

Systematic evidence-mapping of climate change adaptation challenges in urban water systems

Shefali Nayak

shefali.nayak@hcu-hamburg.de

Department of Urban, Regional and Environmental Planning, HafenCity University, Hamburg, Germany
and Department of Earth System Sciences, Faculty of Mathematics, Informatics and Natural Sciences,
Earth and Society Research Hub (ESRAH), University of Hamburg, Hamburg, Germany

Zayra Castillo

Hamburg University of Technology, Hamburg Germany

Rana Ekmekcioglu

School of Integrated Climate and Earth System Sciences, University of Hamburg, Hamburg Germany

Franziska S. Hanf

Systemic Risks, RIFS Research Institute for Sustainability at GFZ Helmholtz Centre for Geosciences,
Potsdam, Germany and Atmospheric Science, Department of Earth System Sciences, Faculty of
Mathematics, Informatics and Natural Sciences, Earth and Society Research Hub (ESRAH), University of
Hamburg, Hamburg, Germany

Nadine Kaul

Department of Earth System Sciences, Physical Geography, Earth and Society Research Hub (ESRAH),
and Department of Biology, Applied Plant Ecology, University of Hamburg, Hamburg, Germany

Leam Martes

Department of Biology – World Forestry, University of Hamburg, Hamburg, Germany

Linda Meier

Department of Earth System Sciences, Physical Geography, Earth and Society Research Hub (ESRAH),
Hamburg, Germany

Feline Schoen

Institute of Geography, University of Hamburg, Hamburg, Germany and Instituto de Ecología y Ciencias
Ambientales, Facultad de Ciencias, Universidad de la República, Montevideo, Uruguay

Malte von Szombathely

Department of Earth System Sciences, Faculty of Mathematics, Informatics and Natural Sciences,
Earth and Society Research Hub (ESRAH), University of Hamburg, Hamburg, Germany

Benjamin Poschlod

Institute for Global Water Security, Hamburg University of Technology, Hamburg, Germany and
Department of Earth System Sciences, Faculty of Mathematics, Informatics and Natural Sciences, Earth
and Society Research Hub (ESRAH), University of Hamburg, Hamburg, Germany

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Abstract

Despite many studies on climate change adaptation, implementation challenges are understudied. After screening over 39,000 articles, we used large language models on 892 articles to map global adaptation challenges in urban water systems. Publications have grown exponentially since 2011, but research is biased toward the Global North. Floods dominate literature, leaving droughts underrepresented despite their socio-economic impact. Our analysis of measure-challenge associations reveals: i) institutional and social challenges are pervasive in all adaptation types, ii) institutional challenges have moderate associations across measures where high frequencies often hinder CCA measures, iii) structural and technological CCA measures receive more research attention than behavioral, social, and anticipatory approaches. Our synthesis identifies research gaps and policy priorities: focus on socio-behavioral and anticipatory adaptation, research in understudied regions, and urgent institutional reform as an adaptation prerequisite.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has indicated that the global population is anticipated to face a reduction in renewable water resources, exacerbating the risks of hydrological drought and water insecurity¹. Climate-related disasters are becoming more frequent and intense, endangering lives, livelihoods, and economic assets². Nearly one-third of urban populations face water scarcity, with projections indicating that this could reach half of urban residents by 2050³. Unplanned urbanization contributes to climate change and urban heat islands, while climate change increases urban vulnerabilities through extreme weather, rising seas, and altered precipitation patterns^{4,5}. Recent research indicates that transformational adaptation and international cooperation are vital for urban water security amid climate change⁶.

Although there is a burgeoning body of scientific knowledge on climate change⁷ and adaptation research⁸, the volume of information on adaptation in the form of reviews^{9,10} remains fragmented. Adaptation in urban areas is frequently characterized as advancing too slowly¹¹. The challenges highlighted are at various governance levels, from local to national, and span different sectors, interacting in a dynamic way that makes adaptation a complex and path-dependent task^{7,12–14}. Additionally, research on the adaptation of urban water systems has either been case-study specific⁶, focused on nature-based solutions¹⁵, water quality¹⁶, flood and drought impacts⁵, and wastewater infrastructure¹⁷, or has highlighted only the impact of climate change and adaptation strategies on urban water systems¹⁸. This continues to provide only partial answers to the various forms of climate change adaptation (CCA) of urban water systems. Previous CCA research has explicitly highlighted the need for more and better synthesis methods that cover overlooked sectors¹³. Therefore, a consolidated knowledge synthesis of CCA is necessary, especially with a focus on urban water systems.

Knowledge synthesis is a process where knowledge is systematically collected, analyzed, and integrated to draw comprehensive conclusions on specific topics and questions¹⁹. They are underrepresented in climate change research field^{20,21}. Systematic evidence-mapping is an endorsed methodology for knowledge synthesis to extract novel and relevant insights from an extensive corpus of literature²². Traditionally, reviews require human coders to synthesize data from peer-reviewed articles, rendering the process laborious and restricted to a limited number of documents²³.

Lately, natural language processing (NLP) is being used to manage vast volumes of literature in the CCA field to overcome previous constraints^{13,24,25}. However, there exists a large number of scientific articles that are thematically distributed broadly, which hinders the precise data extraction of scientific evidence from long-format texts in peer-reviewed journals. Due to this, as of now, many NLP-based meta-analyses and data syntheses have focused on extracting data only from the abstract^{4,6}. This narrows the scope of the research by oversimplifying and disregarding details in the full-text article. With current advancements in large language models (LLMs), NLP enables the automated extraction of information from full-text articles. This creates new potential for information analysis^{25–27}.

Our study leverages advanced NLP automation and aims to fill the persistent knowledge gap on the relationship between urban development constraints, CCA measures, and CCA challenges in the context of urban water systems. We identified 892 relevant studies that formed the basis for a global mapping of adaptation measures and challenges, providing an overview of the current state of research. We used an improved evidence synthesis method as a robust, science-informed global stocktake of CCA challenges. This work may inform the 7th IPCC assessment report, particularly in identifying strategies to address urban water-related risks and contribute to supporting progress towards the Global Goal on Adaptation.

