climate change, adaptation, resilience, water scarcity and climate change adaptation, often using their keywords in the context of these topics, highlighting their significant contributions.

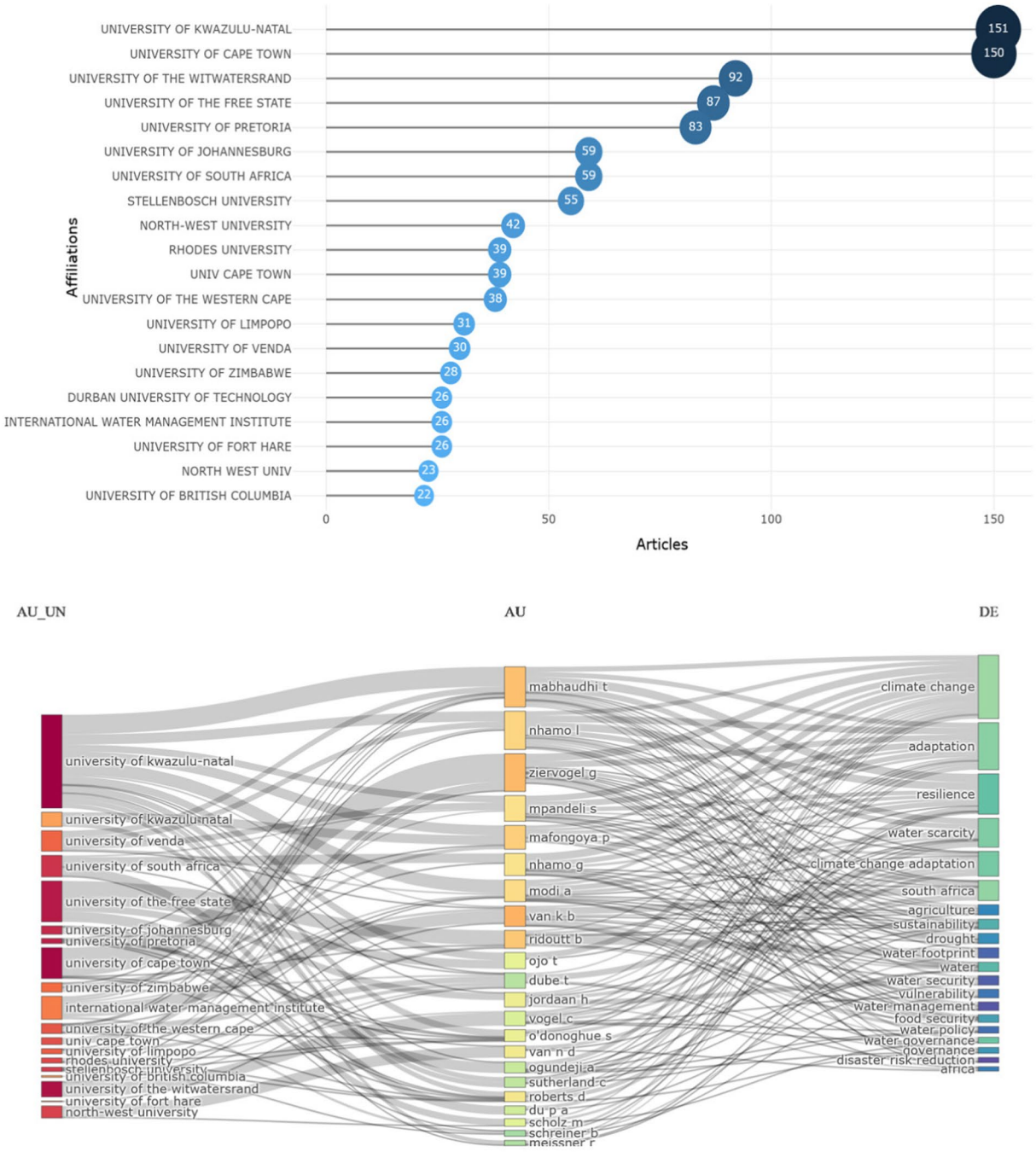
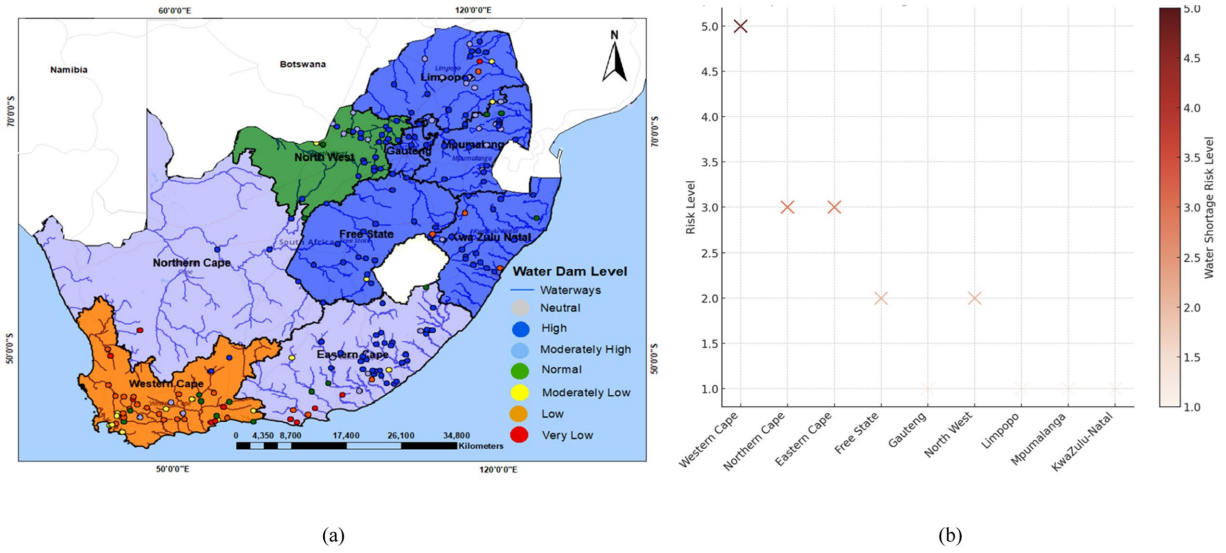


FIGURE 8
The relationship between the top relevant author's affiliations, most-cited authors, and keywords in South Africa.

