

Research

Global trend analysis of climate change adaptation policy and governance in the water sector

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Abstract

Climate change has intensified water scarcity, degraded water quality, and disrupted global water distribution, highlighting persistent gaps in effective climate change adaptation policy and governance (CCA_PG), particularly in water resource management. The study assesses global scientific research trends in the water sector and explores dominant themes in CCA_PG studies from 2007 to 2023 by analyzing 2100 articles downloaded from the Scopus database in BibTeX format for bibliometric evaluation. The CCA_PG field experienced significant growth, with an annual publication increase of 16% over the assessment period. The results reveal a rising global trend in CCA_PG studies, with developed nations such as the USA, United Kingdom, and Australia contributing significantly to research output, whereas developing countries demonstrate limited scholarly contributions. A significant research gap persists in risk assessment and water governance regimes, as climate adaptation and resilience-based interdisciplinary methodologies are predominantly concentrated in developed nations. In addition, the results reveal that “climate change” and “adaptation” are the most frequently used keywords in CCA_PG studies, highlighting their interconnectedness in various water sector research areas. The study underscores the need for a comprehensive strategy that integrates top-down and bottom-up approaches to water resource management, addressing socio-economic, institutional, and biophysical complexities in response to climate change. This study advances climate adaptation and sustainable water management by addressing governance gaps, aligning with SDGs, and fostering international collaboration to enhance policy decision-making in underrepresented regions. The findings support the integration of scientific insights with socio-economic factors to develop equitable and sustainable adaptation strategies that strengthen policy, governance and theoretical frameworks.

Keywords Climate change adaptation · Bibliometrics · Governance · Policy · Water resource

1 Introduction

Climate change is a global challenge causing environmental decline, water crisis, and limited resources, impacting social and environmental aspects, and affecting the global system [56, 69]. Climate change has led to increased droughts, water scarcity, and unpredictable quality, impacting four billion people globally, with half facing water scarcity and half experiencing water shortages [6, 81]. Around 821 million people worldwide are undernourished,

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with one in nine affected by drought, and by 2050, 57% of the global population will live in water scarcity areas for at least a month, with 5.7 billion people experiencing this issue [74, 77]. The global water demand for agriculture is predicted to rise by 60%, exacerbated by unequal population growth in different geographies, which is unrelated to local resources, and the global population is expected to reach 9.4–10.2 billion by 2050, a 22–32% increase [10, 51]. The global water crisis, exacerbated by drought events, is causing a 20–30% increase in global demand by 2050, reaching 5500–6000 km³ per year, necessitating urgent attention to address water scarcity [25, 31]. The severity of climate change, particularly in tropical countries facing droughts, has led to a lack of adequate preparedness among global governments to tackle climate-related water scarcity [1, 55], highlighting the severe situation in these regions.

Pollution complicates global water quality, affecting clean water access, and there exists a gap in mainstreaming climate change adaptation in water resource management, despite increasing global adaptation governance interest [82, 85]. Water scarcity is exacerbated by various developmental factors including governance, institutions, gender inequality, poverty, security, inequitable distribution politics, pollution, wars, education, and health [11, 66]. The lack of centralized governance approaches to address climate change-induced water scarcity, coupled with elusive coordination and centralized climate change adaptation efforts, compromises effective policy implementation, leading to increased water scarcity. Studies show that integrating social and institutional innovation for climate change adaptation policy implementation in different countries is a topic of concern among water policymakers, implementers, and researchers [2, 7, 47, 83]. Countries and institutions are enhancing climate change resilience by promoting climate-water sustainability and implementing sustainable development goals (SDGs), particularly Goal 6 on clean water and sanitation and Goal 13 on climate action. This approach has been adopted to enhance global water access, availability, and quality among climate change vagaries water resource management remains challenged by poor governance, competition, and trade-offs between sectors [62, 84]. For instance, water competition from agriculture, fishing, tourism, energy, and industry is posing a threat to global livelihood systems, and current Central Coast Area policies often lack a multisectoral evaluation of adaptation approaches to water resource management [43, 75]. This research aims to enhance understanding of adaptation approaches in water scarcity sectors by integrating top-down and bottom-up approaches across all disciplines and domains of knowledge, in response to the severe impacts of climate change. Limited studies on climate change adaptation methodologies, considering biophysical, socioeconomic, and historical disasters like droughts and water scarcity, are needed to enhance the local societies' voices in policy decision-making and institutional governance systems [9, 13, 76]. Therefore, this study underscores the need to explore the evolving academic and practical efforts to enhance climate resilience within water management systems, identify research gaps and inform policymakers and practitioners.

