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A transdisciplinary and collaborative urban water security framework: Developed through an interdisciplinary study in Kolkata, India

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Abstract

Urban water security (UWS) is and will remain a crucial issue over the next decades, especially as it is exacerbated by climate change effects and related hazards. Despite the growing number of studies focusing on more diverse dimensions, including social dimensions, of water security and urban dynamics, there is still an absence of comprehensive, interdisciplinary UWS measurement index that takes into account the complexity and multidimensional aspects of water security. This article discusses a new, transdisciplinary community-focused approach to analyzing and responding to water insecurity. It draws on findings from a large study carried out over 4 years with a focus on creating a new and comprehensive way of measuring water security, incorporating biophysical and social factors. The project collected data in Kolkata, India. Kolkata is an important megacity in a developing country, facing rising pressures on water-environmental provision due to rapid population growth and urbanization combined with governance and infrastructural issues. The project team worked collaboratively with affected communities to create a comprehensive framework for measuring and evaluating water security for cities. A water justice approach to water security we argue is particularly important in emerging countries, and one that can be effectively applied to environments where urban growth and resultant shrinking resources have created complicated and fragile systems. This approach adds to existing knowledge and research that focuses on collaborative interdisciplinary methods that aim to create solutions that can help create a sustainable water secure future "leaving no one behind."

KEYWORDS

collaborative methods, emerging megacity, Kolkata, transdisciplinary, water accessibility, water availability, water justice, water risk and hazards

1 | INTRODUCTION

Urban water security (UWS) is at the heart of Sustainable Development Goals (SDGs) (Mukherjee et al., 2022). The concept focuses on the ability to provide enough and safe water to carry out daily activities while at the same time maintaining sustainable environment integrating efforts to meet the SDGs-2030 Agenda. SDG 6 and SDG 11 are particularly important to achieve water security. SDG 6 calls for clean water and sanitation for all people, paying special attention to the needs of women and girls and those in vulnerable situations (Goal 6.2) and on supporting and strengthening the participation of local communities for improving water and sanitation management (Goal 6B). Focusing on urban areas, SDG 11 aims at ensuring the development of sustainable cities and communities by focusing on ensuring access to safe and affordable housing, upgrading socially excluded settlements, investing in public transport, creating green public spaces, and improving urban planning and management in a way that is both participatory and inclusive. Here, we use SDGs as a framework because it emphasizes the multidimensionality and urgency of achieving water security to create better futures. It also highlights that water security needs to be seen as part of a larger environmental, social, political, and economic framework, where it is both *influenced by and influence* society's ability to achieve sustainable futures along these dimensions. We draw on this framework as well as those working for social and environmental justice and see our approach to water security as one of working to achieve water justice.

This article discusses a new transdisciplinary and collaborative approach to water security. Throughout the article, we will outline the approach and show how it helps improve our understanding of the complex and multidimensional concept of water security by analyzing the intertwined biophysical and sociocultural relationships that shape the UWS in an emerging country perspective.

Over the last decades, we have seen several concepts and approaches for assessment of UWS emerging, these include Integrated Urban Water System Modeling (IUWSM) (Behzadian & Kapelan, 2015; Last, 2010; Makropoulos et al., 2008; Mitchell et al., 2001; Rozos & Makropoulos, 2013; Urich et al., 2013; Venkatesh et al., 2014; Willuweit & O'Sullivan, 2013), Water

Footprint (WF) (Hoekstra et al., 2011; Hoff et al., 2014; Vanham, 2012), Driver-Pressure-State-Impact-Response (DPSIR) (Marsili-Libelli et al., 2004; Pirrone et al., 2005; WWAP, 2002, 2006), Water Stress/Poverty Index (Jensen & Wu, 2018; Lawrence et al., 2002; Sullivan, 2002), Index of water security threats (Garrick & Hall, 2014; GWP, 2000; UN-Water, 2013; Vorosmarty et al., 2010), and UWS (Aboelnga et al., 2020; Asian Development Bank, 2013; Gassert et al., 2014; Komnenic et al., 2009; Zhu & Chang, 2020). Appendix A lists a compilation of approaches, dimensions, and issues of quantifying UWS. Although these all contribute to great advances within the area of water security, most fail to consider social perspectives and their relationship with the biophysical environment (Mukherjee et al., 2022; Mukherjee, Sikdar, et al., 2021; Mukherjee, Sundberg, & Schütt, 2021). Furthermore, they fail to include the affected communities, and their unique experiential knowledge. This is a crucial element in understanding, defining, and addressing needs, and in achieving sustainable and lasting implementation of policies and changes.

Some studies have aimed to include the social dimension of water security (Aboelnga et al., 2019; Ahlers et al., 2014; Bakker & Morinville, 2013; Hoekstra et al., 2018; Jepson et al., 2019; Krishna et al., 2023; Lundqvist et al., 2003; Miller et al., 2021; Rains et al., 2019; Rusca et al., 2017; Weststrate et al., 2019; Young et al., 2021) and by doing so they have shown the importance of this dimension not only in understanding barriers to achieving water security, but also the its role in influencing the well-being and everyday lives of those living water insecure lives. We situate our approach in relation to studies like these, emphasizing the importance of inclusion of both the social and biophysical in understanding water related issues. Our approach differs from these in two major ways: First, in that we seek to integrate the social and biophysical more than existing studies have thus far and we therefore see our approach as transdisciplinary, exemplified by how our water security index includes factors from both dimensions; and second, because we make use of collaborative and community focused methods where we work with affected communities across the research process (see methodology for more). Our UWS framework is there therefore advocate inclusive, collaborative, and transdisciplinary UWS—allowing us to understand the complex web of barriers to and opportunities for assuring water security for all in an urban area. In our previous articles, we have presented parts of our index, with a focus on WaSH for example (Mukherjee et al., 2022; Mukherjee, Sikdar, et al., 2021; Mukherjee, Sundberg, & Schütt, 2021). Here, we discuss the full index with its multiple parts and our full framework. This then creates a new addition to newer knowledge and studies that focus on the multidimensional nature of Water Security, including both social and biophysical dimensions (Babel, 2016; Fan, 2014; Nath et al., 2022; Nkiaka, 2022; Octavianti & Staddon, 2021; Veettil & Mishra, 2016; Zende et al., 2018).

This article discusses water security issues and challenges, outlines our approach, and sets out a future research agenda using our new research tool, which we argue can help achieve UWS for the Global South and beyond. To do so, it uses Kolkata, India, as a case study to exemplify the arguments. Kolkata is a growing mega-city in an emerging economy, which is facing rising pressures on water-environmental provisions due to the rapid population growth, urbanization, climate change effects issues related to governance, and infrastructural issues. The article gives an overview of existing knowledge before exemplifying the new approach promoted by outlining findings from a study on Kolkata.

1.1 | Improving water security approaches—so far

During the past few decades, definitions and approaches to study water security have moved from a focus on human livelihood and its involvement with physical water management to its engagement with ecosystems. As a result, there are increasing numbers of studies developing more holistic approaches. We have seen water security become a main concern in policy making in areas such as health, economics, food, energy, and environmental issues (Lundqvist et al., 2003). As mentioned in the introduction, we have also seen new approaches developed that include social and hydrological aspects in their research (Aboelnga et al., 2019, 2020; Jensen & Wu, 2018; Romero-Lankao & Gnatz, 2016; Shi et al., 2021; Van Ginkel et al., 2018). These recent developments are created due to the assumption and acknowledgement that interdisciplinary approaches can improve our analyses by including the multiple core dimensions of water security and that are needed to enhance our understanding of water security and to design better policies and policy implementation models that can help achieve and maintain water security. We here define UWS as a "persistent condition in a limited urban region under which water ecosystems can ensure the adequate access, safety, and affordability of water to meet minimum livelihood standards and human feelings of psychological security" (Huang et al., 2015, p. 3903).

The concept of water security is relatively new, and so far, there is no established and widely agreed upon framework for quantification, particularly not a holistic framework (Mukherjee et al., 2022; Nath et al., 2022; Nkiaka, 2022; Octavianti & Staddon, 2021). We argue, as Mukherjee, Sundberg, and Schütt (2021), for a shift in UWS research toward a field of research that include both human-oriented and environmental perspectives. In our view, this will result in creating UWS strategies that are better placed to securing sustainable futures. This approach is similar to Integrated Water Resource Management (IWRM), a set of principles proposed by United Nations to help achieve sustainable development goals (SDGs) (Aboelnga et al., 2020; Hussein, 2019; UN-Water, 2013). IWRM and water security are conceptually similar (Lautze & Manthrithilake, 2012) but are differentiated by the level and scale factors included. IWRM is designed to address issues at national or river basin scale, whereas water security also captures and focus on issues at local levels. This means that UWS and water security approaches can identify and address water security issues within countries, cities, and local areas that IWRM is not designed to identify nor analyze. Furthermore, instead of having focus on process-oriented approaches, such as IWRM (Phillis et al., 2017), UWS, or water security also considers the complexities linking the biophysical and society, emphasizing needs and demands such as availability, accessibility, quality, and safety issues without ignoring the uncertainties associated.