3.5 Geospatial analysis and risk assessment of water scarcity and its socio-environmental impacts in South Africa

Figures 9a,b shows the spatial distribution and risk assessment of water shortages and their impacts across South African provinces from 2018 to 2022. The spatial data analysis was obtained from the National Integrated Water Information System (NIWIS) database (web-service-based platform). The dataset is a valuable tool for monitoring and assessing water-related issues, emphasizing the need to raise awareness about South Africa's water scarcity and mitigation strategies (Sambo et al., 2015). The results show that water dam levels in provinces like KwaZulu-Natal, Gauteng, Mpumalanga, Limpopo, and parts of Free State are categorized into moderately high (blue shades), indicating a relatively stable water resource status, indicating a healthier water supply (Figure 9a). The water dam levels (green) indicate a balanced state of water availability, with regions like the North West showing no significant shortages or



(a) (b)

FIGURE 9
(A,B) Spatial distribution and risk assessment of water shortages and their impacts across South African provinces from 2018 to 2022.

overabundance indicating a normal distribution of water availability. The Western Cape, Northern Cape, and Eastern Cape are experiencing moderate to very low water levels (yellow to red shades), with areas in the Western Cape showing very low levels (orange to red) indicating a high risk of water shortages. Therefore, this connotes that the intensity of red indicates the severity of water shortage risks, with darker shades indicating higher risks across provinces (Figure 9b). Since 2015/2016, drought in South Africa's Northern Cape, Western Cape, and Eastern Cape provinces has resulted in food and water insecurity for 15 million people, primarily due to global climate anomalies caused by El Niño in northeastern and north-central regions (Ncube and Shikwambana, 2017; Rasul et al., 2021). The development aligns with National Disaster Management reports on severe droughts and flooding events that have severely impacted numerous local communities (Ibebuchi, 2021; Adom et al., 2024). The Eastern Cape and Free State are at risk of water shortages due to changes in rainfall patterns, despite not experiencing immediate crises as severe as western regions. The analysis reveals that rainfall variations in South Africa are causing negative impacts on water dams and river levels, affecting food web production in these dam clusters (Figure 9). Nevertheless, the waterway network demonstrates the interconnectedness of regions through rivers and water bodies, potentially providing relief during shortages or serving as crucial irrigation sources in agriculture. The results reveal that the Western Cape and Northern Cape are identified as high risk due to low dam levels and potential drought conditions, while the Northern Cape faces water shortages across its vast arid lands. The eastern and northeastern provinces, such as KwaZulu-Natal, Limpopo, and Gauteng, have a relatively low risk of short-term water shortages due to their humid climate and better water resources.

Table 4 provides an overview of how different provinces are affected by water shortages based on the dam water level distribution across provinces in South Africa from 2018 to 2022). The table categorizes provinces based on water shortage risk (high, moderate, or low) and dam levels (ranging from very low to high), providing insights into the relationship between water availability and scarcity in different regions (Figures 9a,b and Table 4). Although certain provinces currently maintain high dam levels, future water availability may be impacted by factors such as climate change, population growth, and rising water demand, potentially disrupting the existing balance and increasing the risk of shortages. The analysis reveals significant water shortage risks in certain provinces, particularly the Western Cape, while others maintain relatively stable water availability. This study underscores the necessity of proactive water management strategies, infrastructure investment, and sustainable water use policies to mitigate risks and ensure long-term water security in South Africa.

4 Discussion

This study provides valuable insights into various aspects of the CCWRM_AG studies. Between 1997 and 2022, CCWRM_AG studies identified climate change and water research as the most common keywords (Figures 5, 7). The results reveal that the University of Kwazulu-Natal and the University of Cape Town are the top universities for the author's home country affiliations, according to the findings of the relevant author's research. The study indicates that Kwazulu-Natal province, with its humid climate and abundant water resources, is at a lower risk of short-term water shortages. South Africa's northeastern and north-central regions face water scarcity risks, leading to high scientific production of studies on CCWRM_AG by the region's universities (Figure 7). Between 2015 and 2017, South Africa experienced a 76% average decline in agricultural yield, mainly in the Western Cape, due to severe water scarcity, affecting winter wheat nuts and maize production in the country's largest wheat-growing

TABLE 4 Summary analysis of water shortage in relation to dam water levels (2018–2022).

S/N	Province	Water shortage risk	Water dam level
1.	Western Cape	High risk	Very low (orange)
2.	Northern Cape	Moderate risk	Neutral (light purple)
3.	Eastern Cape	Moderate risk	Normal (light Blue)
4.	Free State	Low risk	High (dark blue)
5.	Gauteng	Low risk	High (dark blue)
6.	North West	Low risk	Moderately high (green)
7.	Limpopo	Low risk	High (dark blue)
8.	Mpumalanga	Low risk	High (dark blue)
9.	KwaZulu-Natal	Low risk	High (dark blue)

province (SADC, 2016; Olabanji et al., 2020). For instance, Siphambe et al. (2024a) propose integrating mitigation strategies like systematic rainwater harvesting into solutions to prevent stormwater generation, thereby improving overall water management beyond just managing runoff. Cape Town can efficiently use its financial resources to establish large-scale rainwater harvesting infrastructure, (Muleta et al., 2020) akin to Frankfurt Airport's underground cisterns system (Aslan and Selçuk, 2018), thereby reducing water waste and promoting efficient reuse. Historical water management techniques, like the "Venetian wells" in 18th-century Venice, can significantly reduce water scarcity and environmental impacts by maximizing rainwater utilization, thereby reducing water scarcity and enhancing overall water quality (Ciriacono, 2018). Furthermore, the study region highlights the significant impact of climate-related water scarcity on various provinces, particularly those affected by water stress and drought-related hazards. The overall analysis includes top-cited articles and the distribution of the author's keywords, most cited journals, word cloud, thematic evolution, and relevant author's affiliations on CCWRM_AG. The study assesses spatial distribution and water shortage risks, suggesting further research on climate change and water resource scarcity in South Africa.