Bibliometrics is a broadly used method for evaluating the scope and appropriateness of research efforts in a specific area of expertise, encompassing quantitative and qualitative aspects [63, 64]. Few bibliometric studies have examined the administrative role of institutional and governance systems in climate change adaptation policies and approaches to water resource governance [5, 8, 16, 57]. The research on global climate policy and governance gaps in water resource management is limited and warrants detailed studies on climate change adaptation policy and governance (CCA_PG) approaches to promote water sustainability amid global water scarcity due to climate change [18, 29, 67]. This study provides valuable insight into previous research on CCA_PG in the water sector [1, 15, 52, 59, 85] but lacks global trend analysis research. Therefore, the water sector plays a crucial role in sustainable resource management, shaping CCA_PG to address climate-induced scarcity, while ongoing challenges necessitate a comprehensive analysis of emerging trends in this field. The study evaluates the global scientific trends in the water sector and explores dominant themes in CCA_PG studies from 2007 to 2023 using bibliometrics. Furthermore, this study appraised published studies on CCA_PG research by analyzing the temporal trends in scientific contributions, country collaboration networks, global citation impact and author's contribution, geographical distribution of journals and author's keywords co-occurrence and institutional affiliations. It seeks to answer two key objectives. (i) What is the global distribution of studies on CCA_PG and intellectual stances in the water sector? (ii) What are the dominant research hotspots in CCA_PG, along with the conceptual guidelines and directions for future studies? This finding can aid policymakers and researchers in devising effective strategies for climate adaptation and sustainable water resource management by strengthening international collaboration and research capacity in underrepresented regions.

2 Data identification and methods

The study analysed Scopus database data from 2007 to 2023 using VOS viewer (v 1.6.20), a web-based bibliometric (RStudio v.3.4.1) software providing a web interface for bibliometric analysis [5, 57]. The database was chosen due to its comprehensive coverage of high-quality articles from various disciplines in over 230 countries published in high-ranking journals [5, 50, 63]. The research period from 2007 to 2023 was chosen to vividly indicate modern research trends in the niche area, considering the global escalating climate change and governance-related water scarcity issues. This study used search criteria for Scopus based on these keywords: (“climate change AND adaptation AND policy AND governance AND water”) AND PUBYEAR > January 2007 AND PUBYEAR < December 2023 in the title, abstracts, and keywords (author keywords and keywords plus) of published articles on CCA_PG research in the water sector. VOSviewer was used to create maps depicting thematic clusters in the study, providing a comprehensive description of the research field through clustering and network analysis of bibliometric data [16, 64]. The VOSviewer software product creates comprehensive maps through nodes sized proportional to the number of documents it characterizes, with connections interconnecting nodes for better visualization [58, 73]. However, the shorter distance between nodes significantly influenced the relationship between the characteristics of the document being studied.

2.1 Inclusion and exclusion criteria

The bibliometric evaluation was limited to articles published between 2007 and 2023, based on inclusion and exclusion criteria. The search terms generated 2823 articles from the Scopus database, including books, conference papers, book chapters, editorials, notes, erratum and short surveys, refined to 2100 and excluded non-English publications to maintain consistency in the dataset. Only peer-reviewed journal articles written in English were considered to ensure quality and accessibility. The original articles were downloaded in BibTex format, and 2100 articles were processed for bibliometric analysis after retrieval. Challenges arise in generating comprehensive datasets and evaluating their scientific significance using citation count and field-weighted citation impact. Additionally, duplicate records and articles lacking substantial discussion on “climate change,” “adaptation,” “policy,” “governance,” and “water,” determined through a keyword search were removed to refine the analysis. As a result, this analysis was streamlined to focus on major studies exploring CCA_PG, specifically in the area of climate change adaptation policy and governance in the water sector. Articles published outside the specified timeframe without focusing on water governance and policy, technical or economic aspects, or these topics were excluded.

3 Results

3.1 Temporal trends in scientific contributions per article and country collaboration networks

Figure 1 shows the evolution of publications on climate change adaptation policy and governance (CCA_PG) in the water sector from 2007 to 2023. The solid blue line represents the number of articles published annually, while the dotted line represents an exponential trend indicating an increasing growth pattern over time. The CCA_PG field experienced a significant increase, with an annual growth of 16% in continued publications output during the years under assessment, indicating a significant increase in the field. From 2007 to 2010, the initial output was minimal, with fewer than 50 articles published annually, indicating a low initial output, while between 2011 and 2016, there was a steady increase in articles published, reaching a peak of 106 in 2015 in the field. Between 2011 and 2016, there was a steady increase in articles published, reaching a peak of 106 in 2015. From 2017 to 2020, there was a significant increase in publications, with the number of articles nearly doubling from 141 to 282, indicating a significant surge in the field. Moreover, the number of publications in this research field increased from 2014 to 2015, but dips occurred in 2016 and 2020, and a sharp increase in 2018, indicating instability in average total citations per article. The exponential growth trend of scientific output is described by equation since ($y = 0.7172e^{0.2168x}$), with a strong fit to the exponential model indicating consistent publication growth. CCA_PG has gained renewed scholarly attention due to various factors, such as the Intergovernmental Panel on Climate Change (IPCC) reports on the crucial role of water in climate change adaptation, advocating for integrated water management, sustainable governance and policies that prioritize resilience against global vulnerabilities [22, 53]. Post-2020, the growth in publications stabilized, with articles fluctuating slightly around 280 between 2021 and 2023.