UWS includes a multidimensionality of factors that influence and shape water security and underlines the importance of a holistic approach for analysis. Achieving UWS means accounting for complex intersecting relations within and across social, cultural, economic, political, and institutional factors, such as gender, caste, religion, and poverty in urban areas as well as biophysical factors. Our framework goes further than previous UWS research and proposes to capture the comprehensive and complex character of UWS through a transdisciplinary and collaborative approach. Here, we build in and integrate the experiences and needs of affected communities and combine these with more traditional biophysical measurements to include the complex set of need, demand, risks, and developmental perspectives. Our framework subscribes to the thought that UWS assessment should address the issues of "too little" (availability and accessibility issues), "too much" (flood and disasters), "too dirty" (pollution), and "too difficult" (conflicting institutional issues).

1.2 | Aim and objectives

The objective of the underlying study that this article draws on was to create a comprehensive, integrated, and inclusive framework to assess UWS in the Global South, using the case of

Kolkata. The overall goal was and is to address and create sustainable solutions to UWS and, in the future, also incorporate measurements that allows the approach to analyze water security in peri-urban, and rural areas. This research is unique due to the inclusion of biophysical and sociocultural factors using collaborative and transdisciplinary approaches allowing us to gain invaluable knowledge of issues related to water security and gender. This transdisciplinary vantage point is crucial to enhance knowledge and create new solutions. Underlying the approach is the conviction that ensuring clean water and sanitation for all, including environment, is fundamental to sustainable growth and development (Barbier & Burgess, 2017). Kolkata, India, was chosen as it serves as an excellent example of mega cities of the Global South through an inclusive Socio-Eco-Hydrological framework of UWS.

In the study, we aimed to answer the following research questions by analyzing data gathered in Kolkata Municipal Corporation (KMC) area, India:

1. What are the key factors affecting UWS of Kolkata?
2. What are the impacts resulting from the rapidly changing socio-eco-environmental processes within the study area affecting water, sanitation, and hygiene (WaSH)?
3. What is the extent of the ability of the polycentric urban region to respond to the varying sustainable and equitable water security at the micro level?
4. How do the social, cultural, economic, political, and institutional factors influence individuals' and specific groups' (groups in vulnerable positions from an intersectional point of view) water security in a megacity?

2 | METHODOLOGY

2.1 | Study area

Kolkata is the largest economic zone on the east bank of Hugli River, situated about 150-km inland from the open sea (Rudra, 2009). With an ever-growing population, the city is increasingly contributing to the deterioration of the river. Sarkar et al (2007) pointed out that the deterioration of Ganga's water quality was directly related to malfunctioning or nonfunctioning of wastewater treatment plants of the city along with its lack of environmental planning and coordination.

The most important distributary of the Ganga is Bhagirathi-Hugli, which is about 500 km in length. With the growth of industrialization in the 18th-century factories and mills producing jute, paper, and leather developed on both the banks of Hugli River. The transformation of agrarian world into an industrial landscape is reflected by the riverfront. With the introduction of railways in late 18th-century industrialization flourished further. Large numbers of people started migrating to Bengal from the neighboring states of Bihar and Orissa. The divide of Bengal in 1947 saw further influx of people because of the incoming refugees from East Pakistan resulting in the dramatic increase of pressure on the already overcrowded banks of the Hugli. The hinterland of Kolkata Port grew larger and larger corresponding to the increase in industry.

The problem of uninterrupted sedimentation has been a great hindrance since the very beginning of the history of the port. The British realized that the urban and industrial wastewater of the city should not be allowed to flow into the main river acting as the lifeline of the entire area. They used the natural wetlands at the eastern fringes of the city as the reservoirs. Moreover, east flowing canals were excavated for the purpose of diverting wastewater toward the wetlands in the east. In independent India, the absence of necessary regulations resulted in indiscriminate dumping of urban and industrial effluents into the river. It increased to an alarming magnitude in West Bengal (Rudra, 2009). February 1985 saw the emergence of an action plan to save the Ganga from further damage. The Ministry of Environment and Forest under Government of India took the initiative. Seventy five percent of the total pollution was found to be caused by municipal sewage coming out of the towns located on the riverbank, and the rest was caused by industrial effluence. The Kolkata Metropolitan Development Authority (KMDA) was entrusted with the main power to prepare, execute, and coordinate the developmental activities of the departments and the agencies of the state government or the local authorities within the Kolkata Metropolitan area.

KMC area, also known as Kolkata city, has a very high population density of 24,000 people per square kilometer or 63,000 per square mile (according to Census of India-2011). This is one of the world's highest densities. The city itself qualifies as a megacity and covers a large surface area that totals 205 km^2 (79.150 $mile^2$). In 1980, the percentage of wetlands within KMC area was 23, but it is decreased to 4% in 2019. River Hugli is the main source of water supply for the KMC areas. According to West Bengal Pollution Control Board (WBPCB), water in the river does not pass the drinking water standard set by the Government of India. After treatment, it is supplied to households but still about 10% of the recognized household within the KMC area are without any water supply connection excluding the socially deprived areas known as *slums* or *basti* (Mukherjee et al., 2020). According to the latest Census data (2011), there is a serious lack of enough stand posts to supply water in these deprived areas. In the most deprived areas, mainly in the center of the city, the stand post and people ratio are more than 0.04, if in usable condition, a similar situation is seen for number of latrines. In centrally located areas defined as slums by the local authorities, one latrine is allocated for more than 25 people. Tube wells are still the common occurrence in these households tapping the groundwater beneath the city area, whereas the number of tube wells is extremely low in comparison to the population depending on them. In most slum areas, there is only one tube well for 40 people or more. According to KMC report (2019), Kolkata city officially has about 12,000 hand tube wells (hand-pumped) used by especially those living in slums and the floating population that enters and exits during office hours daily and around 2500 large tube wells mainly catering to multistoried buildings. The city faces high levels of manganese (concentrations exceed 0.3 mg/L) and iron content (up to 23 mg/L in places) in the groundwater, which can cause serious ailments. At the same time, analysis of arsenic (As) in groundwater samples from across Kolkata failed to detect concentrations >10 μg/L from natural processes. That means there is a continuous source of contamination of groundwater from unregulated industrial activities, which is decreasing water security for millions of people slowly but steadily over time (Mukherjee, Sikdar, et al., 2021).

In our study, we include intersecting characteristics such as gender, ethnicity, religion, and caste matter when studying water security. We have previously discussed the effect of this in terms of access and availability to toilets and WaSH facilities in Mukherjee et al. (2020, 2022). These factors are important across the world, and in Kolkata, they come together and become hugely important as we see economical, demographical, social, and environmental changes increase water insecurity (Dickin et al., 2021; Mukherjee et al., 2020, 2022; Sultana, 2020). Gender matters—for example, females often stay home and face tremendous issues relating to access to WaSH, particularly in socially deprived areas (Dickin et al., 2021; Mukherjee et al., 2022; Roy et al., 1992; Schenk, 2010; Simpson, 2009; Thompson, 2016; Truelove, 2011). Our study is unique in its inclusion of gender along a continuum and through its inclusion of marginalized communities such as the hijra/trans (gender) people. The latter groups are often not properly registered officially, often live-in high levels of deprivation and poverty and are not able to access work (Boyce et al., 2018; Dhall & Boyce, 2015). This means they on the one hand share characteristics and WaSH struggles of those living in poverty and also have the double burden of the hostility toward their very way of living and identity (Boyce et al., 2018; Mukherjee et al., 2020, 2022). Thus, they often face physical humiliation while fetching water or using the common public latrines. On this basis, we include gender along with a range of socioeconomic factors.