The findings reveal that the Western Cape province is the most severely affected by severe water shortages and declining water quality (Figures 9a,b). Studies have shown that dam levels in the Western and Eastern Cape are decreasing, with the Eastern Cape implementing voluntary water restrictions similar to Cape Town, indicating a decline in water resources (Botai et al., 2018; Orimoloye et al., 2019). For instance, over 80% of major catchments are overutilising over 80% of rivers, leading to prolonged dryness in the summer months (Chatanga and Seleteng-Kose, 2021). To improve water supply through 2040 and promote sustainable mining and agricultural practices, the Vaal Gamagara Water Scheme was introduced on June 23, 2016, in the Northern Cape province to minimize water stress (DWS Press Statement, 2016). Studies indicate that climate change in South Africa, particularly in the Northern Cape and Eastern Cape, has resulted in drought hazards and water shortages (Donnenfeld et al., 2018; Mpanyaro et al., 2024). Moreover, Cape Town, a Western Cape city, experienced low average dam levels between 2015 and 2018, indicating ongoing water scarcity-related challenges, as evidenced by the low dam levels between the years, according to previous studies (Botai et al., 2017; Orimoloye et al., 2019; Theron et al., 2021; Wolski et al., 2021; Meza et al., 2021). A study reveals that KwaZulu-Natal overuses 50% of the Pongola-Mtamvuna basin's rivers, with low dam levels during the dry season, exacerbated by high water usage (Awuah, 2020). Cape Town's city, situated in the Western Cape province has created new water constraints, causing water stress on the Karoo and western coast of the country, prompting the city to invent new levels in 2016 (City of Cape Town, 2016).

4.1 Potential climate-related water shortage and plausible mitigation plans in South Africa

The fundamental step in water resource management is planning, developing, and managing water resources in terms of quantity and quality across all users. Climate change and population growth have led to significant variability in global water resources over the past few decades, posing a global water resource vulnerability (Cheo et al., 2013; Thornton et al., 2014). South Africa is facing significant threats to food security due to water scarcity and drought hazards, resulting in socioeconomic loss, ecological biodiversity vulnerability, exposure, and soil moisture deficits (Leal Filho et al., 2022; Du Plessis, 2023). The region has been experiencing severe drought since 2015, exceeding the Department of Water and Sanitation's guidelines, resulting in a water deficit, possibly due to climate change, delayed rains, and reduced dam levels (Enqvist and Ziervogel, 2019; Makaya et al., 2020). South Africa's severe water scarcity, worsened by climate change, is causing increased demand for water in agriculture, due to persistent dry events and increasing short-term and long-term water demand (Calverley and Walther, 2022; Olabanji et al., 2020), but there is limited knowledge on managing this situation at regional and local scales. Therefore, long-term water stress projections, monitoring, impact analysis, adaptive management, and intervention programs can be utilized for risk mitigation in water shortage and reduction plans. Recent climate change and anthropogenic disturbances pose severe threats to water resources, affecting agricultural land, human health, vegetation, and ecosystem functioning (Afuye et al., 2021a; Afuye et al., 2024b). The growing population, industrial expansion, and agricultural demands are escalating the need for efficient resource management, robust governance, technological innovation, and long-term planning. Hence, implementing a multifaceted approach that combines robust institutional and adaptive governance, regulatory policies and economic incentives is crucial for effectively addressing water scarcity and environmental impacts. This would improve the support for guiding water conservation and climate policy interventions for sustainability. This study suggests that improving irrigation techniques, implementing water reuse strategies, and promoting

climate-resilient agriculture can effectively tackle water inequality, population demands, and climate uncertainty in drought-prone areas.

4.1.1 Policy implications for climate change governance and future water resource management in South Africa

Climate change is predicted to exacerbate the effects of dry conditions in various regions, potentially causing significant economic impacts (Leal Filho et al., 2022; Muzammal et al., 2024). The study reveals that certain regions in the country are experiencing severe water stress due to climate change and water scarcity, prompting the declaration of a national emergency if any province or municipality runs out of water supplies. South Africa can tackle water shortages through national conservation and climate policy measures, but a restricted scenario is needed to prevent the cascading effects of climate change on water resources management. The study highlights a gap in the literature on South Africa's climate change and water resource issues and the impact of interventions on rural community resilience structures. Sub-Saharan Africa, including South Africa, is grappling with water scarcity due to climate change, necessitating adaptive governance for managing water resources using tool kits (Nayono, 2014; Critchley et al., 2023). The kits aid in green infrastructure planning for climate-smart cities, requiring continuous monitoring, evaluation, policy application, and Indigenous science for adaptive capacity, sustainable practices, and water resource management. South Africa's research and policy integration is crucial in addressing water scarcity and climate change risks, emphasizing the importance of sustainable water resources in developing effective policies and actions. Effective demand management policies, including rainwater collection, wastewater reclamation and treatment, and water footprint control, can help mitigate climate change-induced water shortages in the region. This study underscores the significance of its findings in guiding future research and policy formulation on water resource management and climate change mitigation in South Africa, potentially influencing scholarly investigations and practical interventions. The policy will guide universities and research centers in creating targeted policies to stimulate scientific inquiry and provide fresh insights into CCWRM_AG studies.

4.1.2 Limitations and future studies

The corporate governance directorate in South Africa is focusing on climate change and water resource management, but there is a need for more targeted policies and funding in research niche areas. The integration of synergies within governance networks is crucial for sustainable water resource management, requiring high-level decision-making and timely resolutions to minimize national and local water scarcity. An all-inclusive, integrated approach to managing water resources, enhancing climate change resilience, and accommodating the growing population is crucial for sustainable water resource management. The integration of climate change and water resource scarcity, combined with adaptive governance and nature-based solutions, will enhance our understanding of these challenges as research progresses. New research on climate change-related water scarcity will provide more comprehensive and sustainable development strategies as empirical studies and solutions continue to develop. The study suggests South Africa implement a networked governance approach for decision-making and multi-level solutions in managing natural water sources and their affected communities for effective and sustainable management. In addition, the study underscores the need for further research on more keyword words to identify significant, historical, and current issues, emphasizing their significance in future studies. Further research should explore innovative solutions to address severe water scarcity and its impacts on agriculture, incorporating networked governance and sustainable development practices to mitigate climate change effects. The study recommends incorporating diverse geospatial and bibliometric research databases to identify potential research development, improvements, and future research hints.