Articles

Year

$y = 0.7172e^{0.2168x}$
 $R^2 = 0,9697$

Year	Articles
2007	8
2008	6
2009	21
2010	32
2011	62
2012	67
2013	71
2014	95
2015	106
2016	98
2017	141
2018	183
2019	181
2020	189
2021	282
2022	278
2023	280

Figure 2 shows collaboration networks among the top 20 most-cited countries in CCA_PG studies in the water sector, illustrating relationships based on co-authorship or joint research in this domain. The CCA_PG studies reveal strong collaborations between countries in the water sector, with thicker lines indicating stronger partnerships and colour-coded nodes indicating regional clusters. The larger nodes indicate the significant roles of major countries like the US, United Kingdom, China, Germany, Australia, the Netherlands and Canada in research and collaboration, indicating strong transatlantic and Commonwealth research ties (Fig. 2). The CCA_PG studies involve other countries such as China, Italy, Spain, Sweden, and Iran, indicating regional or cultural collaborations. The interconnectedness of major global hubs like the US, UK, and China, and smaller nations like Kenya, Malaysia, and Peru, promotes international cooperation and research

The graph shows a network of 20 countries, with nodes colored red or green and edges colored red or green. The red nodes and edges form a dense cluster on the left, while the green nodes and edges form a dense cluster on the right. The two clusters are interconnected by a few green edges.

Red Nodes (Left Cluster): india, italy, switzerland, kenya, china, austria, peru, new zealand, iran, finland, malaysia, sweden, spain.

Green Nodes (Right Cluster): germany, netherlands, united kingdom, united states, south africa, canada, australia.

Inter-cluster Connections (Green Edges): india to germany, india to netherlands, india to united kingdom, india to united states, india to south africa, india to canada, india to australia, germany to netherlands, germany to united kingdom, germany to united states, germany to south africa, germany to canada, germany to australia, netherlands to united kingdom, netherlands to united states, netherlands to south africa, netherlands to canada, netherlands to australia, united kingdom to united states, united kingdom to south africa, united kingdom to canada, united kingdom to australia, united states to south africa, united states to canada, united states to australia, south africa to canada, south africa to australia, canada to australia.

efforts, highlighting the growing global inclusion in research efforts. The CCA_PG network is a global collaboration involving countries from all continents, with the US and UK at the centre and emerging contributors like China, South Africa, and India, addressing water sector challenges through stronger ties among neighbouring nations. The analysis underscores the significance of international cooperation in addressing CCA_PG in the water sector, promoting knowledge sharing, resource sharing, and strategies to enhance global resilience to climate change impacts.

3.2 Global citation impact of articles per country and author's contribution

Table 1 displays the top 20 countries cited most per average article in CCA_PG studies in the water sector from 2007 to 2023, highlighting their research productivity and impact, measured by article counts, total citations, and average article citations (AAC). The United Kingdom ranks highest in total citations (TC) with 38,329 and has the second-highest AAC of 108.27, indicating a substantial volume of impactful research. Despite producing 404 articles with a TC of 28,651, the United States has a slightly lower average influence (70.91) than other countries, indicating a lower output. Germany and Australia have strong AAC values of 96.89 and 69.83, ranking highly in terms of citations of 19,185 and 19,834, respectively. Austria, despite having a low article count of 53, has the highest AAC of 154.30, indicating the exceptional quality and influence of its articles while Switzerland and Malaysia have a small number of articles of 56 and 38, but high AAC values (139.67 and 145.23), indicating focused and high-impact research. It is worth noting that South Africa, India, and Kenya are emerging contributors to the field, with AAC values of 45.19, 51.65, and 99.81 respectively, indicating significant contributions. The results compare high-output countries like the UK, the US, and Germany with high impact, while countries like Austria, Malaysia, and Switzerland achieve high impact with fewer articles, reflecting diverse global participation (Table 1). Consequently, it shows the global distribution of research on CCA_PG studies in the water sector, with countries with fewer articles but high AACs providing critical insights, and those with high output contributing broadly to the field. The majority of cited studies were from developed countries, with a small number from developing countries, indicating low research output possibly due to self-funded research and language barriers [8, 30]. Developed countries' performance in CCA_PG studies is influenced by high publications and article citations, indicating adequate research grants aiding their publications and increased research output [5, 12].

Figure 3 shows the top 20 authors whose articles on CCA_PG studies have received the highest number of global citations. The highest cited author was James F.D. has the highest number of (TC = 2065), followed by Masoud Y. and

Table 1 Top 20 countries most cited per average article citation on CCA_PG in the water sector from 2007 to 2023

S/N	Country	Articles count	TC	AAC
1.	United Kingdom	354	38,329	108.27
2.	United States	404	28,651	70.91
3.	Germany	198	19,185	96.89
4.	Australia	284	19,834	69.83
5.	Netherlands	177	12,825	72.45
6.	Canada	205	11,794	5.82
7.	Sweden	96	10,892	113.45
8.	China	137	12,283	89.65
9.	Switzerland	56	7822	139.67
10.	South Africa	136	6146	45.19
11.	Spain	96	5767	60.07
12.	Austria	53	8178	154.30
13.	Iran	44	6287	142.88
14.	Malaysia	38	5519	145.23
15.	Kenya	49	4891	99.81
16.	Italy	91	5072	55.73
17.	New Zealand	41	6045	147.43
18.	Peru	22	4267	193.95
19.	India	104	5372	51.65
20.	Finland	45	4563	101.4