2.2 | Research methodology

This study takes an interdisciplinary approach and analyses using data in an innovative way. We, as others, argue that interdisciplinary methods allow us to understand the complex web of factors influencing, shaping, and driving water security. We thereby align ourselves with other researchers within these areas that see interdisciplinary methods as the only way to capture the multiple dimensions of phenomena such as water and food security (Tobi & Kampen, 2018). By including biophysical and social data as well as working with communities, we see knowledge production as something that needs to be co-produced across disciplinary boundaries. This is a new type of approaching water security issues that we believe will enhance our understanding of water security and improve the solutions to water security issues. The framework used draws on a process of research methods design commences with identification of the issues, followed by data analysis, and interpretation of the issues associated with UWS components, the latter defined by Grey and Sadoff (2007). When it comes to water security, we then focus on assessing the livability (accessibility and quality in terms of socioeconomic equity issues), viability (availability in terms of socio-physical environmental issues), and sustainability (risk and other environmental factors) of UWS. Collaborative methods are used to engage with communities, ensuring we understand and identify issues relevant to their in-depth knowledge and lived experience, whilst at the same time ensuring that solutions are adapted to their needs and have their 'buy in' to ensure sustainability of solutions (Monk et al., 2003).

The research is transdisciplinary through its inclusion and integration of social, biophysical, and community-based knowledge into an integrated assessment framework. To do so, we made use of GIS mapping, valuation of ecosystem services, quantitative surveys, and qualitative focus groups. We have discussed the sociodemographic elements of this in a previous work (Mukherjee et al., 2020, 2022). Our integrative, collaborative, and transdisciplinary approach was done by working with members of affected communities in workshops and focus groups, which helped us identify key factors and dimensions for our social and biophysical mapping and survey tools. To do so, we also analyzed the results from qualitative focus groups to help create tools representative and in line with the needs highlighted by these community groups. We then moved on to integrate the data collected through all of these methodological tools into an assessment tool and index that could be used to create easy to understand and usable maps and monitoring tools to assess UWS in Kolkata. The community groups were crucial at the research design stage and in our data collection and initial data analysis to ensure they represent and include their experiences. The multiple types of data collections again helped us access and investigate the multiple dimensions of water security, and we had a focus on including populations not before included in this type of research—namely, populations across the gender continuum as well as people of different caste, religion, and ethnicity. The integrated and

TABLE 1 List of methods applied (for details see Appendix A).

Methods	**Literature review**	
	Primary and secondary data analysis	
	Statistical analyses	Principal component analysis
		Descriptive statistics
		Bivariate correlational analysis
		Regression analysis
	Remote sensing data processing	LULC change between 1980 and 2014
		LULC between 2009 and 2019
	Qualitative analysis	Thematic analysis of workshops and focus groups
	Estimation of value of Ecosystem Services (ES)	
	Calculation of Water Quality Index (WQI)	
	Urban Water Security Index creation	WaSH provisions Index (**WPI**)
		Urban Environmental Water Security Index (**UEWSI**)
		Urban Water Security Index (**UWSI**)
		Integrated Urban Water Security Index (**IUWSI**)

transdisciplinary methods meant a long period of data analysis to ensure we integrated types of data, quantitative and qualitative, as well as communicated with members from the community and different disciplinary communities (Table 1).

3 | A NEW FRAMEWORK: RESULTS FROM KOLKATA

Overall, what our findings show is that by taking a collaborative, integrative, and transdisciplinary approach, researchers analyzing water security can enhance our understanding of the crucial issues at hand. This is crucial when we create new policies and responses to these issues. By using our approach, we are able to include not only sensitivities to intra city variations of biophysical factors but also socioeconomic and cultural factors that drive water insecurity. This is crucial as previous studies have not included sufficient appreciation of the intertwined relationships of social and biophysical factors, nor have they captured intracity variation.

3.1 | The Integrated Urban Water Security Index (IUWSI)

In Figure 1, you can see our IUWSI within KMC area is based on the combined (normalized) scores of WaSH Provisions Index (WPI), Urban Environmental Water Security Index (UESI), and Urban Water Security Index (UWSI). The data, method, and measurements included in the index can be found in the appendices. IUWSI creates an evaluation matrix incorporating the key socioeconomic factors affecting UWS of population in Kolkata based on primary data collected in this study and allows us to investigate the trade-offs between urban environmental water security and its peri-urban wetland areas. The calculated IUWSI, borough wise distribution of the scores (Figure 1), suggests that the boroughs X and XII located in the southeast of

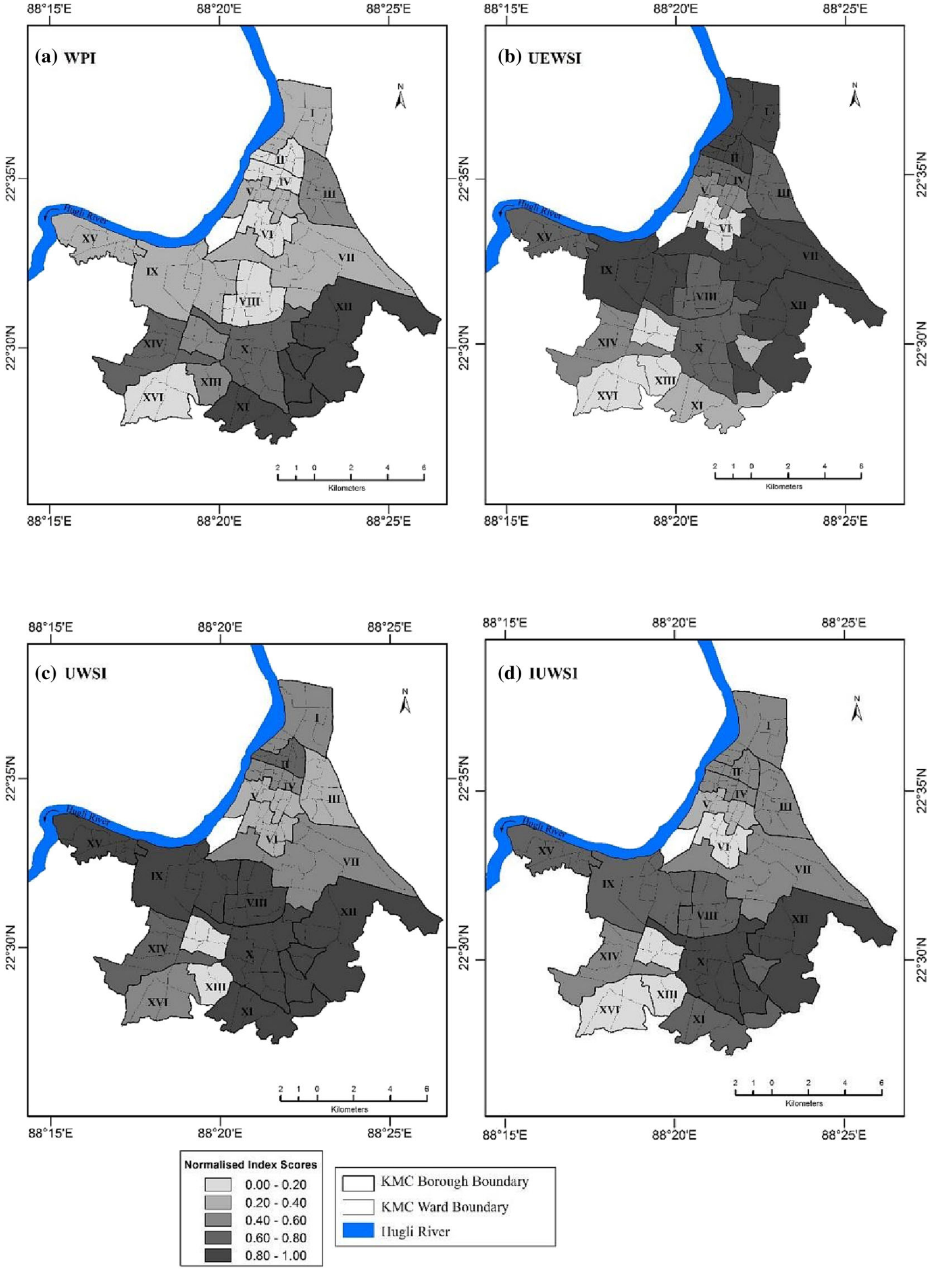

FIGURE 1 Legend on next page.

FIGURE 1 Borough-wise distribution of normalized scores of Urban Water Security Indices, that is, (a) WaSH Provisions Index (WPI), (b) Urban Environmental Water Security Index (UESI), (c) Urban Water Security Index (UWSI), and (d) Integrated Urban Water Security Index (IUWSI) within Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Higher scores represent more water security within a borough. Data source: Indices scores.