5 Conclusion

This study assessed climate change, water resource management, adaptation, and governance (CCWRM_AG) intellectual domain, identified research hotspots, and proposed solutions to tackle water scarcity and environmental impacts in South Africa. The CCWRM_AG field in South Africa is experiencing an 18.98% annual growth in citations per article, with the University of KZN and the UCT ranking first with the highest total number of published top articles, indicating their significant contributions to their home-affiliated institutions. Top authors' articles and citations primarily come from home-affiliated institutions and associated research centers, indicating the significant academic influence these affiliations have on their field. Van Koppen B., a prominent author with 28 cited articles by the International Water Management Institute, has significantly impacted the field of water management through his publications from UKZN and UCT. This connotes that UKZN and UCT are well-positioned to advance their home affiliations' involvement in CCWRM_AG research through collaboration, innovation, and funding opportunities, strengthening their position in the field.

The findings reveal that the Western Cape province experiences severe water shortages, significantly impacting water quality, agricultural productivity, and livelihoods due to critically low dam levels. The Northern Cape also faces water scarcity, particularly in its arid regions, while other provinces maintain relatively stable water availability. Hence, we can infer that climate change exerts a significant influence on weather events like droughts and shifts in precipitation patterns, affecting food web production and ecosystem health in various regions. The study reveals that top South African universities and research centers significantly influence policy through academic influence, particularly in shaping the climate change adaptation landscape. Therefore, this study identifies top articles as leading in water planning and climate policy redesign, demonstrating their effectiveness and proficiency in quality research. This study emphasizes the need for further research on the social impact of water scarcity on communities and residents in South Africa, as most studies focus on physical aspects, neglecting human phase challenges. This study focuses on the core area of CCWRM_AG research, highlighting the knowledge gap in South Africa's climate change-related water scarcity and the need for a broader understanding of social aspects, particularly in Sub-Saharan African countries. As research advances, new empirical solutions are expected to address climate-related water scarcity, paving the way for broader sustainable development plans.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AK: Conceptualization, Data curation, Investigation, Resources, Validation, Visualization, Writing – original draft. GA: Conceptualization, Data curation, Investigation, Validation, Visualization, Formal analysis, Funding acquisition, Methodology, Resources, Software, Supervision, Writing – original draft. SM: Validation, Visualization, Writing – review & editing, Investigation. LZ: Investigation, Resources, Validation, Visualization, Writing – review & editing. RA: Investigation, Validation, Visualization, Writing – review & editing. MS: Investigation, Project administration, Resources, Writing – review & editing, Funding acquisition, Validation, Visualization. DD: Investigation, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the Govan Mbeki Research Development Center (GMRDC), University of Fort Hare, and the Global Change Institute (GCI), University of Witwatersrand, Johannesburg, South Africa.

Acknowledgments

All thanks to the Govan Mbeki Research Development Center (GMRDC), University of Fort Hare and the Global Change Institute (GCI), University of Witwatersrand, Johannesburg, South Africa for their support of this research and for creating an enabling environment for research. Special thanks to the National Integrated Water Information System (NIWIS), Web of Science and Scopus databases, and the RStudio team for providing data and tools for analysis and to the reviewers for their wonderful insights that strengthened this paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Adom, R. K., Reid, M., Afuye, G. A., and Simatele, M. D. (2024). Assessing the implications of deforestation and climate change on rural livelihood in Ghana: a multidimensional analysis and solution-based approach. *Environ. Manag.* 74, 1124–1144. doi: 10.1007/s00267-024-02053-6

Adom, R. K., and Simatele, M. D. (2021). Analysis of public policies and programmes towards water security in post-apartheid South Africa. *Water Policy* 23, 503–520. doi: 10.2166/wp.2021.017

Adom, R. K., Simatele, M. D., and Reid, M. (2022). Addressing the challenges of water energy-food nexus programme in the context of sustainable development and climate change in South Africa. *J. Water Clim. Change* 13, 2761–2779. doi: 10.2166/wcc.2022.099

Afuye, G. A., Kalumba, A. M., Busayo, E. T., and Orimoloye, I. R. (2021b). A bibliometric review of vegetation response to climate change. *Environ. Sci. Pollut. Res.* 29, 18578–18590. doi: 10.1007/s11356-021-16319-7

Afuye, G. A., Kalumba, A. M., Ishola, K. A., and Orimoloye, I. R. (2022). Long-term dynamics and response to climate change of different vegetation types using GIMMS NDVI3g data over Amathole District in South Africa. *Atmos.* 13:620. doi: 10.3390/atmos13040620

Afuye, G. A., Kalumba, A. M., and Orimoloye, I. R. (2021a). Characterisation of vegetation response to climate change: a review. *Sustain. For.* 13:7265. doi: 10.3390/su13137265

Afuye, G. A., Kalumba, A. M., Owolabi, S. T., Thamaga, K. H., Ndou, N., Sibandze, P., et al. (2024b). Analyzing spatiotemporal variations and dynamics of vegetation over Amathole district municipality in South Africa. *Environ. Dev. Sustain.* 1, 1–26. doi: 10.1007/s10668-024-05221-0

Afuye, G. A., Nduku, L., Kalumba, A. M., Santos, C. A. G., Orimoloye, I. R., Ojeh, V. N., et al. (2024a). Global trend assessment of land use and land cover changes: a systematic approach to future research development and planning. *J. King Saud Univ. Sci.* 36:103262. doi: 10.1016/j.jksus.2024.103262

Afuye, G., Ojeh, V., Okunlola, B., and Adejokun, V. (2018). Heat-sum calculation in forecasting maize Phenological stages and harvesting date in Lagos south west, Nigeria. *J. Geogr. Environ. Earth Sci. Int.* 13, 1–12. doi: 10.9734/JGEESI/2017/34670

Al-Hemoud, A., Al-Dousari, A., Al-Dashti, H., Petrov, P., Al-Saleh, A., Al-Khafaji, S., et al. (2020). Sand and dust storm trajectories from Iraq Mesopotamian flood plain to Kuwait. *Sci. Total Environ.* 710:136291. doi: 10.1016/j.scitotenv.2019.136291

Aria, M., and Cuccurullo, C. (2017). Bibliometrix: an R-tool for comprehensive science mapping analysis. *J. Informet.* 11, 959–975. doi: 10.1016/j.joi.2017.08.007

Aslan, D., and Selçuk, S. A. (2018). A biomimetic approach to rainwater harvesting strategies through the use of buildings. *Eurasian J. Civil Eng. Arch.* 2, 27–39. doi: 10.11113/ijbes.v9.n3.969

Awuah, A. K. (2020). *Exploring the implementation of integrated water resources management (IWRM) and adaptive management (AM) at a local scale: A case study of the uMngeni catchment*. KwaZulu-Natal (Doctoral Dissertation).