TC Total Citations, ACC Average article citation

Benjamin P., with (TC = 1669 and 1350), respectively. In particular, James F.D.'s research explores global climate change adaptation challenges, policy development, and decision-making in sectors like water, assessing human adaptation progress and dynamics at different temperature thresholds, while Masoud Y.'s research focuses on examining institutional constraints in groundwater resource management through CCA_PG studies. This study highlights the significant impact of two influential researchers in the CCA_PG field, focusing on their productivity and average total citations to measure the author's contribution in a specific field [79]. Other notable authors include Felix C. (TC = 1243 citations), Ford Lee, B. (TC = 1415), and Tristan P. (TC = 1239) also have substantial contributions based on their high citation counts, while authors, like Louis L. (TC = 502), Shaib L. (TC = 563), and Walter L.F. (TC = 354), received moderate recognition in the field. On the other hand, authors with relatively lower citations including Mulala S.D. (TC = 42), Dany V. (TC = 103), and Michael H. (TC = 266) have fewer citations compared to others in this list. The study reveals a significant influence of a small group of researchers in the CCA_PG studies, with a significant decrease in citation counts from top to lower-ranked authors. The highest citations indicate groundbreaking or highly referenced studies, indicating the influence of diverse authors with varying impacts on the field, emphasizing the importance of diverse contributions.

3.3 Geographical distribution of journals and author's keywords co-occurrence

Table 2 shows the top 20 journals publishing articles on climate change adaptation and policy governance (CCA_PG) studies within the water sector from 2007 to 2023. The results show that Sustainability (Switzerland) is the top journal with the highest number of publications ($n = 106$), followed by Environmental Science and Policy, accounting ($n = 52$), and Global Environmental Change ($n = 43$) making them a crucial research platform. The field, comprising 33.4% of total articles, is distributed across large journals and covers research across various fields, indicating extensive coverage across various research areas [51]. The Lancet journal, despite its small number of publications, has garnered the highest total citations at 8724, indicating its significant impact on the field. Moreover, Global Environmental Change and Climatic Change are two high-impact journals that balance high output and impact with 49 and 43 publications and 5911 and 2109 citations, respectively (Table 2). Specialized and focused journals like Nature Climate Change and Marine Policy have published significant contributions in niche areas with 9 and 10 publications and 1535 and 780 citations respectively. Some less-known journals, like The Lancet and Ecological Economics, maintain significant citation counts, indicating high-quality or groundbreaking articles. Journals cover a wide range of topics, from environmental science and Policy and climate and Development to interdisciplinary publications like The Lancet, and Wiley Interdisciplinary Reviews. The study reveals key academic sources on climate change adaptation and governance in the water sector, revealing both quantity and impact across journals, despite potential inconsistencies in total citations.

Figure 4 shows lines connecting nodes, with thicker lines indicating stronger connections or frequent co-occurrences of two keywords in the same article. The nodes are categorised into clusters with similar thematic content, with larger nodes in publications indicating more frequent usage, and smaller nodes in other areas indicating less frequent usage. The green cluster includes keywords like adaptive management, governance approach, and vulnerability, focusing on decision-making and governance strategies while the red cluster, centred on climate change and adaptation, is closely linked with keywords such as sustainability, mitigation, and environmental policy. The blue cluster encompasses water

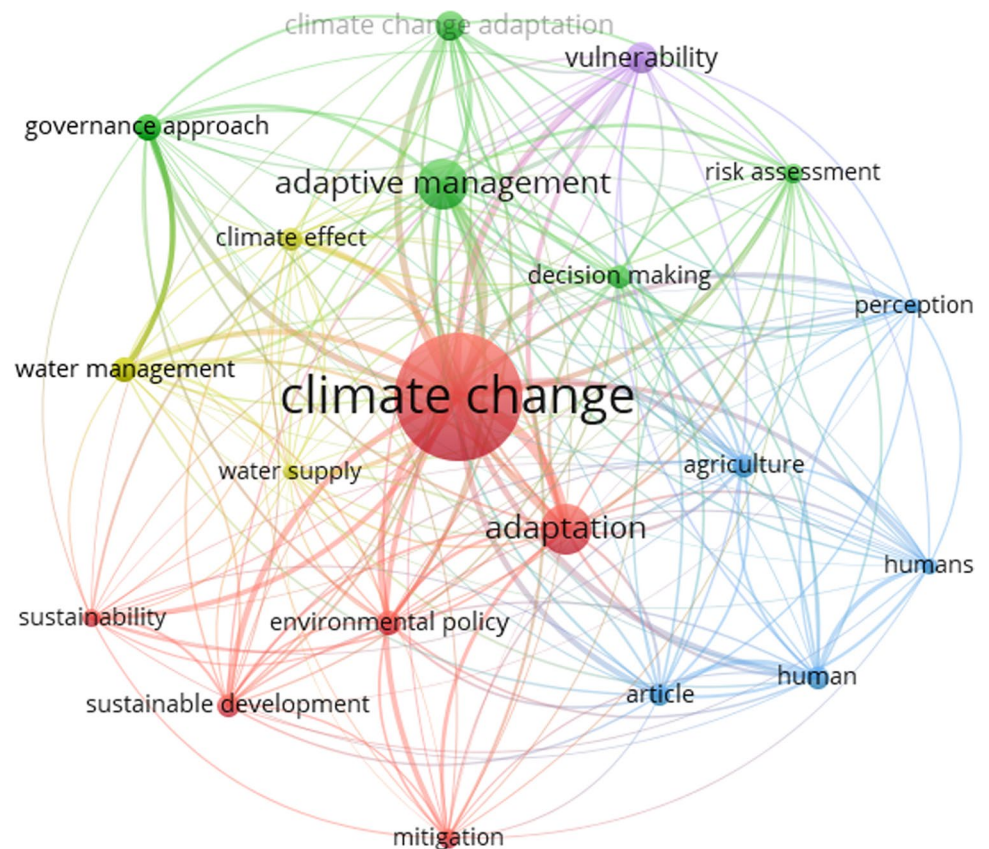
Fig. 3 Top 20 global citations of authors' articles in CA_PG studies