Results

Patterns in climate change adaptation research for urban water systems

As shown in Fig. 1(a), there has been strong exponential growth in the number of publications on CCA research on urban water systems since 2011. Note that data extraction was concluded in July 2024, which accounts for the shorter length of the 2024 bar. Given that this point in time is approximately mid-year, it can be inferred that the bar length would be approximately double if the data for the entire year were considered. Certain years stand out in particular; 2011 was the most expensive year (\$380 billion globally) for losses due to natural hazards. Many countries in the developed world (Thailand, New Zealand, Japan, Australia, and the USA) have been hard hit by various types of water-related natural hazards²⁸. In 2012, the IPCC published its Special Report on Managing Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), which analyzed the link between climate change and extreme events and set a new standard for climate risk research and adaptation strategies. The report became a foundational guideline for global adaptation and disaster risk planning². Several international research programs and collaborative studies, such as the "governance of adaptation to

climate change," outlined in scientific papers, have been initiated or extended. These efforts emphasize real-world trials, stakeholder participation, and hotspot collaboration²⁹. The next spike in publications occurred after 2015, which can be attributed to the Paris Agreement, especially as the agreement intensified global scientific efforts to better understand climate impacts, adaptation, and mitigation strategies³⁰. There was a decline in publication outcomes in 2021, which we link to the global COVID-19 crisis.

Fig. 1(b) shows the number of identified case study cities mentioned in peer-reviewed publications categorized by their population size. The distribution broadly reflects the global proportion of cities within each population bracket, with slightly greater representation of megacities exceeding 10 million inhabitants based on World Urbanization Prospect 2025^{31,32}. The slight emphasis on megacities is valuable as it highlights the influence of population dynamics in large and densely populated urban environments. Despite their slightly higher relative representation in our dataset, the absolute number of studies specifically addressing water management challenges in megacities under conditions of rapid population growth remain limited^{33–35}. This thematic gap constrains effective planning and implementation in cities exceeding certain population thresholds, even though research on urban expansion and flood risk consistently shows that large-scale urbanization amplifies such challenges^{33–35}.

The highest number of publications originated from Asia, followed by Europe, North America, Africa, Oceania, and South America (Fig. 1c). Although the Emergency Events Database (EM-DAT) similarly identifies Asia as the most disaster-affected region, Tin et al.⁶⁸ reported a different ordering of incident counts for 1995–2022, namely, the Americas, followed by Africa, Europe, and Oceania. This divergence between the disaster incidence ranking and publication output suggests a geographic imbalance in the literature, with Global North cities disproportionately represented. The number of research studies is strongly dominated by floods, and this pattern is noticeable across all continents except Oceania. Floods are among the most extensively studied natural hazards because of their high frequency and significant human and economic impact^{36–38}, where urban areas are comparatively underrepresented in studies addressing global flood risk. Global reviews also confirm that the literature on flood risk, modelling, and response is more developed than that on drought³⁹, which is due to the contrasting nature of their occurrences. Floods have a rapid onset and impact, whereas droughts have a prolonged onset and impact⁴⁰. Droughts are one of the most expensive natural hazards for society⁴¹; however, there is lower public awareness and visibility compared to dramatic flood events, Olazabal et al.⁴² highlights the mismatch between physical drought risks and institutional/ public perception of drought. This has led to a disparity in the volume of drought and flood research globally³⁶. Research focusing exclusively on droughts as isolated hazards, particularly within an urban environment⁴³, is less common than studies on floods and sequential hazards. Here, we confirm that this disparity also applies to studies on the challenges of CCA in urban water systems.

An analysis of the geographical and regional patterns of the reviewed publications shows a heterogeneous spatial distribution of urban water research (Fig. 1d). Most case studies are published for China and the USA, followed by Australia, India, Brazil, and South Africa. There is a lack of peer-reviewed publications from Eastern Europe, Central Asia, parts of North and Northwest Africa, and countries such as Paraguay, Venezuela, Bolivia, Guatemala, Suriname, Trinidad and Tobago, and Barbados. Within Europe, there are strong disparities in the distribution of the identified publications. The Netherlands and the United Kingdom exhibit the highest volume of scientific research on climate change adaptation and urban water management, with Germany and Italy closely following. France is comparatively underrepresented in Western Europe. Several factors may have contributed to this pattern. Research capacity in climate adaptation may be concentrated in Paris, with limited coverage of other urban contexts. In addition, the institutional positioning of urban planning and development within administrative structures has been reported to be comparatively weak⁴⁴. Methodological factors may also play a role, as the search string may not capture locally specific terminology and relevant studies may be published in French-language outlets.

There are studies indicating structural challenges in integrating adaptation into urban water policy, as recognized by the OECD and World Bank in Central Asia and Eastern European countries, while lacking robust local academic literature or systematic case studies in international reviews⁴⁵. Our results indicate that Africa has a disproportionately low publication rate, except for South Africa. The study by Doswald et al.⁴⁶ maps an evidence gap that highlights that the geographic coverage of urban water management systems is clustered within a selected group of countries. Many North and Central African nations are either underrepresented or are almost absent in the published research on climate change adaptation with respect to urban water.

Overall, evidence-mapping the case studies of the 892 selected articles reveals that most publications are from China, the United States, and India. While the number of cities in a country may drive the research needs and opportunities, our analysis shows that some countries are studied more or less than their urban population suggests (Fig. SX1). In Australia⁴⁷, the United Kingdom⁴⁸, and the Netherlands⁴⁸, the number of publications is high despite the relatively small number of large cities, indicating a disproportionately strong research focus on the urban scale. Conversely, Japan, Vietnam, Nigeria, France, Russia, and the Philippines, despite having numerous cities, are underrepresented in publications, indicating a disparity between the urban population and research output. Countries such as Brazil, Indonesia, Mexico, and South Africa occupy an intermediate position, with a moderate number of large cities and publications. Also, Italy, Spain, Germany, and Poland, display a balanced representation in the European domain.

Urban development constraints linked to measures and challenges in climate change adaptation

Based on the strong growth in CCA research on urban water systems after 2011 (Fig. 1a), we narrowed our analysis from 2011 to 2024 to examine the links between urban development constraints and CCA measures and challenges. In Fig. 2(a), our analysis shows that environmental, institutional, and

infrastructural urban development constraints dominate research across all continents, whereas social and economic issues receive comparatively less attention. In Asia, intensifying environmental, infrastructural, and institutional pressures are driven by rapid urbanization, population growth, and climate change. Europe shows a similar pattern, although social challenges are relatively more prominent in Asia. In contrast, in Africa and South America, a proportionally greater emphasis is placed on social urban development constraints, whereas in North America and Oceania, the focus is primarily on institutional, infrastructural, and environmental aspects.