Aznar-Sánchez, J. A., Belmonte-Ureña, L. J., Velasco-Muñoz, J. F., and Manzano-Agugliaro, F. (2018). Economic analysis of sustainable water use: a review of worldwide research. *J. Clean. Prod.* 198, 1120–1132. doi: 10.1016/j.jclepro.2018.07.066

Bianucci, P., Sordo-Ward, A., Lama-Pedrosa, B., and Garrote, L. (2024). How do environmental flows impact on water availability under climate change scenarios in European basins? *Sci. Total Environ.* 911:168566. doi: 10.1016/j.scitotenv.2023.168566

Bonilla, C. A., Merigó, J. M., and Torres-Abad, C. (2015). Economics in Latin America: a bibliometric analysis. *Scientometrics* 105, 1239–1252. doi: 10.1007/s11192-015-1747-7

Booth, L., Fleming, K., Abad, J., Schueller, L. A., Leone, M., Scolobig, A., et al. (2020). Simulating synergies between climate change adaptation and disaster risk reduction stakeholders to improve management of transboundary disasters in Europe. *Int. J. Disaster Risk Reduction* 49:101668. doi: 10.1016/j.ijdrr.2020.101668

Botai, C. M., Botai, J. O., and Adeola, A. M. (2018). Spatial distribution of temporal precipitation contrasts in South Africa. *S. Afr. J. Sci.* 114, 70–78. doi: 10.17159/sajs.2018/20170391

Botai, C. M., Botai, J. O., De Wit, J. P., Ncongwane, K. P., and Adeola, A. M. (2017). Drought characteristics over the Western Cape Province, South Africa. *Water* 9:876. doi: 10.3390/w9110876

Busayo, E. T., Kalumba, A. M., Afuye, G. A., Ekundayo, O. Y., and Orimoloye, I. R. (2020). Assessment of the Sendai framework for disaster risk reduction studies since 2015. *Int. J. Disaster Risk Reduction* 50:101906. doi: 10.1016/j.ijdrr.2020.101906

Calverley, C. M., and Walther, S. C. (2022). Drought, water management, and social equity: analyzing Cape Town, South Africa's water crisis. *Front. Water* 4:910149. doi: 10.3389/frwa.2022.910149

Carr, A. S., Chase, B. M., Boom, A., Meadows, M. E., and Sanchez, J. M. (2022). Variability in soil and foliar stable carbon and nitrogen isotope compositions in the winter rainfall biomes of South Africa. *J. Arid Environ.* 200:104726. doi: 10.1016/j.jaridenv.2022.104726

Chao, Q., and Feng, A. (2018). The scientific basis of climate change and its response. *Glob. Energy Interconnect.* 1, 420–427. doi: 10.14171/j.2096-5117.gei.2018.04.002

Chatanga, P., and Seleteng-Kose, L. (2021). Montane palustrine wetlands of Lesotho: vegetation, ecosystem services, current status, threats and conservation. *Wetlands* 41, 1–19. doi: 10.1007/s13157-021-01470-1

Cheo, A. E., Voigt, H. J., and Mbua, R. L. (2013). Vulnerability of water resources in northern Cameroon in the context of climate change. *Environ. Earth Sci.* 70, 1211–1217. doi: 10.1007/s12665-012-2207-9

Ciriacono, S. (2018). Management of the lagoon and urban environment in 18th-century Venice. *Water Hist.* 10, 141–161. doi: 10.1007/s12685-018-0218-5

City of Cape Town. (2016). *Residential water restrictions explained*. Cape Town now has 6 levels of water restrictions, with 6 being the highest and only implemented when dam levels are 'critically low'. Previously the most severe restrictions were level 4. Available online at: http://www.capetown.gov.za/Family%20and%20home/residential-utility-services/residential-water-and-sanitation-services/2016-residential-waterrestrictions-explained.

Critchley, W., Harari, N., Mollee, E., Mekdaschi-Studer, R., and Eichenberger, J. (2023). Sustainable land management and climate change adaptation for small-scale land users in sub-Saharan Africa. *Land* 12:1206. doi: 10.3390/land12061206

De Moya-Anegon, F., Guerrero-Bote, V. P., López-Illescas, C., and Moed, H. F. (2018). Statistical relationships between corresponding authorship, international co-authorship and citation impact of national research systems. *J. Informet.* 12, 1251–1262. doi: 10.1016/j.joi.2018.10.004

Donnenfeld, Z., Hedden, S., and Crookes, C. (2018). *A delicate balance: Water scarcity in South Africa*.

Du Plessis, A. (2023). "South Africa's impending water crises: transforming water crises into opportunities and the way forward" in South Africa's water predicament: Freshwater's unceasing decline. ed. A. Du Plessis (Cham: Springer International Publishing), 143–170.

Du Plessis, A., and Du Plessis, A. (2017). *Water scarcity and other significant challenges for South Africa*. Freshwater challenges of South Africa and its upper Vaal River: Current state and outlook. pp. 119–125.

Du Preez, C. C., and Van Huyssteen, C. W. (2020). Threats to soil and water resources in South Africa. *Environ. Res.* 183:109015. doi: 10.1016/j.envres.2019.109015

DWS Press Statement. (2016). *DWS press statement, June 2016*. Available online at: http://www.dwa.gov.za/Communications/PressReleases/2016/MS%20-%20R18bn%20water%20infrastructure%20investment%20launched%20in%20Northern%20Cape.pdf.