Table 2 Top 20 journals on CCA_PG in the water sector from 2007 to 2023

Source	NP	TC
Sustainability (Switzerland)	106	1524
Environmental Science and Policy	52	1749
Global Environmental Change	49	5911
Mitigation and adaptation strategies	38	1595
Regional environmental change	34	2233
Climatic Change	43	2109
Nature Climate Change	9	1535
Wiley interdisciplinary reviews	39	913
Environment and Planning	13	961
Climate and Development	39	913
Local Environment	20	636
Environment, Development and Sustainability	25	1165
Journal of Cleaner Production	30	1304
Ecological Economics	11	706
Journal of Environmental Management	21	1384
The Lancet	9	8724
Climate Policy	19	1150
Review of Policy Research	7	143
Science of the Total Environment	27	1479
Marine Policy	10	780

N Note Number of articles, *TC* Total citations

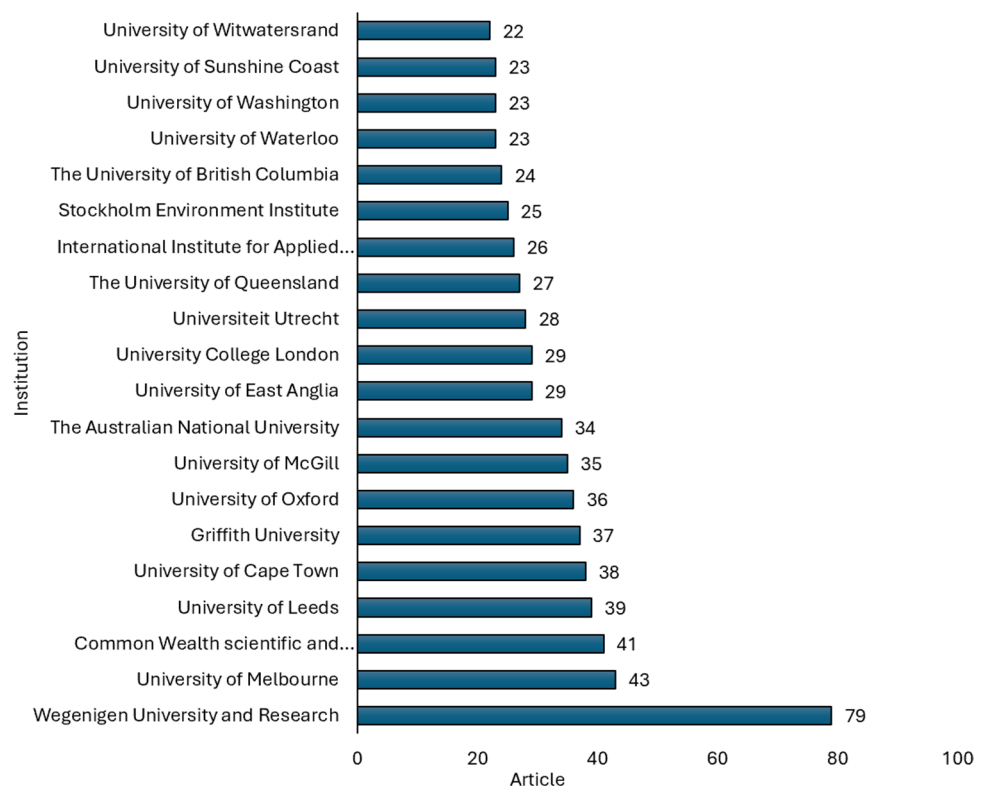
Fig. 4 Top 20 authors key-words co-occurrence network on CCA_PG in the water sector

supply, agriculture, humans, and risk assessment, highlighting the societal and sectoral impacts of climate change. The purple and yellow clusters include specific terms like perception, climate effect, and sustainable development, highlighting distinct specialized research areas. It is worth noting that climate change ranked the highest appearing keyword term, accounting for 1237, followed by adaptation accounting for 472, and vulnerability with 130 occurrences. The author's keywords in CCA_PG studies were rarely used in drought, water supply, risk assessment, and perception, suggesting the need for future research in these areas. Research often integrates environmental sustainability with management practices, as emerging themes such as sustainability, water management, and decision-making demonstrate strong connections. Nevertheless, risk assessment and vulnerability focus on assessing risks and understanding how communities or systems adapt to climate challenges. Moreover, keywords like governance approach and environmental policy emphasise the role of policy and governance in addressing climate adaptation challenges in the water sector. The research in CCA_PG is multi-disciplinary, integrating themes of climate change, governance, sustainability, and societal impacts, as demonstrated by the co-occurrence network. The centralized positioning of climate change and adaptation in this field underscores their significance, while the network reveals diverse and interconnected research areas within the water sector, highlighting both broad and specialized fields of study.