KMC area have higher UWS. This is crucial and shows the importance of indices and analysis that can capture local and within city variation in water security. The distribution of boroughs with lowest IUWSI scores is concentrated mainly in the southern part of the KMC area (boroughs XIII and XVI) and in the center of the city (borough VI).

Comparing the scores of IUWSI with the scores of other three water security indices in this study (WPI, UESI and UWSI) reveals that within KMC areas, the combined outcome of the scores follows the UWSI scores more prominently than other indices (Figure 2). Therefore, the scores from IUWSI showed higher scores for some boroughs, for example, borough XI, where UWSI score was distinctively lower. The similar difference can be seen for boroughs I, II and VIII, where WPI scores were lower, but scores of IUWSI were comparatively higher. Our previously published paper also revealed that "… the most water insecure boroughs are those which are either regarded colloquially (because, unlike many cities, Kolkata does not have any official central business district) as the "central business district" (borough VI) where the main railway station, Sealdah and the biggest market, Burrabazar, are located, and the area which is going through a continuous infrastructural alteration due to urbanization (borough XIII and XVI) including bridges and other developmental activities are taking place …" (Mukherjee et al., 2022, p.16).

3.2 | What does the IUWSI reveal about UWS in Kolkata?

The next sections discuss the key answers to each of the research questions, outlining findings and sets out the ways our integrated, interdisciplinary bottom-up index can contribute to our understanding of UWS:

1. What are the key factors affecting UWS of Kolkata?

The results of the IUWSI, as the SDGs, reveal the complexity and multiplicity of the issues by showing how the combined effect of both biophysical and social factors affect the water security of a city (Figures 1 and 2) vary across the KMC area. Boroughs X and XII have higher scores in both UESI and UWSI, but according to WaSH Provisions Index (WPI) borough was in the second highest category (score ranges between 0.06 and 0.80) (Figure 1). Similarly, Borough VI scored low in both WPI and UEWSI, which made it to rank the lowest in IUWSI, albeit having not so low scores for UWSI. Similar examples can be drawn from other boroughs too for all the indices including the combined IUWSI.

Thus, water security in a city is driven by a complex and intersecting set of biophysical and social factors—which need to be dealt holistically. We found that levels of water security vary within a city and its subadministrative units (e.g., wards, boroughs, and districts) as well as within and across groups in society. UWS is not only essential in urban planning to manage cities' water infrastructures and strengthen their disaster resilience and adaptive capacities but

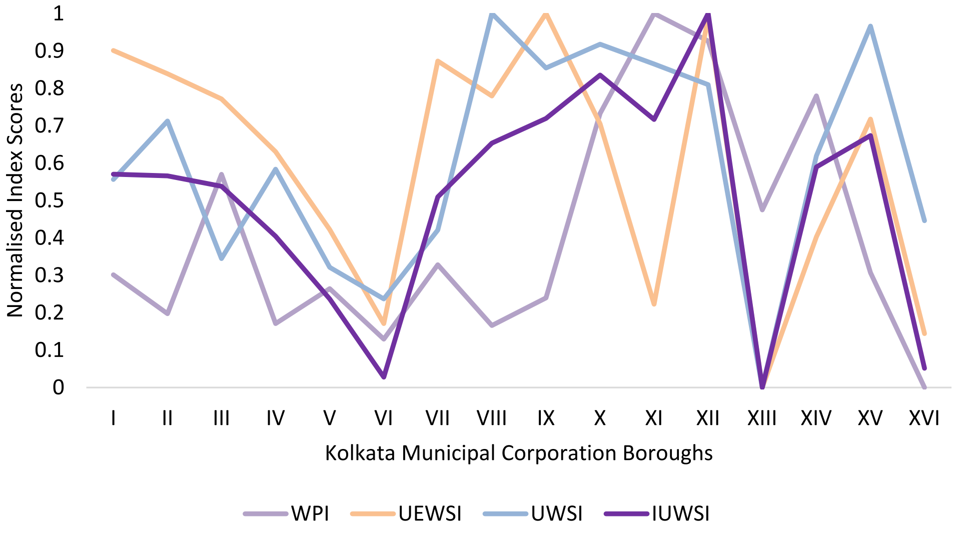

FIGURE 2 Borough wise distribution of normalized scores of Urban Water Security Indices, that is, WaSH Provisions Index (WPI), Urban Environmental Water Security Index (UESI), Urban Water Security Index (UWSI), and Integrated Urban Water Security Index (IUWSI) within Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Data source: Survey data (2018–2019).

also to promote inclusive and equitable water governance. Decision making, governance, and socioeconomic factors, for example, gender, caste, religion, along with the biophysical factors (mainly water availability, water quality and ecosystem), play important roles in achieving UWS for all. We will show the ways in which they matter when answering our second research question.

Based on the results obtained from the satellite data-based land use–land cover classifications, household survey, available literature, and documents from public institutions, this study found that unprecedented population growth since 1980, a changing climate, rapid urbanization, expansion of infrastructure, migration, land conversion and pollution render into changes in the city's water fluxes, water pathways, water stores, and water use. Population density and per capita resource-use have been increased dramatically over the past four decades in KMC area. Concurrently, urban ecosystems have undergone substantial modifications that affect the availability, quality, and consumption patterns of the water resources in KMC. Therefore, the following intersecting biophysical and social factors lay the foundation of the assessment signaling the direction of change required to achieve UWS:

- **Availability:** Availability of both surface and groundwater and where relevant other sources of water (e.g., water reuse and rainwater harvesting), taking account of diversity, quality, and renewability of water.
- **Accessibility:** The extent of access to water for human use, including both domestic and industrial water uses, considering water treatment capacity, coverage, and affordability.
- **Risks and hazards:** The extent of water related risks, including flood risk and health related risks.
- **Ecosystem:** The extent of freshwater ecosystem services in the era of rapidly changing climate and urbanization.

- **Capacity:** Institutional capacity to manage water resources in terms of water supply and water demand and water-related disasters.
- **Responses:** The effective and participatory nature of the governance and adaptation planning.

By considering the complex and multiple functions of water as a resource across the urban landscape, this study found that Hugli River in the west, a huge wetland system in the East, and the deltaic plain of Ganga-Brahmaputra does not prevent Kolkata from becoming a water-insecure city. Increased water use associated with domestic and small-scale industries and real estate business is leading to changes in water supply infrastructure, high rates of groundwater use, and new water conveyance networks. Poor and inadequate living conditions and municipal services expose to lethal health and sanitation issues (Douglas, 1983). These problems are especially critical in socially deprived areas, commonly known as slums, *basti* and squatters, in fringe areas (Kundu, 2003). Households in peri-urban fringe areas, which include the newly added wards, such as 101, 141-46, are lacking access to piped water supply from the municipal corporation. The residents must either use the groundwater through hand-pumped tube wells or get access from KMC supports such as water delivery by water trucks few times a week. The increasing number of people living in areas defined as slums by the KMC has been the key concern for urban planning in respect to accessibility of safe drinking water and availability of adequate sanitation facilities (Sau, 2017).

2. What are the impacts resulting from the rapidly changing socio-eco-environmental processes within the study area affecting water, sanitation, and hygiene (WaSH)?

The 2011 Census of India reveals that 17.4% of urban households in India live in deprived areas in urban landscapes, which are designated as slums in the Census dataset. The increasing number of the people living in these areas poses serious challenges to the provision of basic urban water, sanitation, and hygiene (WaSH) services. Through our integrative and transdisciplinary approach, this study assessed the present situation of water, sanitation, and required hygiene provisions within the areas defined as slums of Kolkata, India. We found lack of supplies associated with WaSH provisions in these underprivileged areas of Kolkata. The WaSH provisions in the disadvantaged areas within Kolkata city are facing various issues back to regularity, quality, and quantity of supplied water.

Additionally, there is poor maintenance of existing WaSH services including latrine facilities and the per capita allocation for a sustainable water security among the dwellers of these deprived pockets. Providing required WaSH provision is a human right according to United Nation. Perceived susceptibility of risks from contaminated water and lack of proper sanitation and hygiene needs to be addressed in the light of social exclusion factors. By adding to the existing understanding of the importance of factors such as gender, religions, and knowledge of drinking water in slums the study analyses the links between physical and social issues determining vulnerability and presence of deprivation associated with basic WaSH provisions as human rights of these deprived slum communities. Our collaboration with affected community groups and multipronged approach helped us design an approach that allowed us to delve deeper into what matters, socially and biophysically, when we measure UWS. The results from the analyses of indices and the crosstab show that water security correlates with socioeconomic factors; 86% respondent from the general caste category have presence of toilet in their houses, but for the SC/ST/OBC, it is only 13.6%. The presence of toilet in the house seemed to demonstrate biasness toward Cis-male (25.6%) and female (33.7%) against transsexuals (15.9%) and intersex (13.1%) respondents, Bengali-speaking (82.8%) respondent against other Indian language speakers (17%), and Hindu (86.2%) respondents against Muslims (10.8%) and others (2.6%); 38% of the respondents who are in unorganized business(es) and 69.2% of the respondent who work in the unorganized sectors do not have toilet in the houses.