Structural/physical types of CCA measures are consistently one of the most published categories across all continents, closely followed by technological measures, indicating growing research interest, investment in innovation, and prioritization of infrastructural solutions for CCA (Fig. 2b). These are followed by ecosystem-based CCA measures, with a slightly higher publication rate since 2020. Institutional/policy CCA measures are recognized as critical, yet the growth in scientific research is less steep compared to technological and structural CCA measures. Behavioral/social CCA measures are often published on par with institutional/policy CCA measures, highlighting the acknowledged need for social research in climate science and societal shift⁴⁹ in CCA practice. Anticipatory CCA measures remain the lowest in publication numbers, suggesting that explicitly proactive adaptation strategies remain underexplored relative to other CCA classifications. Studies show that this is due to the high cost of early adaptation and budgetary constraints, to which countries adapt reactively⁵⁰. Reactive measures with the lowest publication rates indicate a scholarly shift away from reactive solutions. However, the ground reality tells a different story: The IPCC report indicates that local governments that have begun to implement adaptation strategies often take a reactive or event-driven approach, primarily relying on technical solutions⁵¹. This underscores the disconnection between local governmental entities and the broader scientific community. Publications on cities in Africa and South America exhibited a sharp decline in 2021 (Fig. SX2), attributable to the global COVID-19 pandemic, whereas research output in Europe, Asia, North America, and Oceania remained largely unaffected. This disparity underscores persistent differences in global scientific research infrastructures.

An analysis of the classification of CCA challenges across the reviewed scientific literature (Fig. 2c) highlights that institutional and structural/physical CCA challenges are consistently the highest category of challenges mentioned in the scientific literature. We find this pattern to be stable across all continents (Fig. SX3) as well as from 2011 to 2024. This is followed by social CCA challenges and then technical CCA challenges, which are the third and fourth most frequently mentioned challenges across all continents. Since 2016, there has been a slight rise in ecosystem-related CCA challenges, which can be linked to the increased implementation of ecosystem-based adaptation strategies, such as nature-based solutions, after the Paris Agreement. Although economic CCA challenges are comparatively less frequently mentioned, they are reported sufficiently to warrant the creation of a distinct classification. The classification with the fewest publications is anticipatory CCA challenges, which are directly linked to social or institutional issues related to the acceptance of a specific CCA measure.

Evidence synthesis of the association strength between climate change adaptation measures and challenges

Fig. 3 shows the association strength of CCA measures and CCA challenges, indicating thematic linkages between their categories. However, association strength does not imply causality. In the case of measures and challenges from the same categorical domain, strong association strengths align with their thematic linkage, providing empirical confirmation of the robustness of the methodology. We find the strongest positive associations between behavioral/social CCA measures and social CCA challenges, followed by ecosystem-based CCA measures and ecosystem-based CCA challenges. Ecosystem-based CCA challenges are likely due to ecosystem complexities, which are the inherent, intricate, and unpredictable nature of ecosystem-based CCA measures, sometimes further worsened by climate change⁵². Finally, the technological CCA measures and technical CCA challenges are strongly associated. It is imperative to prioritize the resolution of technical issues, including the operation and maintenance of technology⁷³ to effectively implement future-proofing measures. By resolving these human, technological, and systemic barriers, the implementation of solutions becomes considerably feasible.

Moreover, institutional CCA challenges exhibit low to moderate association strengths (close to 1.0) with all other adaptation measure types, and their high marginal frequency of over 8,900 mentions indicate that they are the most frequently reported. This suggests that institutional CCA challenges, such as leadership dependence, silo organization, and spatial policy mismatches, are pervasive across all forms of adaptation measures, illustrating the importance of institutions for adaptation⁵³. Further, we find a notable positive association between institutional/policy CCA measures and social CCA challenges. This is in line with recent assessments of social disparities^{54,55}, highlighting that equitable adaptation requires transformative changes in planning, governance, and resource management, guided by social justice principles to address the fundamental drivers of urban water-related risk.

Furthermore, we analyzed the association strength between the categories of urban development constraints and the categories of CCA measures (Fig. SX4), as well as categories of urban development constraints with the categories of CCA challenges (Fig. SX5). For all possible combinations, we find no significant dependence between the presence of specific urban development constraints and the existence of particular CCA measures or challenges. However, this finding is solely based on the mention of urban development constraints, but not their magnitude. While the magnitude of social, environmental, institutional, infrastructural, and economic urban development constraints varies substantially across the globe^{3,56,57}, our assessment cannot provide insight into whether the severity of constraints affects CCA measures or CCA challenges.

Discussion

Addressing the relationship between CCA measures and challenges is a critical component of climate change research. It identifies the most prevalent obstacles encountered by scientists, policymakers and

practitioners in the implementation process. Recognizing these challenges in advance is crucial for developing revised plans that avoid similar or recurring impediments. We identified four key findings by exploring their significance in research and policy-making concerning CCA measures and challenges in urban water systems.

First, our findings reveal a notable global bias in research and publication. Even when most countries are well-represented in the scientific literature, the proportion relative to the number of cities with populations over 100,000 is imbalanced. The results also show a heterogeneous spatial distribution of case studies investigated in peer-reviewed articles. Our results indicate that Africa has a disproportionately low publication rate, except for South Africa. Neglecting to study climate adaptation and urban development constraints in Africa increases the vulnerabilities of cities that are rapidly urbanizing and facing multiple climate-related threats. Mwenje et al.⁵⁸ and Servièrès et al.⁵⁹ highlight that this lack of attention worsens existing issues such as insufficient infrastructure and governance deficiencies, resulting in significant socioeconomic and environmental impacts.

Second, our results highlight the disparity between flood and drought research. The data indicate that research studies are predominantly focused on floods, a trend observable across all continents, with the exception of Oceania. Australia successfully managed its millennium drought (1996-2009) with record-low rainfall; however, the drought response was not adequate⁶⁰ as decision-making was crisis driven and fragmented rather than long-term adaptive governance. Urban drought can lead to water shortages, with reduced urban water system reliability. Previous research on urban water systems shows drought responses are tied to maintaining supply reliability, but drought still strains demand and can expose weak points in urban water management⁶². Further research on urban drought is crucial in identifying vulnerable systems and communities, so cities can plan water-saving, adaptation, and emergency response measures before shortages become crises. Cape Town gained attention in the period of 2016-2018 while affected by severe drought, highlighting the importance of infrastructure diversification and better groundwater management⁶³. Despite projections of more frequent and severe occurrences, particularly in cities, research gaps concerning floods, droughts, and sequential events persist owing to ongoing issues with awareness, funding, and visibility of these crises⁴². The current adaptation approach is fragmented, often focusing on either flood or drought⁶⁴. This approach of targeting only one extreme can fail under rapid transition⁶⁵. Sustainable urban water futures require a radical shift in society's urban climate adaptation imaginaries toward transformative adaptation that addresses the root causes of water-related risks and vulnerabilities. This approach must also be holistic, considering synergies between flood and drought measures to effectively manage the complex urban water risk-adaptation nexus⁶⁶. Therefore, we call for further research that examines floods and droughts as functionally interconnected phenomena, with a focus on integrated adaptation strategies.