3.4 Institutional affiliations per article publications

Figure 5 shows the top 20 collaborations among institutions on climate change adaptation policy and governance (CCA_PG) studies in the water sector, highlighting the number of articles published by these institutions. Wageningen University and Research has the highest number of articles (79), followed by the University of Melbourne (43), and Common Wealth Scientific and Industrial Research Organization (41), indicating primarily national collaboration. The University of Cape Town and the University of Witwatersrand are the only African institutions on the list, contributing the least number of articles among the top 20 developed countries institutions, with 38 and 22 articles respectively. This may be largely due to low research output from developing countries in terms of regional representation contributions. The gap between developed and developing countries is significant, necessitating urgent coordinated research efforts and reevaluating climate policy incentives to bridge this gap [48, 49, 64]. Research indicates that addressing complex communication networks and resource constraints in climate change adaptation methodologies necessitates specialized knowledge in both technical and communication domains [65, 71]. The results reveal a

Fig. 5 Top 20 institutional affiliations per article publications on CCA_PG studies in the water sector



significant difference in article contributions between Wageningen University and other institutions, with only one surpassing the 70-article mark, indicating a significant disparity in the overall contribution range, as shown in Fig. 5.

4 Discussion

This study analyzed published articles on CCA_PG using bibliometrics, examining temporal trends in scientific contributions, country collaboration networks, global citation impact and author's contribution, geographical distribution of journals and author's keywords co-occurrence. Furthermore, it explores the evolution of global water sector research, highlighting key themes in CCA_PG studies, major contributors, and institutions while examining the interconnected influence of corporate governance, climate change adaptation, and sustainability on societal impacts. During the survey period, the average growth per article indicates a sharp increase in research on CCA_PG studies due to global climate change and water scarcity challenges. The growing interest in CCA_PG studies in the water sector is expanding research opportunities and promoting interdisciplinary collaborations, driven by global climate agreements and heightened awareness of water-related climate risks [21, 36]. This study provides a detailed analysis of key academic sources on CCA_PG studies in the water sector, highlighting their quantity and impact across various journals. The study reveals a small group of researchers significantly influencing CCA_PG studies, with a decline in citation counts from top to lower-ranked authors. The study shows significant research gaps, especially in risk assessment and water governance regimes. The dominance of climate adaptation and resilience-based interdisciplinary methodologies in developed nations is largely due to their widespread adoption in developing regions [9, 64].

4.1 Disparities in research contributions between developed and developing countries

The study reveals significant disparities in research contributions, with developed countries like the USA, UK, and Australia producing the majority of CCA_PG studies, characterized by well-funded institutions and strong publication networks. Conversely, developing nations, particularly Africa and South America, contribute less. Research output in developing countries is often hindered by financial constraints, inadequate institutional support, and language barriers, leading to limited international collaboration. For instance, countries like Peru, Finland, and Malaysia have shown low research output and single-country publications during the survey period. Moreover, research from developing nations often appears in regional journals that may not be indexed in major databases, resulting in lower global recognition. The low publication rate in CCA_PG studies in developing countries is largely due to the lack of investment, which is a significant factor contributing to the field's low rate [5, 70]. This indicates a need for stronger research networks and funding mechanisms to bridge the gap. The extant literature underscores the need for increased autonomous research funding, effective collaboration, and technical expertise in Global North countries to enhance research capacity and meet growing regional demands. Regional representation institutions like the University of Cape Town and the University of Witwatersrand showcase African institutional participation, while others like the Stockholm Environment Institute highlight European contributions. However, the presence of institutions from diverse regions, including Australia, South Africa, North America, and Europe, exhibit active global collaboration, indicating a strong global presence in various fields. Wageningen University and Research is a leading figure in climate change adaptation policy and governance studies, particularly in the water sector, according to a report by the Dutch government's research department [14, 28]. Addressing these disparities requires global collaboration, increased investment in research capacity-building, and equitable access to scientific resources, with joint projects fostering knowledge transfer and strengthening research in underrepresented regions.

4.2 Addressing research gaps in global climate adaptation governance: integrating water risk and sociopolitical dimensions for sustainable development

The effectiveness of global climate adaptation governance is being enhanced by reinforcing its theoretical foundation through climate governance theories. This study's findings align with multiple climate governance theories, including adaptive governance, polycentric governance, transnational governance, institutional theory, and environmental justice theory [53, 54, 60, 83]. The integration of various theoretical perspectives enhances the comprehension of