Edokpayi, J. N., Makungo, R., Mathivha, F., Rivers, N., Volenzo, T., and Odiyo, J. O. (2020). "Influence of global climate change on water resources in South Africa: toward an adaptive management approach" in Water conservation and wastewater treatment in BRICS nations. eds. P. Singh, Y. Milshina, K. Tian, D. Gusain and J. P. Bassin (Amsterdam, Netherlands: Elsevier), 83–115.

Ellegaard, O., and Wallin, J. A. (2015). The bibliometric analysis of scholarly production: how great is the impact? *Scientometrics* 105, 1809–1831. doi: 10.1007/s11192-015-1645-z

Enqvist, J. P., and Ziervogel, G. (2019). Water governance and justice in Cape Town: an overview. *Wiley Interdiscip. Rev. Water* 6:e1354. doi: 10.1002/wat2.1354

Eslamian, S., Mohri-Isfahani, E., Mahdavi, A., Rajaei-Rizi, F., Marzi-Nouhedani, M., Ghasemi-Zanyani, M., et al. (2017). "Integrated water resources management under water scarcity" in Handbook of drought and water scarcity. ed. S. Eslamian (Boca Raton, FL: CRC Press), 677–697.

Fabian, P. S., Kwon, H. H., Vithanage, M., and Lee, J. H. (2023). Modeling, challenges, and strategies for understanding impacts of climate extremes (droughts and floods) on water quality in Asia: a review. *Environ. Res.* 225:115617. doi: 10.1016/j.envres.2023.115617

FAO. (2020). *Food balance sheets*. In: Food and agriculture Organization of the United Nations. Rome. Available at: www.fao.org/economic/ess/fbs. (Accessed April 28, 2020).

Forssman, T. (2022). *Approaching identity in southern Africa over the last 5000 years*. In: Oxford Research Encyclopedia of Anthropology.

Fróna, D., Szenderák, J., and Harangi-Rákos, M. (2019). The challenge of feeding the world. *Sustain. For.* 11:5816. doi: 10.3390/su11205816

Gagolewski, M. (2011). Bibliometric impact assessment with R and the CITAN package. *J. Informet.* 5, 678–692. doi: 10.1016/j.joi.2011.06.006

García, L., Rodríguez, D., Wijnen, M., and Pakulski, I. (2016). Earth observation for water resources management: Current use and future opportunities for the water sector. Washington, DC: World Bank Publications.

Gusenbauer, M., and Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google scholar, PubMed, and 26 other resources. *Res. Synth. Methods* 11, 181–217. doi: 10.1002/jrsm.1378

Huang, J., Mondal, S. K., Zhai, J., Fischer, T., Wang, Y., Su, B., et al. (2022). Intensity-area-duration-based drought analysis under 1.5° C–4.0° C warming using CMIP6 over a climate hotspot in South Asia. *J. Clean. Prod.* 345:131106. doi: 10.1016/j.jclepro.2022.131106

Ibebuchi, C. C. (2021). Revisiting the 1992 severe drought episode in South Africa: the role of El Niño in the anomalies of atmospheric circulation types in Africa south of the equator. *Theor. Appl. Climatol.* 146, 723–740. doi: 10.1007/s00704-021-03741-7

Idris, O. A., Opute, P., Orimoloye, I. R., and Maboeta, M. S. (2022). Climate change in Africa and vegetation response: a bibliometric and spatially based information assessment. *Sustain. For.* 14:4974. doi: 10.3390/su14094974

Izah, S. C., Jacob, D. E., Nelson, I. U., and Avez, S. (2024). "Urban water crisis in the global south" in Water crises and sustainable Management in the Global South. eds. S. C. Izah, M. C. Ogwu, A. Loukas and H. Hamidifar (Singapore: Springer Nature Singapore), 45–83.

Kaba, A. J. (2024). A survey of the geographic area, altitude, coastline, and climate of African countries and regions: implications for Africa's development. *J. Sustain. Dev.* 17, 57–80. doi: 10.5539/jsd.v17n3p57

Kahil, M. T., Dinar, A., and Albiac, J. (2015). Modelling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *J. Hydrol.* 522, 95–109. doi: 10.1016/j.jhydrol.2014.12.042

Leal Filho, W., Totin, E., Franke, J. A., Andrew, S. M., Abubakar, I. R., Azadi, H., et al. (2022). Understanding responses to climate-related water scarcity in Africa. *Sci. Total Environ.* 806:150420. doi: 10.1016/j.scitotenv.2021.150420

Madondo, M., and Nkwana, H. M. (2021). *Exploring South Africa's National Climate Change Response White Paper, 2011: Challenges and prospects for public policy*.

Mahlalela, P. T., Blamey, R. C., Hart, N. C. G., and Reason, C. J. C. (2020). Drought in the eastern cape region of South Africa and trends in rainfall characteristics. *Clim. Dyn.* 55, 2743–2759. doi: 10.1007/s00382-020-05413-0

Makaya, E., Rohse, M., Day, R., Vogel, C., Mehta, L., McEwen, L., et al. (2020). Water governance challenges in rural South Africa: exploring institutional coordination in drought management. *Water Policy* 22, 519–540. doi: 10.2166/wp.2020.234

Mathetsa, S. M., Simatele, M. D., and Rampedi, I. T. (2022). A water-centric approach in the assessment and governance of the water-energy-climate change Nexus in South Africa. *Front. Sustain. Food Syst.* 6:691704. doi: 10.3389/fsufs.2022.691704

Mbokodo, I. L., Bopape, M. J. M., Ndarana, T., Mbatha, S. M., Muofhe, T. P., Singo, M. V., et al. (2023). Heatwave variability and structure in South Africa during summer drought. *Climate* 11:38. doi: 10.3390/cli11020038

Mbuqwa, P., Magagula, H. B., Kalumba, A. M., and Afuye, G. A. (2024). Interdecadal variations in agricultural drought monitoring using land surface temperature and vegetation indices: a case of the Amahlathi local municipality in South Africa. *Sustain. For.* 16:8125. doi: 10.3390/su16188125

Meissner, R., and Funke, N. (2014). "The politics of establishing catchment management agencies in South Africa: the case of the Breede–Overberg catchment management agency" in The politics of River Basin Organisations (United Kingdom: Edward Elgar Publishing), 184–209.