Eighty-one percent of the total respondent ($n = 755$) depend on the piped water supply for drinking, and among them, only 8% use that for household works; 43% of the total respondents depend on the water from stand-posts; 82.3% respondents are of general (upper) caste that have direct water supply in the house. For the Scheduled Caste or Scheduled Tribes (SC/ST) or Other Backward Castes (OBC), 73% have direct supply in the houses altogether. The majority are the Bengali speakers (83.7%), among them almost 83.4% have direct water supply in their houses; 15.9% of other-Indian language speakers have this direct water supply facilities in their houses. Hindus have the maximum share (86.6% houses have direct water supply facilities). Cis male (34.9%) and females (25.2%) have the higher shares of direct piped water facilities in their houses than trans (17%) and intersex (11.05%) respondents; 2.3% of respondents who are in unorganized sector of business have direct water supply facility in their houses. For workers in unorganized sectors, only 1.8% have direct water supply facilities within their houses.

Overall, this shows on the one hand the importance of including social, economic, and cultural characteristics when analyzing UWS; we cannot create sustainable solutions without understanding the complex set of interrelations between social and biophysical factors. It therefore underlines the importance of tailoring responses to UWS to the diverse needs and risk of different groups within the city. Lastly, we argue that this multidimensional approach to UWS should be used across the world to better understand UWS.

3. What is the extent of the ability of the polycentric urban region to respond to the varying sustainable and equitable water security at the individual level?

The polycentric urbanization in and around Kolkata city (in particular KMA area) has a historical element since the 1980s—the Development Perspective Plan of the Calcutta Metropolitan Development Authority conceived polycentricity against the binodal development of the city. We refer to Mukherjee (2020) "Blue Infrastructures" (chapter 7) for detailed explanation of the history behind urban spatiality. Sustainable and equitable water security can prevent the destruction of ecological integrity and environmental pollution for both nature and the human society. This study finds that the wetlands within and surrounding KMC areas have been reduced comprehensively in the last decade due to the conversion of wetlands into various other LULC classes in expanding Kolkata city. However, and crucial in underlining the need to include these areas in studies on UWS, peri-urban wetland supports the UWS by providing the enough ecosystem services. The transformation in extent of water-related ecosystem is a crucial indicator to UWS, which also measures the quantity of water contained in various water-related ecosystems. Quantitative analysis of LULC change, hence, is important for studying the corresponding impact on the ecosystem service value (ESV) and water quality that helps in decision-making in securing urban water future and ecosystem conservation.

Based on land use and land cover (LULC) data retrieved from remote-sensing interpretation, this research computed the changes of ecosystem services values (ESV) associated with the LULC dynamics, water quality, and finally, UWS during the premonsoon and postmonsoon periods of 2009, 2014, and 2019 of Kolkata city and its peri-urban wetlands, named East Kolkata Wetlands (EKW). By doing so, we found that the area under wetlands has been reduced comprehensively during 2009–2019 due to the conversion of wetlands into various other classes such as urban settlements. Furthermore, the quality of surface water bodies (such as river, lake, canal, and inland wetlands) has deteriorated. The groundwater quality is still under control, but presence of iron, arsenic, manganese, and other metals are clear indication of urban expansion and related activities in the area. As a result, there has been a combined change in the ESV during this time frame. In the premonsoon period, there is an increase in total ESV from US$ 53.14 million in 2009 to US$ 53.36 million, and US$ 59.01 million in 2014 and 2019, respectively. In the postmonsoon period, the ESV decrease from US$ 67.42 million in 2009 to US$ 64.13, and US$ 61.89 million in 2014 and 2019, respectively. These changes can be attributed to the peri-urban wetlands and the benefits or services arising out of it that contribute more than 50% of the total ESV.

4. How do the social, cultural, economic, political, and institutional factors influence individuals' and specific groups' (groups in vulnerable positions from an intersectional point of view) water security in a city?

Our framework allows us to unpack the main factors responsible for a water insecurity in a city; structural inequalities in the society, a lack of comprehensive and efficient water management in places that are already suffering from water stress, as well as a global trend of water consumption that is growing at more than twice the rate of the population increase in the last century (Arnell, 2004; Hejazi et al., 2014; Myrttinen et al., 2018; Vörösmarty et al., 2000). As we have seen, the impacts of these dynamics vary for different groups in society, with gender often playing a major, but not exclusive, role in mediating needs, vulnerabilities, and access to coping strategies (Myrttinen et al., 2018). Here, gender refers to socioculturally and politico-economically constructed roles, expectations, and responsibilities ascribed to men and women, girls, boys, and persons with other gender identities, which change overtime, are context- and history-specific and are inseparable from power relations and societal value systems (Myrttinen et al., 2018). We found that not only social, economic, cultural, or political position but also physical positions, that is, urban/peri-urban/rural setting matters in determining and shaping UWS. "As she works at the TG board and task force she says even these places do not have proper toilets for the TG. She feels trans-men are in more need of water especially when the transition is going on. In Urban areas comparatively Trans women get better access to water and toilets due to pay and use toilets. Trans Men have no security. Biologically they are not comfortable in men's toilet. Many trans people who work on road cannot afford to buy water while working. Water had always been an issue but there was no body to take it forward as an issue before. Everything is inter linked such as hygiene, sanitation, access to toilet and access to drinking water. Getting access to clean water is their right for equality as well." A respondent's response when asked for their views on water security in Kolkata city. These expectations and cultural norms are constantly co-produced, re-enforced and re-negotiated by and between all members of a given society, with others exercising more definitional power over people who provide certain types of privileges or deprivation in terms of religion, caste, socioeconomic classes, and political advantages (Myrttinen et al., 2018).

The research has highlighted the specific needs and vulnerabilities of sexual and gender minorities for whom violence is a daily experience especially in conflict affected settings more than other gendered counterparts (Castañeda & Myrttinen, 2014). Another respondent expressed, "When we are talking about intersectional approach the baseline should be the grass-root people. The idea of power privilege or hierarchy and idea of empathy is important while talking of centralization. Our education doesn't cater to empathy. People with greater purchasing capacity do use more water while people who cannot or hardly afford it use less than required. Marginalised sections of all strata must come together because oppressors are one. They are the corporate; they are the people in the power positions. We are fighting amongst ourselves and they get the benefit out of it. Solidarity is required. May be our education should imply in generalised idea of consent, of choice, of empathy, of accumulation of resources. If you have a clear idea of these one could realise what are the basic needs and their right to access these. I am getting it so I am using it is not the solution. This is where the idea of community building comes. That idea has to develop and it's a long journey. She doesn't believe in sensitize first and then work. Rather both should go simultaneously. For instance, if people do not know what is gender neutral toilet (she took the reference of the photo of a girl posing with a poster demanding gender neutral toilet which became a meme with the message that the girl wants to pee with the boys)."

Sexual and gender minorities often face disadvantages due to the existing homophobic discrimination institutionalized in society, government or international institutions or their local representatives (Sexual Minorities Uganda [SMUG], 2016). (Gender) Binary approaches to survey questionnaires or interviews may miss out on seeing the LGBTIQ dimension and subsequently fail to capture such discrimination or additional challenges faced by LGBTIQ persons for enjoying the basic right to water. Investigating local forms of non-binary identities and relationships can help researchers and practitioners to improve their understanding of the nuances of fragility and resilience related to water and peace and to decolonize their approaches.

Further, such investigation can foster better understanding of the intersectional impact on power and privileges related to water, or the vulnerabilities to violent abuse and support needed. To date, not enough research is open to such nuances, which means that an important dimension is missed out. This can be seen in the examples from Kolkata where LGBTIQ were not considered in any Government report or Census data till date.

We have created a set of recommended UWS responses based on our findings that can be found in Table B1 in Appendix B.