Third, although ecosystem-based CCA measures are increasingly researched and impacted^{67,68}, we find a concentration in adaptation literature primarily focusing on infrastructural and technological adaptation measures, alongside integrated approaches where an ecosystem-based strategy is

incorporated. We find a comparatively low research focus on socio-behavioral adaptation measures. Socio-behavioral adaptation measures encourage individuals and communities to modify or adopt behaviors in response to climate change. These measures recognize human behavior is complex, often needing information, incentives, and structural support to shift practices and enhance adaptive capacity. Aoki et al.⁶⁹ highlight that technical or infrastructure-based climate solutions often underperform if they ignore human behavioral responses or community norms. This underscores the necessity for further scientific investigation in policy-oriented and socio-behavioral adaptation research fields. The results also indicate a slight trend towards anticipatory CCA measures mentioned in the scientific literature, as well as a scholarly shift away from reactive measures based on the data collected in our study. However, the reality is that most governments take an event-driven and tangible solution⁵¹. This highlights the opportunity for more transdisciplinary collaboration to bridge the science-policy-practice gap.

Fourth, the clustering of the strongest associations is identified around social CCA challenges, with the link to CCA measures of socio-behavioral adaptations being the most pronounced. Future research should focus on areas of socio-behavioral CCA, for example, to promote water conservation education in disadvantaged neighborhoods, thereby contributing to the empowerment of resident⁷⁰. Furthermore, the strong link to institutional CCA measures indicates that policy goals and local social conditions cannot be considered independently from one another; it is important to address limited community engagement and participation and the social vulnerabilities⁷¹ of communities at risk. Ignoring these CCA challenges renders any type of CCA measure inefficient.

Ecosystem-based CCA measures are strongly associated with structural/physical measures due to their inherent combination (e.g., bio-swales, infiltration trenches, green roofs). They show a moderate-low association with social, technical, and institutional challenges. Ried et al.⁵² highlight their role in enhancing social resilience by maintaining services like water retention and erosion prevention, often outperforming traditional methods. These measures are multi-purpose and more efficient than conventional solutions, using natural processes. Institutional challenges are minor or addressable through better coordination. Policy integration is feasible, with successes in frameworks like EU strategies⁷² emphasizing ecosystem approaches. Although institutional CCA challenges exhibit significant moderate-low associations, they are reported at a high frequency across all categories of CCA measures, highlighting that fragmented governance⁷³ and institutional inertia⁷⁴ as a critical bottleneck globally affect CCA progress.

While the identified associations suggest potential links, we recommend further studies with complementary approaches, including system dynamics modeling^{75–77}, network analysis⁷⁸ and agent-based modeling⁷⁹, to further support the causation and complexity of these interactions and emergent behavior across scales. Moser et al.⁸⁰ suggests adopting a structured diagnostic tool for identifying barriers in planned adaptation processes, which identifies three phases: understanding (problem detection, information gathering, and redefinition), planning (option development, assessment, and selection), and management (implementation, monitoring, and evaluation).

Although evidence mapping supported by LLMs offers a valuable approach to synthesizing global scientific progress, it is subject to certain limitations. Our abstract screening filtered only English-language articles. We infer that the lack of scientific studies in parts of Europe, Central Asia, and South America is due to them being published in a language other than English. Further, our data collection excludes grey literature, books, and reports that may cover localized CCA challenges, especially from the Global South, which were not part of our analysis. Furthermore, we constrained our article selection to require the abstract to mention barriers, challenges, or barriers. There might be articles on CCA where challenges are mentioned in the full text but not in the abstract. Our methodology is capable of assessing the mention of urban development constraints, CCA measures, and CCA challenges, but it does not capture the magnitude of these categories. In a recent study⁸¹, the importance of measuring urban climate adaptation through indicators and metrics is emphasized as crucial for successful CCA management. Nevertheless, they emphasize that there is a lack of comprehensive understanding regarding the measurement of CCA, particularly concerning the methods of measurement. Notably, in approximately 48% of cases, the indicators and metrics did not specify a unit of measurement across the adaptation cycle, scale, and sectors⁸¹. The evidence mapping in this study builds on peer-reviewed scientific articles reporting adaptation case studies, while articles are rarely published on missed opportunities or non-implemented adaptation measures (*publication bias*). Hence, our assessment strongly underrepresents barriers such as undetected problems, unavailable information, and insufficient planning. However, this bias emphasizes the importance of exploring and understanding the scientifically documented challenges and barriers in this study.

In the context of large-scale review text mining, LLMs can accelerate repetitive tasks. However, they do not yet possess the reliability required to supplant thorough human validation, especially in scenarios where accuracy, transparency, and reproducibility are of paramount importance⁸². Petzold et al.⁸³ highlighted in their research that 65% of the researchers from the Global Adaptation Mapping Initiative consider NLP at least somewhat useful; to ensure reliability it is important to combine NLP with other analytical methods. We employed NLP with human involvement to aid in synthesizing the evidence for CCA in urban water systems. This facilitated a comprehensive review of a substantial number of papers, which would have otherwise necessitated significantly more time and human resources. This novel method illustrates how AI can be combined with thorough and transparent review processes for evidence synthesis in adaptation research, thereby improving policy-relevant evaluations to address disparities between the Global North and Global South.

Methods

We conceptualized a novel hybrid workflow for qualitative text analysis, integrating human- and LLM-guided elements within five iterative phases. The general direction consists of human scoping, LLM-guided narrowing, and human refinement of the results. We used a well-established method for a systematic quantitative literature review developed by Pickering and Byrn⁸⁴, along with a similar approach by Berrang-Ford⁸⁵. We then adapted the existing method to assess journal articles on CCA

measures and challenges within urban water systems worldwide. Systematic quantitative reviews adhere to the Preferred Reporting Items for Systematic Reviews (PRISMA) guideline⁸⁶, where other studies^{87–89} have used systematic reviews to advance CCA research in the themes of adaptation planning in large cities, adaptation policy research, and the effectiveness of adaptation. Our study uses the existing PRISMA guidelines but adapts them to include LLM-guided coding.

Fig. 4 presents an overview of the review methodology merging PRISMA guidelines with LLM support, where the five phases are described in detail in the following sections.

Identification

We generated a search string using an interactive query formulation search approach⁹⁰ to test and evaluate the keywords and data that were gathered. Thereafter, we ran the final search terms through the databases (Web of Science and Scopus). Subsequently, the resulting datasets, comprising peer-reviewed journal articles, conference papers, books, and book chapters published between 1990 and 2024, were extracted on July 26, 2024. The total number of imported articles was 39332.