Meissner, R., and Meissner, R. (2017). *Water governance and management and climate change*. Paradigms and theories influencing policies in the South African and international water sectors: PULSE^3, a framework for policy analysis, pp. 25–87.

Meza, I., Rezaei, E. E., Siebert, S., Ghazaryan, G., Nouri, H., Dubovyk, O., et al. (2021). Drought risk for agricultural systems in South Africa: drivers, spatial patterns, and implications for drought risk management. *Sci. Total Environ.* 799:149505. doi: 10.1016/j.scitotenv.2021.149505

Mndela, M., Moss, S., Gusha, B., Thamaga, K. H., Afuye, G. A., Abdo, H. G., et al. (2023). Functional trait responses of C4 bunchgrasses to fire return intervals in the semi-arid savanna of South Africa. *Diversity* 15:1201. doi: 10.3390/d15121201

Mpanyaro, Z., Kalumba, A. M., Zhou, L., and Afuye, G. A. (2024). Mapping and assessing riparian vegetation response to drought along the Buffalo River catchment in the eastern Cape Province, South Africa. *Climate* 12:7. doi: 10.3390/cli12010007

Muche, G., Schmiedel, U., and Jürgens, N. (2012). BIOTA southern Africa biodiversity observatories vegetation database. *Environ. Monit. Assess.* 4, 111–123. doi: 10.7809/b-e.00066

Muleta, B. M., Seyoum, T., and Assefa, S. P. (2020). *GIS-based assessment of potential area of rain water harvesting for crop production at Daro-Labu District, west Hararghe, Oromia, Ethiopia*. (Doctoral Dissertation, Haramya University).

Munyai, R. B., Chikoore, H., Musyoki, A., Chakwizira, J., Muofhe, T. P., Xulu, N. G., et al. (2021). Vulnerability and adaptation to flood hazards in rural settlements of Limpopo Province, South Africa. *Water* 13:3490. doi: 10.3390/w13243490

Muzammal, H., Zaman, M., Safdar, M., Adnan Shahid, M., Sabir, M. K., Khil, A., et al. (2024). "Climate change impacts on water resources and implications for agricultural management" in Transforming agricultural Management for a Sustainable Future: Climate change and machine learning perspectives. eds. S. Kanga, S. K. Singh, K. Shevkani, V. Pathak and B. Sajan (Springer Nature Switzerland: Cham), 21–45.

Nayono, S. (2014). *Development of a sustainability-based sanitation planning tool (SuSTA) for developing countries*. Case study: Integrated water resources

management (IWRM) project, Gunung Kidul, Indonesia (doctoral dissertation, doctoral dissertation, faculty of civil engineering, the Bauhaus-university Weimar, Germany. Available online at: https://www.e-pub.uni-weimar.de/opus4/front door/index/index/docId/2222.

Ncube, B., and Shikwambana, S. (2017). *Coping and adaptation strategies for agricultural water use during drought periods*. Water Research Commission Report No. KV, 363, 17.

Nduku, L., Kalumba, A. M., Munghemezulu, C., Mashaba-Munghemezulu, Z., Chirima, G. J., Afuye, G. A., et al. (2021). Earth observation systems and pasture modeling: a bibliometric trend analysis. *ISPRS Int. J. Geo Inf.* 10:793. doi: 10.3390/ijgi10110793

Nduku, L., Munghemezulu, C., Mashaba-Munghemezulu, Z., Kalumba, A. M., Chirima, G. J., Masiza, W., et al. (2023). Global research trends for unmanned aerial vehicle remote sensing application in wheat crop monitoring. *Geomatics* 3, 115–136. doi: 10.3390/geomatics3010006

Olabanji, M. F., Ndarana, T., and Davis, N. (2020). Impact of climate change on crop production and potential adaptive measures in the Olifants catchment, South Africa. *Climate* 9:6. doi: 10.3390/cli9010006

Orimoloye, I. R., Belle, J. A., Olusola, A. O., Busayo, E. T., and Ololade, O. O. (2021). Spatial assessment of drought disasters, vulnerability, severity and water shortages: a potential drought disaster mitigation strategy. *Nat. Hazards* 105, 2735–2754. doi: 10.1007/s11069-020-04421-x

Orimoloye, I. R., Ololade, O. O., Mazinyo, S. P., Kalumba, A. M., Ekundayo, O. Y., Busayo, E. T., et al. (2019). Spatial assessment of drought severity in Cape Town area, South Africa. *Heliyon* 5:e02148. doi: 10.1016/j.heliyon.2019.e02148

Ozano, K., Roby, A., MacDonald, A., Upton, K., Hepworth, N., Gorman, C., et al. (2022). *Groundwater: Making the invisible. Visible: FCDO briefing pack on water governance, finance and climate change*.

Pahl-Wostl, C. (2019). The role of governance modes and meta-governance in the transformation towards sustainable water governance. *Environ. Sci. Pol.* 91, 6–16. doi: 10.1016/j.envsci.2018.10.008

Qureshi, M. I., Khan, N., Qayyum, S., Malik, S., Hishan, S. S., and Ramayah, T. (2020). Classifications of sustainable manufacturing practices in ASEAN region: a systematic review and bibliometric analysis of the past decade of research. *Sustain. For.* 12:8950. doi: 10.3390/su12218950

Rasul, G., Neupane, N., Hussain, A., and Pasakhala, B. (2021). Beyond hydropower: towards an integrated solution for water, energy and food security in South Asia. *Int. J. Water Resour. Dev.* 37, 466–490. doi: 10.1080/07900627.2019.1579705

SADC. (2016). *Over 41.4 million people in southern Africa are food insecure*. Available online at: https://www.sadc.int/news-events/news/over-414-million-people-southern-africa-are-food-insecure/2016.

Sambo, A., Pott, A., Kime, D., and Strydom, C. J. (2015). *The National Integrated Water Information System (NIWIS) for South Africa*. In: 36th hydrology and water resources symposium: The art and science of water: The art and science of water. Barton, ACT: Engineers Australia, pp. 1229–1236.