4 | DISCUSSION AND CONCLUSIONS

The findings presented here outline a holistic, integrative, inclusive, transdisciplinary, and collaborative approach to study water security. Through the discussion, we have shown the knowledge created so far by using this new approach, and we propose that other studies applies similar interdisciplinary approaches that can help deepen our approaches of water security. The article has discussed a social and biophysical approach, integrating the two to a larger degree than has been done before, and we propose that this approach should be adapted and applied further to include the peri-urban and rural on the one hand, and to be used in other countries and similar places when studying issues related to water security. This is because a lack of holistic understanding of all factors shaping, influencing, and driving water security, we run the risk of missing out key parts of the overall image. Historically, we have seen piecemeal solutions to water security issues because of this, and we argue that holistic approaches are crucial for sustainable solutions for all. In the specific case of Kolkata, we have outlined key UWS issues throughout this article using our integrated, transdisciplinary, and collaborative approach. This approach has shown us the following are key dimensions in UWS framework and analyses:

4.1 | UWS is a complex system

UWS is a complex system where multiple actors and factors are at play. It is a difficult task to address water insecurity issues disentangling this web of factors. The assessment framework has been conceptualized to facilitate active discussion and mitigation approaches between participating experts and the stakeholders. It is a collaborative bottom-up approach that can be scaled up to regional and national levels to be incorporated in different levels' planning and management decisions. Engaging wider public in debates and research on emerging scientific issues such as UWS is required to provide deeper understanding of UWS and to create successful adaptive plans for capacity building and making the society more resilient to the climate change related disasters in developing and emerging countries.

4.2 | Peri-urban wetlands support securing Kolkata's urban water and related ecosystems

This study shows the importance of including the role of peri-urban wetlands and the benefits or services from its ecosystem for securing a city's water and environmental security, again, an argument for approaches that can capture the complexity of water security. For mega cities like Kolkata the need is even stronger. The process of rapid urbanization has blurred the distinction between the "urban" with the "peri-urban" zones, which used to play a role as intermediary between urban and rural areas. There is a need to understand and document social, economic, and institutional characteristics of peri-urban regions in a better way. The unplanned and unregulated development process in KMC areas has proved to be unsustainable and has become a serious threat to the city and its environment. The growth has affected basic amenities, especially water supply for the increasing population in the newly developing areas.

4.3 | The socially excluded's insecure UWS

The study shows that there are vulnerabilities to water security in terms of WaSH in socially deprived and excluded areas; however, there are also variations within these geographical areas. This study identified that within areas characterized by deprivation and social exclusion, based on ethnicity, religion, socioeconomic standing, and gender matters, in determining who is more water insecure. In consequence, water and sanitation experts should take not only biophysical factors into account conducting the WaSH infrastructure planning, but how they are associated with socioeconomic, cultural, and demographic characteristics. Hence, multidimensional vulnerability to water insecurity should be considered in water security research.

4.4 | UWS assessment requires interdisciplinary approach

The results indicate that there is a need to analyze and address water security issues in a way that include across and within city and ward variations. Research (particularly for urban areas) needs to be focus on understanding the link between this spatial heterogeneity and water accessibility issues. This understanding is crucial for the management of current urban water systems as well as for the planning of sustainable development and policies on urban system structure and function. Cities function as a melting pot for people with differing cultural backgrounds, religions, interests, and social statuses. As the results show that ethnicity, religion and language are crucial in influencing and understanding who are water-insecure, more research is needed on these aspects to fully understand the complex interactions especially because cities are not only growing in population but are also becoming increasingly diverse.

4.5 | Inclusive quantitative UWS assessment framework

This study provides a unique interdisciplinary quantitative assessment framework to quantify UWS at the borough level and to define practical dimensions that identify water-insecure areas in both spatially and socially against others and allocate limited resources prudently, particularly for the Global South. This novel approach would help policy makers and water stakeholders to address their objectives to manage their available water and social resources in a sustainable, environmentally, and socially just way and achieve UWS security for all.

The inclusive framework for UWS assessment frames the challenge of UWS of Kolkata city beyond the traditional indicators such as quantity of supplied water, water accessibility and sanitation or water quality. Rather, it captures the issues of water insecurity holistically along its four major dimensions of UWS—availability, accessibility, quality water-related risk and hazards, and essentially related them with society and the individuals—to reach at the conclusion: how and where a city is becoming water insecure. Hence, the empirical approach of the study focused on the spatial analysis of all the components of UWS with a megacity perspective from emerging economies. The findings also suggest empirical evidence that water insecurity of a city cannot be only due to the malfunction or inadequacy of city's water system but also from the disparity, inequality, and exclusion in the society, which hampers the overall well-being of the city. Hence, along with conventional quantifiable components of bio-physico-chemical dimensions, social capital was considered as a key dimension of UWS with the anticipation of capturing the entirety by individual socioeconomic groups for the policy measure to improve water security.

4.6 | Adequate, high-quality data are crucial

The biggest challenges the Global South faces regarding assessment of achieving UWS are inadequate, unreliable, low quality, sociopolitically as well as technologically biased, non-inclusive and unorganized databases. With robust and trustworthy data on UWS, cities in the Global South lack proper management of its water resources and the demand of the growing population. Steps for identification, collection and analysis of data and statistical tools for UWS assessment need to start with prioritizing water security objectives. Strengthening water data institutions, establishing sustainable water data monitoring systems, adopting water data standards, and embracing an open data approach to water data access and licensing are essential.

Finally, it can be concluded that Kolkata city or the areas under KMC's jurisdiction is the oldest metropolis of India with one and half century old water supply system. The upgradation of infrastructure and increase in per capita water supply over time must be prioritized to improve its UWS. For that reason, this study provided the integrated and inclusive assessment framework, which can be used for a better understanding of the status of UWS across the city toward implementable decision making.

AUTHOR CONTRIBUTIONS

Subham Mukherjee: Conceptualization; methodology; formal analysis; validation; formal analysis; investigation; data curation; visualization; writing—original draft preparation; software; resources; project administration; funding acquisition. **Trude Sundberg**: Software; resources; writing—review & editing; supervision; project administration; funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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APPENDIX A: METHODOLOGY APPLIED

Some of the methods were published in our earlier publications. The references are given in the respective sections for detailed information.

1) Literature review (for details, please see Mukherjee, Sundberg, & Schütt, 2021)
   a. Data used: Academic literature including peer reviewed journals, theses, books, gray literatures such as reports from local, national, and international agencies, government documents, and Internet-based news reports.
   b. Method(s): The literature review was performed in three parallel steps: The first one was to set the background and to formulate the aims, objectives, and the scope of the study, while the second one was to define the challenges in terms of research questions, particularly from the study area, upon which the third phase of literature review was performed to select the methods and data, interpret the findings and justify the methodological choices for both quantitative and qualitative strategic assessments.

2) Primary and Secondary Data Processing
   i. Primary Data Processing
      a. Data used: The primary data base on a survey using (1) Stratified Random Sampling collection of data from 45 households from each borough of KMC and (2) two LGBTQ focus groups consisting of 35 respondents were conducted in November-December 2018. Total respondents were 720 + 35 = 755. Furthermore, the survey included the presence of drinking water provisions and toilets in the house. The respondents were a mixed from slum and non-slum areas of the entire KMC.
      The survey questionnaire forming the basis of the household survey consisted of 48 questions divided into five segments.
      - The first four segments are differentiating issues of (32 questions) four components of water security (water availability, water accessibility, water quality, and water risks and hazards).
      - The last segment included demographic data (16 questions) assemblage to reflect the social aspects of water security in the city's neighborhood which includes information on socioeconomics such as income, literacy, gender, religion, and ethnicity (based on language spoken) statistics.
      b. Method(s): The primary data is based on a household survey using Stratified Random Sampling method. It collected data from 50 households from each of the boroughs of Kolkata Municipal Corporation (KMC) area. Altogether, 720 households were surveyed within November–December 2018.
   ii. Ancillary Data Processing
      a. Data used: Census data of India, 2011, Reports, official documents, and published materials from the State Water Investigation Department (SWID) and Department of Urban Development of Government of West Bengal.
      Public toilets and Slum data from the Kolkata Municipal Corporation (KMC) (Department of Slum Development, Department of Water Engineering), and Kolkata Municipal Development Authority (KMDA). These include information on socioeconomics such as condition of the slum housing, income, literacy as well as water provisions in term of latrines, dugwell, tubewell, and standposts; data on gender, religion and language statistics were also obtained from this data set.

b. Method(s): The ancillary data were taken into consideration not only to fulfill the gaps inherited in primary data sourced from household survey, such as population data, but also to support the findings and maintain the consistency using different statistical methods used in this study. Census Data of India (2011) was used to extract the detailed slum data (Census of India, 2011).