Human screening

We then uploaded the references into Rayyan.ai⁹¹, an online tool that helps organize and review research papers for systematic reviews and related evidence syntheses. It allows researchers to obtain search results from different databases, find and remove duplicates, and review titles and summaries using customizable inclusion and exclusion criteria in a single interface. We used it to remove duplicates from the combined articles of Web of Science and Scopus, where the remaining number of articles amounted to 22602. To select the barriers and challenges criteria for a more thorough assessment, we screened the articles based on their titles, keywords, and abstracts based on our fundamental thematic criteria, such as adaptation, urban setting, and inclusion of a case study. We excluded any references to adaptation that concentrated on particular species or ecosystem⁹ and instead adopted the IPCC's definition of climate-resilient water-related adaptation⁹². At this stage, we applied our initial exclusion criteria, which eliminated any article that was “not urban,” “not a city (towns and villages),” “related to agriculture,” “not directly water-related,” “related to organisms and biology,” or categorized as a “review.” No inclusion criteria were applied at this stage. These steps reduced the number of articles to 1843.

Human-coding and review

We iteratively designed a coding matrix based on a research outline guiding this knowledge synthesis. Therefore, two authors independently coded a random sub-selection of 150 test papers and compared their results to ensure clarity of the questions within the coding matrix. The resulting matrix consisted of 12 questions to be answered by reviewers coding the articles (see Supplement). While nine questions are binary or optional, three questions require elaborate answers linked to the categories classified for them. We tokenized the categories for each classification to guide the reviewers.

Based on the existing urban development literature^{93,94}, we classified urban development constraints into five broad categories (Table 1): environmental, institutional, social, infrastructural, and economic.

Table 1. Categories of urban development constraints with examples

Category	Selection of examples	Overlapping category
Environmental		
	encroachment of rivers	Institutional
	floodplains by physical developments	Infrastructural
Institutional		
	path dependence	
	unplanned land-use	Environmental
Social		
	fear of the unknown	Institutional
	limited community engagement, empowerment, and participation	
Infrastructural		
	use of non-permeable paving in urban areas	Environmental
	outdated gray infrastructure	Institutional and Environmental
Economic		
	insufficient resources (capital and human)	Institutional
	urban flooding	Social and Environmental

Furthermore, we classified CCA measures into seven distinct categories (Table 2): structural/physical, ecosystem-based, institutional/policy, behavioral/social, technological, anticipatory, and reactive, based on the existing literature^{95–99}.

Table 2. Categories of CCA measures with examples

Category	Selection of examples	Overlapping category
Structural/ Physical		
	permeable pavements	Technological
	rainwater harvesting systems	Anticipatory and Technological
Ecosystem-based		
	bio-swales; artificial ponds;	Structural/ Physical and Technological
	green-roofs; rain gardens	Structural/ Physical and Technological
Institutional/ Policy		
	adopting sponge city regulations and permits	
	public, private partnership and financing	Behavioral/ Social
Behavioral/ Social		
	implementing reduced irrigation regime in water scarce region	Institutional
	water conservation education	Institutional
Technological		
	underground retention tanks	Structural/ Physical
	leak detection and repair program	Institutional
Anticipatory		
	relocation of residents from flood-prone areas	Structural/ Physical
	early warning systems	Institutional
Reactive		
	water trucking	Institutional
	pluvial flood insurance	Institutional and Behavioral/ Social

Additionally, we identified the common interacting challenges associated with these adaptation measures, classifying them into seven categories (Table 3): structural/physical, ecosystem-based,

institutional, social, economic, technical, and anticipatory, as informed by current scientific discours⁵³. We studied the different types of challenges in adapting to climate change and how they are governed. Then, we decided to add a new category of barrier to the list as ‘economic’, which is not independently listed as a measure but has the capacity to derail a measure by coming up as a challenge¹⁰⁰.

Table 3. Categories of CCA challenges with examples

Category	Selection of examples	Overlapping category
Structural/Physical		
	large land area requirement	Institutional
	old water piping system	Technical
Ecosystem-based		
	selection of the proper type of vegetation	
	higher and steeper flood walls have degraded habitats and obstructed public riverside amenities	Social
Institutional		
	siloed implementation	
	short-term policies	
Social		
	litter and inadequate community cooperation	Institutional
	contested community leadership	
Economic		
	high operational cost	Institutional
	high retrofitting cost	Social
Technical		
	lack of sufficient technical references, design standards and guidelines	Institutional
	experiments are necessary to test hydraulic parameters	
Anticipatory		
	political contestation over land and housing subsidies	Institutional
	uncertainty in future extreme rainfall intensities at sub-daily scales	Technical

We then developed a human review protocol along with additional information relevant to ensuring consistency within the human reviewers (see Supplement). This protocol outlines the research approach, details the literature search strategy, explains how the papers should be reviewed, and indicates how the final findings will be presented¹⁰¹. Although no review methodology can fully capture all relevant

literature, this process is a well-established method for obtaining a comprehensive understanding of the literature in a transparent, consistent, and reproducible manner⁸⁴.

The authors of this study formed an interdisciplinary team of reviewers and conducted a human full-text analysis of 369 articles out of 1843 (equaling 20 %) to support prompt engineering for the LLM (Fig. 4). Based on their answers within the coding matrix, we iteratively developed prompts (see Code Supplement) for the LLM to guide the review process¹⁰².

LLM-screening and review

In this analysis, we used the LLM-automated reflective generative pre-trained transformer (GPT) *OpenAI o3*¹⁰³. The *o3* model achieves an accuracy on par with human performance in full-text reviews with well-designed prompts. For review tasks with clear instructions and robust prompts, the performance of LLMs can rival human performance¹⁰⁴. Integrating LLMs into the full-text screening process can reduce the time spent manually assessing documents while maintaining or even improving accuracy¹⁰⁵.

We then used the LLM to code all of the imported 1843 articles. By leveraging the LLM’s coding capabilities for a large number of articles with accuracy, we implemented the inclusion criteria (Fig. 4). We included articles that were peer-reviewed, focused on case study(s), as the evidence map is designed to build on concrete, locally observed challenges at the urban scale rather than on studies addressing broader regional, national, or continental levels. In the next step, we added further exclusion criteria, excluding all books, conference papers, and opinion articles, followed by articles with no explicit adaptation focus, with large case study areas instead of city cases, and studies without urban development constraints or natural hazards.