CCA_PG issues and aids in the identification of effective policy solutions. For instance, a study underscores the influence of economic, political, and social factors on involuntary immobility, highlighting the need for policies that align with aspirations and capabilities while integrating a global support mechanism [68]. Despite limited data on affected populations, targeted policy interventions can enhance resilience, address migration constraints and adaptation needs and ensure vulnerable communities are integrated into climate change adaptation strategies. Insights from the climate change-immobility nexus, based on perspectives of voluntarily immobile populations in African coastal communities, underscore the need for inclusive and adaptive governance frameworks [40]. Several research gaps persist in CCA_PG studies, with a limited focus on water risk assessment, governance regimes, and the socio-political dimensions of adaptation strategies [20, 34, 35, 41]. The keyword co-occurrence analyses revealed an underrepresentation of terms like “drought,” “water supply,” “risk assessment,” “perception,” and “decision-making,” indicating a need for further exploration in these areas. The intersection of climate adaptation, governance, and sustainable development goals (SDGs) CCA_PG research is closely linked to Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). Improving water sustainability policies and addressing governance gaps in developing nations can enhance climate resilience and disaster preparedness. Furthermore, this study aligns its findings with established climate adaptation frameworks, including the Intergovernmental Panel on Climate Change (IPCC) adaptation framework, the United Nations Framework Convention on Climate Change (UNFCCC) adaptation pathways, and the Sendai Framework for Disaster Risk Reduction. These frameworks emphasize risk-based adaptation strategies, resilience-building, and multi-stakeholder engagement, all of which are key themes emerging from this study. Consequently, by reinforcing the significance of these global frameworks, this research underscores the need for governance models that integrate both top-down and bottom-up approaches in adaptation planning and implementation. Effective climate change adaptation policy and governance (CCA_PG) strategies, aligned with global frameworks, must prioritize equity and justice to prevent disproportionate climate change impacts on marginalized communities. Furthermore, the study reveals a shift towards interdisciplinary research considering socioeconomic, biophysical, and institutional aspects of climate change adaptation studies. This study advocates prioritizing transboundary technology integration and inclusive policy frameworks to enhance global water sustainability efforts.

4.3 Transforming climate adaptation governance: bridging multi-level policy gaps, advancing equity, and leveraging technology for resilient societies

The findings have significant policy implications, highlighting the need for integrated, multi-level governance strategies that align with holistic and adaptive approaches to achieving sustainable development goals. Climate adaptation efforts are constrained by weak governance structures and fragmented policies, particularly in water-scarce regions, where limited resources and regulatory capacity hinder effective national and local strategies, ultimately undermining global sustainability goals [9, 35]. As a result, inadequate adaptation policies have far-reaching global implications, exacerbating water scarcity, increasing the frequency of extreme events, and intensifying socio-economic vulnerabilities [32, 37]. A growing concern is that climate variability, driven by global climate change, threatens the sustainability of various sectors, including water resources, with significant impacts on human health, agriculture, and ecosystems [1, 4, 24, 33, 38, 78]. The underfunding of global climate change adaptation efforts and the growing finance gap pose significant challenges to effective policy implementation [17, 44]. The international community must prioritize adaptive governance to mitigate vulnerabilities caused by extreme weather events and shifting climatic patterns in ecosystems, economies, and societies. A recent study emphasizes the need for comprehensive strategies to address the multifaceted impacts of climate change on water systems, emphasizing the integration of scientific knowledge into governance and policy frameworks [31]. The disparity in governance frameworks indicates a need for more inclusive ones that empower local stakeholders, emphasising the need for more effective and equitable governance systems. This research underscores the significant global impact of adaptation policies on sectors like agriculture, infrastructure, and public health, influencing local and regional outcomes, global markets, migration patterns, and international security. Climate change adaptation research emphasizes the global link to social equity and justice and the need for effective governance mechanisms to enhance water management resilience policy tools [72]. The intersectionality of social equity and justice is crucial in addressing climate change adaptation. Climate impacts disproportionately affect vulnerable populations, especially in developing countries lacking resources for adaptive measures, highlighting the need for equitable policies to prevent marginalized groups from being overlooked [23,

70]. For instance, community-based adaptation strategies, which empower local actors, are increasingly recognized as crucial for promoting inclusivity and fostering long-term resilience [3]. However, the lack of addressing equity concerns in adaptation policies can lead to the perpetuation of existing inequalities and undermine their global effectiveness. Future climate adaptation governance research should prioritize transboundary collaboration and knowledge sharing to address global challenges such as rising sea levels and water scarcity, recognizing climate change as a borderless issue.

Studies show that individuals and households are crucial in implementing climate change adaptation measures, yet they are often underrepresented in institutional responses [27, 61]. Moreover, researchers advocate for the creation of regional governance frameworks that foster joint resource management, disaster response, and data exchange [19, 46]. For instance, international organizations like the United Nations Framework Convention on Climate Change (UNFCCC) play a crucial role in facilitating partnerships and ensuring compliance with global adaptation goals, making their role pivotal in achieving these goals. Advancements in artificial intelligence, remote sensing, the Internet of Things (IoT), and climate modeling are transforming climate governance and adaptation research in the water sector by enhancing risk assessments and enabling targeted interventions [42, 80]. A study underscores the role of technology in climate adaptation governance, emphasizing the integration of advanced technologies into policy frameworks and the advancement of digital tools and emerging trends in adaptation strategies [39]. Predictive models aid policymakers in identifying climate-vulnerable areas, guiding infrastructure investments, and ecological restoration [26]. However, to maximize their effectiveness, research must address the digital divide to ensure the equitable distribution of technological benefits and enhance adaptive capacities at local, national, and global levels by improving access to digital technologies. Achieving this requires substantial investment and international cooperation to strengthen adaptive capacities and promote fair resource distribution. Future research on climate change adaptation policy and governance in the water sector must bridge the digital divide to ensure the equitable global distribution of technological benefits through inclusive, collaborative, and advanced approaches.