3) Statistical analyses
   c. Data used: Survey data comprising of questionnaire divided between 4 components of water security (Water Availability, Water Accessibility, Water Quality and Water Risks and Hazards).
   Sociodemographic variables collected through Household Survey and ancillary data.
   d. Method(s):
      1. Principal component analysis (PCA): Principal Component Analysis (PCA) allows to identify the principal directions in which the data vary by transforming a set of correlated variables into a set of uncorrelated 'components. Principal components are the eigen vectors of a variance–covariance matrix. The first principal component is selected as the linear index of all the variables that captures the largest amount of information common to all the variables, which may then be used as the index. This approach allows the determination of the most appropriate weightings for each variable to derive an index, which captures maximum variation.
      2. Descriptive statistics: Methods of descriptive statistics were applied to assess the distribution of data (Boxplot), linear correlation between variables (Pearson's *r* and chi square test) and recapitulate the relationship between different variables (Crosstab) in SPSS.

4) Remote Sensing Data Processing (for details, please see Mukherjee et al., 2018)
   a. Data used:
      1) Landsat Multispectral Scanner (MSS) image (path 148, rows 44 and 45) DoA: 16.01.1980,
      2) Landsat Thematic Mapper (TM) image (path 138, row 44) DoA: 14.11.1990; 10.05.2009 and, 15.10.2009.
      3) Landsat Enhanced Thematic Mapper Plus (ETM+) image (path 138, row 44) DoA: 17.11.2000,
      4) Indian Remote Sensing (IRS) Resourcesat-1 Linear Imaging Self-Scanning Sensor (LISS) III image (path 108, row 56) DoA: 03.02.2010 and
      5) Indian Remote Sensing (IRS) Resourcesat-1 Linear Imaging Self-Scanning Sensor (LISS) III image (path 108, row 56) DoA: 11.04.2014.
      6) Landsat Operational Land Imager (OLI) (path 138, row 44) DoA: 22.04.2014; 16.11.2014; 06.05.2019; 30.11.2019.
   b. Method(s): There are two different Land use-land cover (LULC) change detection performed:
      1) LULC change between 1980, 1990, 2000, 2010 and 2014 for an overview analysis using three major LULC classes—urban settlements, vegetation, and wetlands within Kolkata Municipal Corporation (KMC) areas.
      2) LULC change between 2009, 2014 and 2019 for detailed study using six major LULC classes—urban settlement, agricultural lands, vegetation, lakes, inland wetlands, and open spaces within KMC areas and its peri-urban wetlands namely, East Kolkata Wetlands (EKW).

For both, first, standard set of imagery was geometrically and radiometrically corrected, thereupon image was co-registered to match the overlay with sub-pixel accuracy (RMS errors ≈ 0.21). For re-sampling, nearest-neighborhood technique was performed for the classification to retain the original pixel values. The maximum likelihood based supervised classification was employed to detect the changes in LULC within the Kolkata Municipal Corporation area (KMC). Classification of LULC was performed on co-registered images using a non-parametrical feature-space classifier on ERDAS Imagine software (v. 2015), and the LULC classes were mapped. For the assessment of the accuracy level of the classification procedure topographical maps (scale 1:50,000 surveyed in 1975–1976 by the Survey of India), complemented by ground-truth data obtained from field surveys between 2008–2018 and analysis of secondary data collected within 2008–2018 were compared with the classified satellite imagery. The average overall accuracy obtained for all was 85%.

5) Estimation of Value of Ecosystem Services and Changes in Value Due to LULC Changes (for details, please see Mukherjee, Sikdar, et al., 2021)
   a. Data used: To quantify the ecosystem service value (ESV) for the six land use categories urban settlement, agricultural lands, vegetation, lakes, inland wetlands, and open spaces, the Global value coefficients (GVCs) proposed by Costanza et al. (1997) have been used after suitable modification. The modified ESVs were estimated following Mamat et al. (2018) based on the ecosystem service valuation model of Costanza et al. (1997). All estimated monetary values given in US$ are based on the 2018 valuation.
   b. Method(s): The following equations are applied to quantify ESV:

$$ESVk = Ak \times GVCk \tag{A1}$$

$$ESV_t = \Sigma A_k \times GVC_k \tag{A2}$$

$$ESV_f = \Sigma A_k \times GVC_k \tag{A3}$$

where ESV_k is the ecosystem service value (ESV) for individual land use categories, ESV_t is the total ecosystem service value and ESV_f is the individual ecosystem service function; Ak is the area in hectare (ha) and GVC_k is the global value coefficient (US\$ ha^{-1} $year^{-1}$) for land use category k. GVC_{kf} is the global value coefficient (US\$ ha^{-1} $year^{-1}$) for land-use type k and ecosystem service function type f.

After estimation of total ecosystem service values (ESV) the average ecosystem service value (ESV_{avr}) is computed applying:

$$ESV_{avr} = ESV_t / U_a \tag{A4}$$

where ESVavr is the average ecosystem service value (US$ ha−1year−1), ESVt is the total ecosystem service value (US$ ha−1year−1) for a certain study year and Ua is the total geographical area of the urban area (ha).

Using the concept of elasticity applied in economics, coefficient of sensitivity (CS) has been calculated as follows:

$$CS = [(ESVj - ESVi)/ESVi]/[(VCjk - VCik)/VCik] \tag{A5}$$

where CS is the coefficient of sensitivity, ESV is the estimated ecosystem service value, GVC is the global value coefficient after Costanza et al. (1997), i and j denotes the initial and adjusted values respectively, lastly k represents the land use category.

6) Calculation of Water Quality Index (for details, please see Mukherjee, Sikdar, et al., 2021
   a. Data used:
   b. Surface water quality data were obtained from West Bengal Pollution Control Board (WBPCB) of 13 stations, including:
      - River
      - Inland wetlands (canal and ponds)
      - Lakes
      Groundwater quality data from 270 groundwater monitoring stations were provided by McArthur et al. (2018).
   c. Method(s): To calculate the WQI the Canadian Council of Ministers of the Environment (CCME*) model was used. The CCME WQI model consists of three measures of variance from selected water quality objectives: scope, frequency, and amplitude. The resulting CCME WQI values range between 0 and 100, representing the overall water quality. The CCME WQI values are then converted into rankings by applying the index categorization scheme. Chemical and bacteriological parameters considered as per CCME WQI categorization schema.

7) Formulation of Urban Water Security Indices (for details, please see Mukherjee et al., 2022)

This study aims to formulate an integrated index which is a composite measure of more than one index accumulating scores from a variety of individual variable. In order to capture the Urban Water Security (UWS) issues holistically, the study constructed three indices, namely, (i) WaSH provisions Index (WPI), (ii) Urban Environmental Water Security Index (UEWSI), and (iii) Urban Water Security Index (UWSI). At the end, Integrated Urban Water Security Index (IUWSI) was formulated aggregating the other three indices at the borough level to have a normalized borough-wise comprehensive value representing urban water security of KMC area, which can be regarded as final outcome of the study.

The method of each index construction followed 4 general steps: (1) selection of variables, (2) probing the empirical relationships of variables (3) weighing the variables and combining them into an index, (4) validating the index by examining the scores with the sociodemographic variables as well as the evidence from literatures.

i. WaSH provisions Index (WPI) (for details, please see Mukherjee et al., 2020)

Using the ward-wise frequencies of water provision based on the Survey and Census data of India (2011), a WaSH provisions (WP) index of a ward as a normalized weighted average was applied, defined as follows:

$$WPindex(non\text{-}normalized) = \frac{\frac{l}{p}}{2} + \frac{\left(\frac{s}{p} + \frac{d}{p} + \frac{t}{p}\right)}{6}. \tag{A9}$$

$$WPindex(normalized) = \frac{index - min(index)}{max(index) - min(index)} \in [0,1]. \tag{A10}$$

with $l/p = $ latrines person^{-1}, $s/p = $ standposts person^{-1}, $d/p = $ dugwells person^{-1} and $t/p = $ tubewells person^{-1}.