In order to evaluate the results of the LLM, we conducted human-led statistical validation. Therefore, we randomly selected ten articles from the review matrix (see Supplement). Seven human reviewers independently reviewed the same ten predetermined articles. Answers to the eight questions that were one-word or yes/no were evaluated by virtue of the majority and assigned binary scores (0 or 1). In the case of the four descriptive questions, we compared the answers of the LLM against the union of all human answers (not the consensus) to calculate the F1 score¹⁰⁶, precision, recall, and hallucination for each question within each paper. We calculated an F1 score for each paper by averaging the scores for the 12 questions and then calculated the average of the ten papers. The LLM achieved an F1 score of 82%, indicating a strong performance (see Supplement) with a hallucination rate of 18% (Table 4). We note that the reported hallucination rate does not necessarily only consist of LLM hallucinations but may also contain cases where none of the seven human reviewers found the respective answer.

Table 4. Validation metrics of the LLM performance based on seven human reviewers and ten articles

F1 Score	Precision	Recall	Hallucination
~82%	~83%	~61%	~18%

Ultimately, we included 892 articles representing a diverse body of literature addressing themes such as climate adaptation, flood and drought management, nature-based solutions, urban water governance, and heat management through water.

Data analysis

We conducted a descriptive analysis to explore the publication time, location of the case study(s), population of the studied city(s), and type of water-related hazards based on LLM output.

For thematic analysis, we tokenized various urban development constraints, CCA measures, and CCA challenges into categories (see Table 1-3). The tokenization process helps classify themes and extract topics.

In order to relate the results from the thematic analysis, we conducted a relational analysis between the categories of urban development constraints with CCA measures and challenges, as well as CCA measures with CCA challenges. We calculated the association strength for each combination, following Steijn¹⁰⁷. Here, the association strength between the categories is a probabilistic normalization of their co-occurrence counts, expressed as the ratio of their joint probability to the product of their marginal probabilities. This measure quantifies the non-random relatedness between terms relative to their individual frequencies, enabling a robust assessment of their joint occurrences¹⁰⁷. A strong positive association strength (>1.0) between two categories indicates that they co-occur significantly more frequently than expected under random chance, given their individual occurrence rates. This suggests a meaningful thematic linkage or conceptual overlap between the categories in the analyzed articles, beyond mere frequency biases. Conversely, a value below 1.0 reflects co-occurrence less frequent than random, while exactly 1.0 denotes independence. Further, we test the independence of the co-occurrences of categories based on a χ^2 -test at a 95% significance level.

Declarations

Data availability

All data underlying the figures in this manuscript are openly available at <https://doi.org/10.5281/zenodo.19866111>

Code availability

The code underlying the results is available at <https://doi.org/10.5281/zenodo.19866118>

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Contributions

S.N.: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Visualization, Writing—Original Draft. B.P.: Conceptualization, Methodology, Formal Analysis, Validation, Writing—Review & Editing, Supervision. R.E.: Formal Analysis, Review & Editing. F.S.H., N.K., M.S.: Validation, Writing—Review & Editing. Z.C., L.M., F. S., and L.M.: Validation, Review, & Editing. All authors have read and approved the manuscript.

Ethics Declaration

The authors declare no competing interests.

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Figures

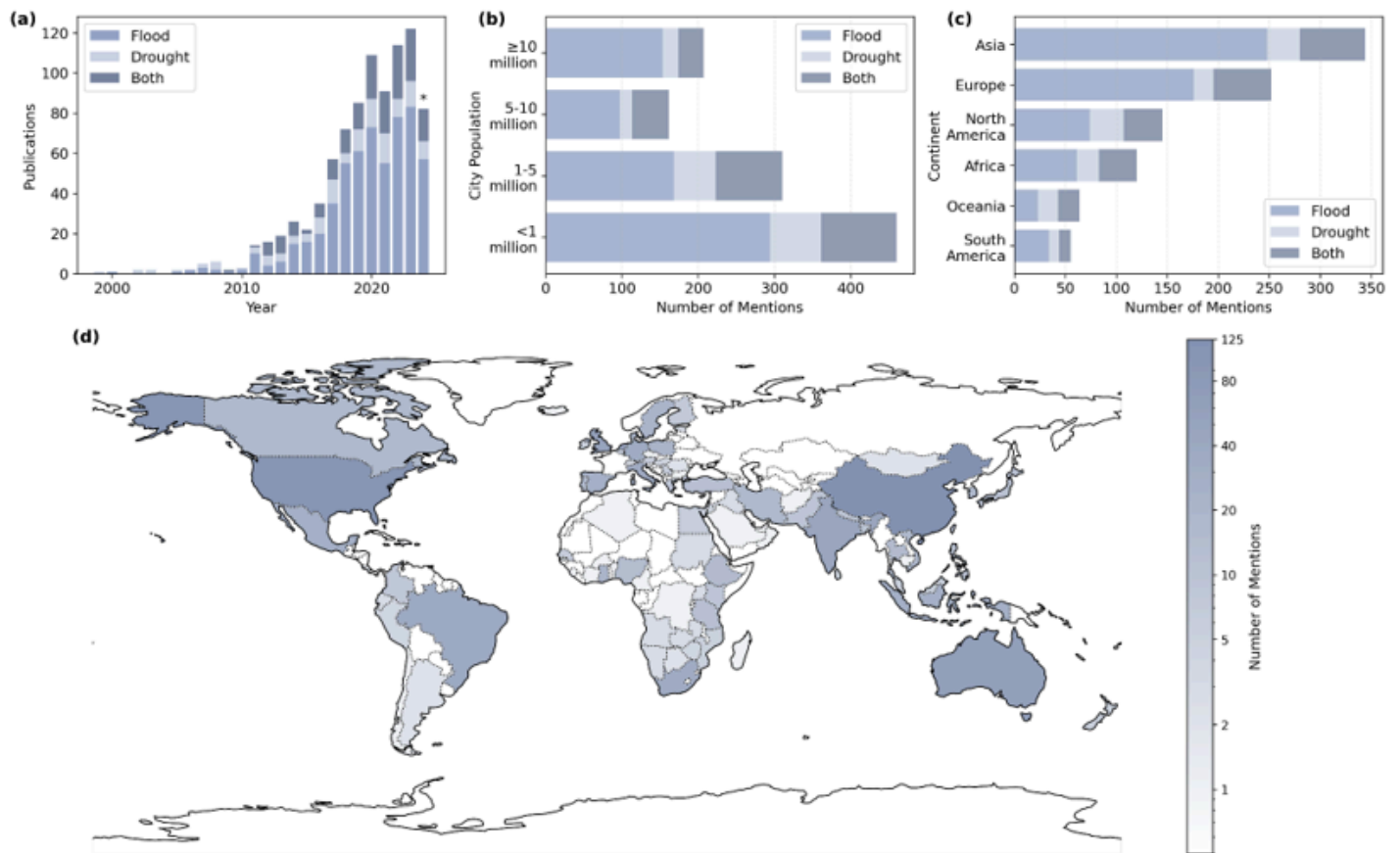


Figure 1

(a) Publication trajectory for water-related adaptation challenges grouped by the water-related hazard type. **(b)** Categorization of the case study cities by population size. Each publication may contribute multiple cities mentions across population categories. **(c)** Categorization per continent, where each publication may contribute multiple cities mentions across different continents. **(d)** Spatial representation of the case studies in the selected literature, where each publication may contribute multiple case studies across different countries.