4.4 Global policy implications and future strategies for climate governance and adaptation

This study underscores the growing global focus on CCA_PG and calls for decisive action by policymakers and environmental stakeholders in climate governance and adaptation strategies. The future climate governance strategies are comprised of several crucial components as follows.

1. Strengthening adaptive water governance frameworks requires climate adaptation policies to shift from reactive measures to proactive, long-term strategies that integrate scientific research, local knowledge, and socioeconomic considerations. Policies must be adaptable to the changing climate risks and uncertainties, ensuring they are flexible and responsive to the changing landscape.
2. Enhancing multi-level and cross-sectoral collaboration in climate governance requires coordinated efforts among national, regional, and local governments, alongside partnerships with non-governmental organizations, the private sector, and communities. Strengthening these linkages enhances resource allocation, data sharing, and the effective implementation of policies.
3. Bridging the research gap between developed and developing nations underscores disparities in research output, emphasizing the need for enhanced collaboration and capacity-building to foster equitable knowledge production. Implement targeted funding and capacity-building initiatives to enhance research and policy development in under-represented regions, fostering South-South and North–South collaborations to facilitate knowledge exchange and inclusive policy formulation.
4. Many developing nations still view climate adaptation as a secondary concern, despite the need to integrate it into their national development agendas. Governments should mainstream climate adaptation into national development policies, ensuring it is in line with economic growth, infrastructure planning, and disaster risk reduction.
5. Leveraging data-driven approaches using remote sensing, geographic information systems (GIS), and artificial intelligence in climate adaptation can enhance forecasting accuracy and risk assessments. Digital technologies can enhance climate governance through real-time monitoring, predictive modeling, and evidence-based decision-making, necessitating government investments in early warning systems and stakeholder engagement.
6. Aligning climate policies with SDGs is crucial, given their strong intersection between climate governance and sustainability, particularly SDG 6 and SDG 13. Therefore, adaptation policies should be designed to support broader

sustainability targets, integrating equity and justice considerations into climate governance to prevent disproportionate impacts on marginalized communities.

Therefore, implementing these strategies enables governments and institutions to strengthen climate resilience, optimize water resource management, and develop more effective and inclusive climate governance policies. The global community can enhance climate resilience by prioritizing equity, leveraging innovation, and fostering international cooperation among societal actors to develop resilience-focused strategies through effective adaptation governance to address complex climate change challenges.

4.5 Study limitations

The study highlights the limitations of bibliometric analysis, and focusing on one database including language bias, as it only included English-language articles, potentially excluding relevant research published in other languages. However, the exclusion of non-English-speaking regions, especially in Latin America, Africa, and Asia, may underrepresent their research contributions from certain countries or institutions. Future research could enhance global research representation by incorporating multiple databases like Web of Science and Google Scholar and exploring multilingual bibliometric approaches. Hence, effective climate change adaptation policy and governance in the water sector require observational studies to assess qualitative societal impacts and practical implementation. Qualitative analyses, such as expert interviews and case studies, can enhance understanding of climate change adaptation policy and governance in the water sector, complementing bibliometric findings.

5 Conclusion and recommendations

The study assessed the global research trajectory in the water sector and identified dominant themes in CCA_PG studies through bibliometric evaluation. The CCA_PG field exhibited significant annual growth, with a sustained increase in publication output throughout the assessment period. The study shows an increasing global trend in CCA_PG studies, with developed nations like the USA, United Kingdom, and Australia significantly contributing to article counts while developing countries have limited outputs. There exists a significant gap in research on risk assessment and water governance regimes, with climate adaptation and resilience-based interdisciplinary methodologies being dominant in developed nations. The study reveals that climate change and adaptation are frequently used keywords in CCA_PG studies, highlighting their interconnectedness in water sector research, governance, and policy approaches, indicating their relevance for further studies. The study underscores the need for a comprehensive strategy that integrates top-down and bottom-up approaches to water resource management, addressing socio-economic, institutional, and biophysical complexities in response to climate change. This study enhances climate adaptation and sustainable water management by addressing governance gaps, aligning with SDGs 6 and 13, and fostering international collaboration to develop policies that mitigate water scarcity and strengthen disaster resilience in developing countries. It provides a strategic roadmap for developing nations to advance CCA_PG research, enhance water governance, and mitigate global climate change impacts on water resources through sustained research, empirical studies, and innovative solutions for sustainable water management. This study recommends integrating scientific insights with socio-economic factors in climate change adaptation research to develop equitable, sustainable strategies that inform policy and governance while refining theoretical frameworks to enhance adaptation strategies. Future research should prioritize national adaptation strategies, ecosystem-based adaptation, nature-based solutions, community-driven governance, and cross-sectoral integration to enhance sustainable water management.

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Data availability Data used in this study are available on request. Requests for access to these data should be made to Gbenga Abayomi Afuye [afuyeabayomi@gmail.com].

Declarations

Ethics approval and consent to participate and publish Not applicable.

Competing interests The authors declare no competing interests.

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