The variable "latrines person^{-1}" was considered as a representative of sanitation provision, while the remaining variables represent water sources. Therefore, total number of latrine person^{-1} (l/p) was given same weight as the sum of the remaining three WaSH provisions ($s/p = $ standpost person^{-1}, $d/p = $ dugwells person^{-1} and $t/p = $ tubewells person^{-1}). Normalization to WP index values between 0 and 1 allows to assess inter-ward-variability in water security provisions.

ii. Urban Environmental Water Security Index (UEWSI) (for details, please see Mukherjee, Sikdar, et al., 2021)

The urban environmental water security index (UEWSI) has been calculated based on results of LULC change analysis between 2009, 2014, and 2019, and Intensity indices (Su et al., 2011; Suja et al., 2013; Tate et al., 2005; Zhou et al., 2014), which explain the degree of change in average ecosystem services value (ESV) in each borough (an administrative block comprising several lowest administrative units called ward) of Kolkata Municipal Corporation and East Kolkata Wetlands for the given period of time. The temporal and spatial variation of the UEWSI was prepared using the following equations:

Pre-Monsoon Ecosystem Services Valuation Index:

$$\mathrm{ESVI}_{\mathrm{prm}} = \sum (\Delta ESprmx * 100)/AT * \Delta t) \tag{A11}$$

Post-Monsoon Ecosystem Services Valuation Index:

$$\mathrm{ESVI}_{\mathrm{pom}} = \sum (\Delta ESpomx * 100)/AT * \Delta t) \tag{A12}$$

Pre-Monsoon LULC Intensity Index:

$$\mathrm{PRM\,II} = \sum (\Sigma \Delta C1 * 100)/AT * \Delta t) \tag{A13}$$

Post-Monsoon LULC Intensity Index:

$$\mathrm{POM\,II} = \sum (\Sigma \Delta C2 * 100)/AT * \Delta t) \tag{A14}$$

Urban Environmental Water Security Index:

$$\mathrm{UEWSI} = \sum\nolimits_{-1}^{1} [(ESVIprm + ESVIpom + PRMII + PPOMII) + SuplWQI] \tag{A15}$$

where $\Delta ESprm_x$ and $\Delta ESpom_x$ denote the change of the borough wise average ESV in US$ between 2009 and 2019 during pre-monsoon or post-monsoon seasons; x is the individual borough of KMC; $\Delta C1$ and $\Delta C2$ are the change in area (ha) for all LULC classes over the total study period during pre- and post-monsoon seasons respectively; AT is the total area (ha) of the borough; and Δt is the time (Year) span of the study period between 2009 and 2019.

Weightage for Supplied Water Quality Index ($SuplWQI_x$) is a value assigned to tested supplied water's (or main source of drinking water's) category in the Canadian Council of Ministers of the Environment (CCME) water quality index (WQI) scheme for each borough (example: 1 for poor, 2 for marginal, 3 for fair, 4 for good and 5 for excellent) where the supplied water is considered as the main source of water for drinking purpose.

Normalization of UEWSI values (−1 to 1) allowed assessing inter-borough variability in environmental water security displayed in a map using ArcGIS 10.6 (ESRI, Redland, CA, USA).

iii. Urban Water Security Index (UWSI) (for details, please see Mukherjee et al., 2022)

The Urban water security index at the borough level was calculated based on Survey data, as:

$$\mathrm{UWSI} = (\mathrm{Avl} * \mathrm{w1}) + (\mathrm{Acs} * \mathrm{w2}) + (\mathrm{Wqt} * \mathrm{w3}) + (\mathrm{Wrh} * \mathrm{w4}) \tag{A16}$$

where

Avl = Score for *Water Availability* variables.

Acs = Score for *Water Accessibility* variables.

Wqt = Score for *Water Quality* variables.

Wrh = Score for *Water Risk and Hazards* variables, and,

w1, w2, w3, w4 are the weights assigned (determined by the "loadings" of PCA) for each factor.

Then, the UWS Index scores were used to categorize each borough on the 0–10-point scale (Category of security status) classifying the status of urban water security, as follows:

8–10: Very Secured.

6–8: Secured.

4–6: Around acceptable threshold.

2–4: Insecured.

0–2: Very Insecured.

iv. Integrated Urban Water Security Index (IUWSI)

Integrated urban water security index (IUWSI) comprises all the indices mentioned in the previous chapters. It can then be calculated as:

$$\mathrm{IUWSI} = (\mathrm{WPI} + \mathrm{UEWSI} + \mathrm{UWS})\,[0,1] \tag{A17}$$

where WPI is WaSH Provisions Index, UEWSI is Urban Environmental Water Security Index, and UWS is Urban Water Security Index.

APPENDIX B

TABLE B1 Recommended responses for achieving urban water security (UWS) in Kolkata city excerpted from the study.

UWS issue	Challenges	Recommended responses
Water availability	Decreasing wetlands and shrinking groundwater level (potentiometric surface)	Determining and ensuring minimum water flows, and regulating the timing of the flows, to maintain rivers and other aquatic ecosystems and their resources and diversity of existing and potential services
		Construction of new wetlands inside the city and at its periphery
		Creating artificial recharge zones
		Promoting, supporting, and developing infrastructures for rainwater harvesting
		Frequent maintenance and protection of piped services and stand posts for water supply in order to avoid leakage and wastage of water due to the missing stopper
		Strict and sustainable urban development policy to plan and implement
		Map out and involve local communities and the varying levels of availability issues along social, cultural, economic, and political dimensions and how they overlap with the biophysical.
		Involve communities and representatives from these communities.
		Construct solutions appreciating who is water insecure (deprivation, gender, caste, ethnicity, religion) and how responses affect and resolve issues of inequity in water availability.
Water accessibility	Less number of inclusive public toilets and insufficient water supply	Implementing policies to control consumer demands for water resources, and specifically managing the distribution of, or access to, water based on needs, including allocating existing water resources according to a hierarchy of neediness, rather than increasing the quantity of available water
		Augmentation of supply of water to all the households
		Increase the number of stand posts to deliver municipal supplied water even to the most remote deprived areas inside, and at the periphery of, the city

(Continues)

TABLE B1 (Continued)

UWS issue	Challenges	Recommended responses
		Building new inclusive public toilets and proper management of the existing public toilets for all
		Establishment and management of water ATMs at the important points of the city, e.g. railway stations
		Map out and involve local communities and the varying levels of accessibility along social, cultural, economic, and political dimensions and how they overlap with the biophysical.
		Involve communities and representatives from these communities.
		Construct solutions with appreciation of who is water insecure (deprivation, gender, caste, ethnicity, religion) and how responses affect and resolve issues of inequity in accessibility.
Water quality	Surface water pollution and groundwater contamination	Reducing the load of contaminants emanating from point and nonpoint sources, including water reuse and recycling and pollution reduction at the source, as well as preventing the entry of such polluting materials into receiving water systems through nonpoint source
		Provisioning sustainable wastewater management
		Restoration and consistent cleaning of the sewage systems, canals, and other inlet points
		Restrict urban and peri urban industries with strict pollution control measures
		Promotion of using biofuels and/or alternative sustainable energy sources to control the heavy metal and other carcinogenic contamination to the nearby waterbodies/aquifer
		Map out and involve local communities to understand how the deteriorated water quality affects populations along social, cultural, economic, and political dimensions.
		Involve communities and representatives from these communities.
Water risks and hazards	Increasing rate of seasonal waterborne diseases	Frequent checking and cleaning of roads, waterlogged areas, bushes, and pathways of drainage water.
		An emergency medical team need to be ready, specially, for deprived areas opened for 24 × 7.
		Map out and involve local communities to understand the health impacts across populations considering inequity and

TABLE B1 (Continued)

UWS issue	Challenges	Recommended responses
		inequality along social, cultural, economic, and political dimensions.
		Involve communities and representatives from these communities to build solutions and responses apt to address issues, build a community wide awareness and sustainable solutions across communities and social strata and in particular in deprived areas, and communities.
	Flooding during the rainy season and water scarcity during dry periods	Routine and appropriate management of the drainage systems to make them ready for, particularly, rainy seasons
		Promotion of rainwater harvesting system
		Creation and restoration of urban wetlands
		Include knowledge about which groups in the populations are already water insecure as a baseline when creating responses to disasters.
		Creating ongoing community involvement with particular water insecure communities which would enable a faster response to and understanding of the impact of disasters and a better ability to respond adequately.
Ecosystem	Rapid urbanization and loss of green and blue patches	Identifying effects of anthropogenic interventions on service-providing Units at different spatial scales
		Consideration of relationships between human, biodiversity and water-ecosystem service provision and management interventions
		Creating, supporting and promotion of infrastructures for vertical and horizontal, wherever applicable urban gardening using harvested rainwater and/or safe gray waters
		Creation of community spaces for meeting, building local knowledge of issues and sustainable solutions e.g., urban garden and spaces for conflict resolutions, these should be accessible to ALL.