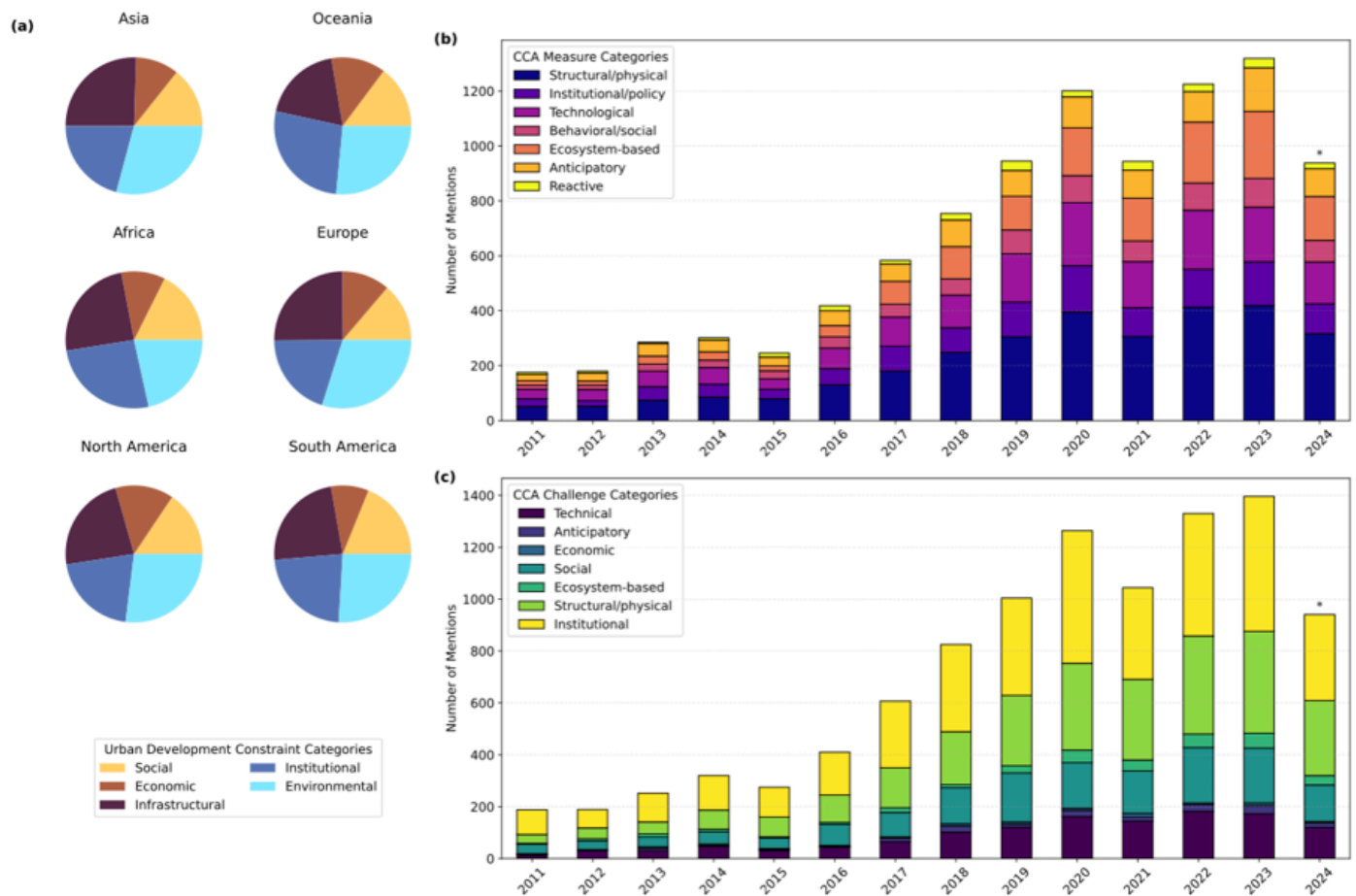


Figure 2

(a) Fraction of urban development constraint categories per continent (each urban development constraint mentioned in a publication is assigned to a category and counted) **(b)** Number of mentioned CCA measure categories per year (each CCA measure is assigned to a category and counted. Multiple measures per publication are allowed.) **(c)** Number of mentioned CCA challenge categories per year (each CCA challenge is assigned to a category and counted. Multiple measures per publication are allowed.)