Sanbi, S. (2020). *Biodiversity mainstreaming and policy advice assessment*.

Saygitov, R. T. (2018). The impact of grant funding on the publication activity of awarded applicants: A systematic review of comparative studies and meta-analytical estimates. *Biorxiv* 2018:354662. doi: 10.1101/354662

Serame, S. M., and Afuye, G. A. (2024). Geographic information systems methods in practice: higher education curricula and practitioner registration standards in South Africa. *Trends Higher Educ.* 3, 1053–1071. doi: 10.3390/higheredu3040061

Sheffield, J., Wood, E. F., Pan, M., Beck, H., Coccia, G., Serrat-Capdevila, A., et al. (2018). Satellite remote sensing for water resources management: potential for supporting sustainable development in data-poor regions. *Water Resour. Res.* 54, 9724–9758. doi: 10.1029/2017WR022437

Shinga, P. S., Tesfamichael, S. G., Sibandze, P., Kalumba, A. M., and Afuye, G. A. (2024). Modelling spatiotemporal patterns of wildfire risk in the garden Route District biodiversity hotspots using analytic hierarchy process in South Africa. *Nat. Hazards* 121, 1945–1969. doi: 10.1007/s11069-024-06877-7

Shiriyedete, J., Khan, A., and Ehiane, S. O. (2024). Strategic intervention: water crisis and its impact on sustainable development in Cape Town, South Africa. *Environ. Soc. Psychol.* 9:2656. doi: 10.59429/esp.v9i8.2656

Sibandze, P., Kalumba, A. M., Aljaddani, H. A., Zhou, L., and Afuye, G. A. (2024). Geospatial mapping and meteorological flood risk assessment: a global research trend analysis. *Environ. Manag.* 75, 137–154. doi: 10.1007/s00267-024-02059-0

Siphambe, T. V., Ahana, B. S., Aliyu, A., Tiwangye, A., Fomena-Tchinda, H., Tchouandem-Nzali, C., et al. (2024b). Controlling stormwater at the source: dawn of a new era in integrated water resources management. *Appl Water Sci* 14:262. doi: 10.1007/s13201-024-02324-x

Siphambe, T. V., Aliyu, A., Souadji, K., Bayongwa, S. A., Amans, T., Fomena-Tchinda, H., et al. (2024a). Mitigating flash flooding in the city: drain or harvest? *Water Supply* 24, 812–834. doi: 10.2166/ws.2024.023

StatsSSA. (2021). *Mid-year population estimates, 2021*. Pretoria: Statistics South Africa. Available online at: http://www.statssa.gov.za/publications/P0302/P03022021.pdf. (Accessed September 15, 2021).

Strauss, J. A., Swanepoel, P. A., Laker, M. C., and Smith, H. J. (2021). Conservation agriculture in rainfed annual crop production in South Africa. *S. Afr. J. Plant Soil* 38, 217–230. doi: 10.1080/02571862.2021.1891472

Tapela, B. (2015). Water governance in traditional rural communities of South Africa. WRC Report NK8/1092. Pretoria: Water Research Commission.

Thakur, R. (2024). *The impacts of climate change on water resources in the Anthropocene: mitigation and adaptation strategies in Southern Africa*. In: Climate Change and Socio-political Violence in Sub-Saharan Africa in the Anthropocene: Perspectives from Peace Ecology and Sustainable Development, pp. 77–90.

Thamaga, K. H., Gom, S., Adesola, G. O., Ndou, N., Muavhi, N., Mndela, M., et al. (2024). Integration of geospatial-based algorithms for groundwater potential characterization in Keiskamma catchment of South Africa. *Groundw. Sustain. Dev.* 26:101262. doi: 10.1016/j.gsd.2024.101262

Theron, S. N., Archer, E., Midgley, S. J. E., and Walker, S. (2021). Agricultural perspectives on the 2015-2018 Western cape drought, South Africa: characteristics and spatial variability in the core wheat growing regions. *Agric. For. Meteorol.* 304-305:108405. doi: 10.1016/j.agrformet.2021.108405

Thornton, P. K., Ericksen, P. J., Herrero, M., and Challinor, A. J. (2014). Climate variability and vulnerability to climate change: a review. *Glob. Chang. Biol.* 20, 3313–3328. doi: 10.1111/gcb.12581

UNESCO. (2021). *The United Nations world water development report 2021*: Valuing Water. United Nations.

United Nations (2023). The sustainable development goals report: Towards a rescue plan for people and planet. New York: UN Publications.

Visser, M., van Eck, N. J., and Waltman, L. (2021). Large-scale comparison of bibliographic data sources: Scopus, web of science, dimensions, Crossref, and Microsoft academic. *Quant. Sci. Stud.* 2, 20–41. doi: 10.1162/qss_a_00112

Wang, Z., Zhao, Y., and Wang, B. (2018). A bibliometric analysis of climate change adaptation based on massive research literature data. *J. Clean. Prod.* 199, 1072–1082. doi: 10.1016/j.jclepro.2018.06.183

Wolski, P., Conradie, S., Jack, C., and Tadross, M. (2021). Spatio-temporal patterns of rainfall trends and the 2015–2017 drought over the winter rainfall region of South Africa. *Int. J. Climatol.* 41, E1303–E1319. doi: 10.1002/joc.6768

World Meteorological Organization. *Requirements for earth surface albedo*. Available online at: https://www.wmo-sat.info/oscar/variables/view/54 (Accessed April 10, 2020).

Yildiz, V., Hatipoglu, M. A., and Kumcu, S. Y. (2022). "Climate change impacts on water resources" in Water and wastewater management: Global problems and measures. eds. M. Bahadir and A. Haarstrick (Cham: Springer International Publishing), 17–25.

Zyoud, S. H., and Fuchs-Hanusch, D. (2017). A bibliometric-based survey on AHP and TOPSIS techniques. *Expert Syst. Appl.* 78, 158–181. doi: 10.1016/j.eswa.2017.02.016

Zyoud, S. H., and Zyoud, A. H. (2021). Mapping environmental impact assessment research landscapes in the Arab world using visualization and bibliometric techniques. *Environ. Sci. Pollut. Res.* 28, 22179–22202. doi: 10.1007/s11356-021-13696-x