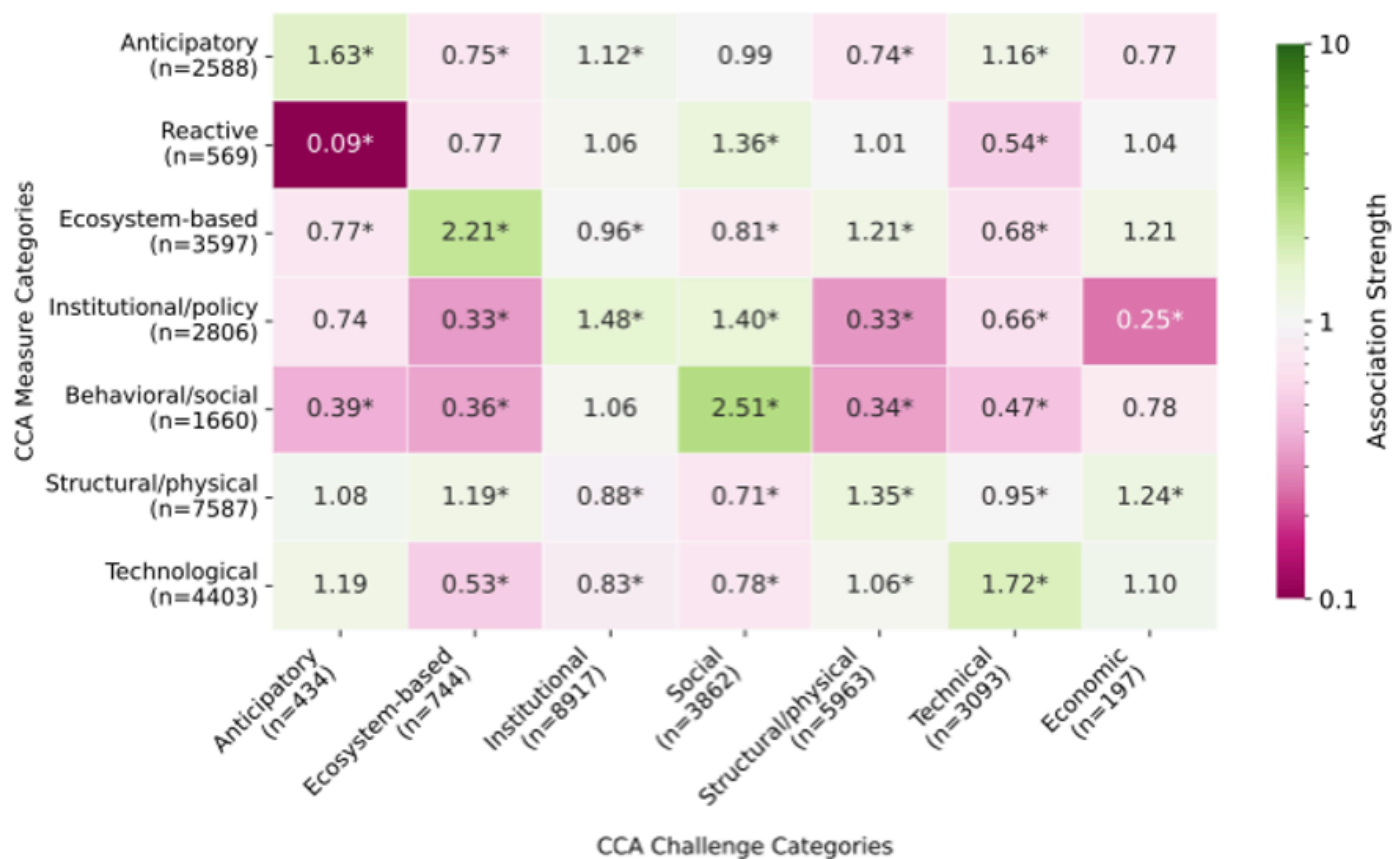


Figure 3

Heatmap showing the association strength between CCA measures and CCA challenges. Asterisks denote non-independent co-occurrences based on the χ^2 -test at a 95% significance level.

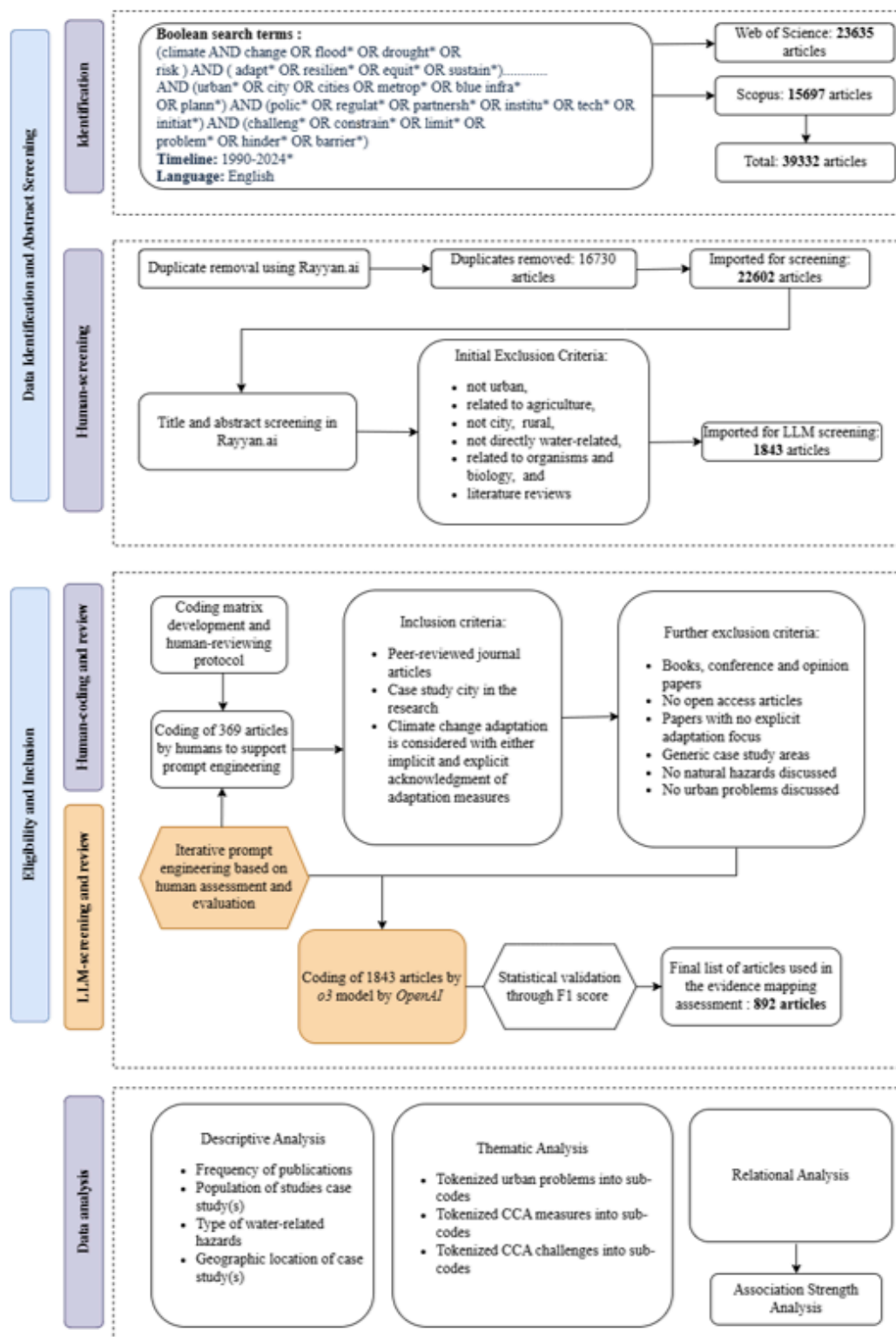


Figure 4

Schematic overview of the methodological review workflow with the inclusion of human (purple) and LLM (orange) support. The workflow adheres to the PRISMA (blue) guideline⁸⁶

Supplementary Files

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