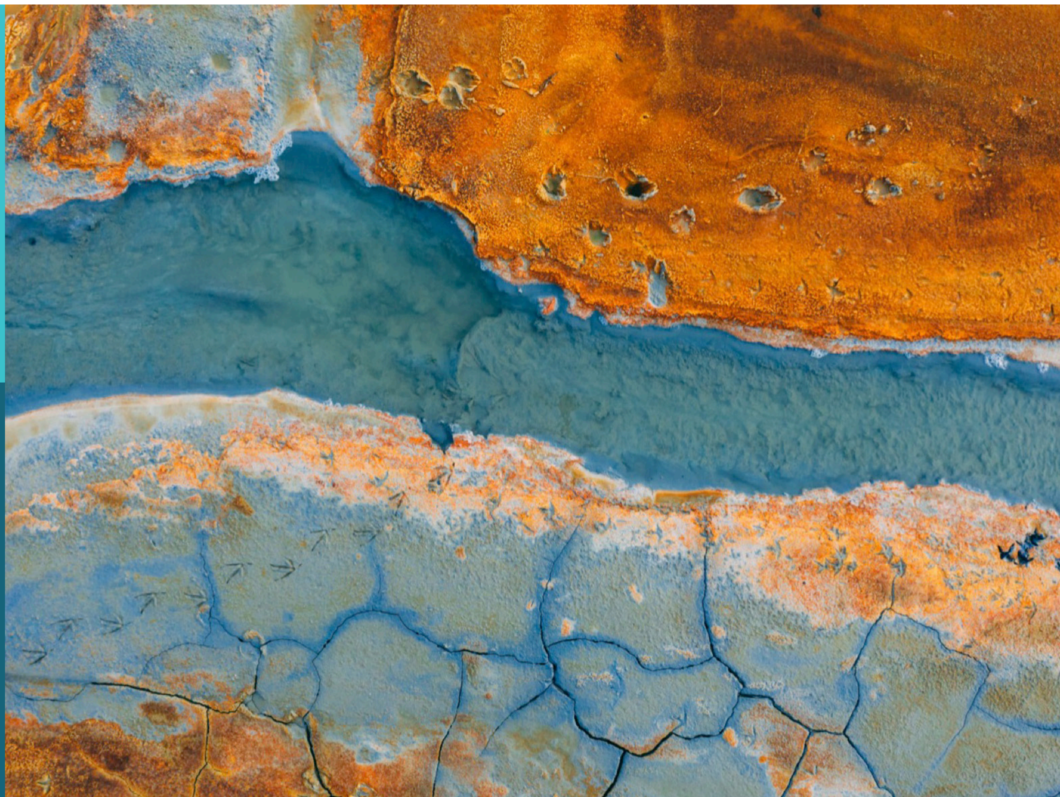
frontiers | Research Topics

Solutions to water crises (related to actual interventions)

Edited by
Jenia Mukherjee, Saket Pande, Melissa Haeffner, Sara Marks, Pieter van Oel, Matthew R. Sanderson and Adriana Allen

Published in
Frontiers in Water



ISSN 1664-8714
ISBN 978-2-8325-4214-9
DOI 10.3389/978-2-8325-4214-9

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Solutions to water crises (related to actual interventions)

Topic editors
Jenia Mukherjee — Indian Institute of Technology Kharagpur, India
Saket Pande — Delft University of Technology, Netherlands
Melissa Haeffner — Portland State University, United States
Sara Marks — Swiss Federal Institute of Aquatic Science and Technology, Switzerland
Pieter van Oel — Wageningen University and Research, Netherlands
Matthew R. Sanderson — Kansas State University, United States
Adriana Allen — University College London, United Kingdom

Citation
Mukherjee, J., Pande, S., Haeffner, M., Marks, S., van Oel, P., Sanderson, M. R., Allen, A., eds. (2024). *Solutions to water crises (related to actual interventions)*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4214-9

Table of contents

frontiers | Frontiers in Water

TYPE Editorial
PUBLISHED 21 November 2023
DOI 10.3389/frwa.2023.1270291

OPEN ACCESS

EDITED AND REVIEWED BY
Alessandro Pagano,
Istituto di Ricerca Sulle Acque IRSA-CNR, Italy

*CORRESPONDENCE
Jenia Mukherjee
jenia@hss.iitkgp.ac.in

RECEIVED 31 July 2023
ACCEPTED 03 November 2023
PUBLISHED 21 November 2023

CITATION
Mukherjee J, Marks S, Haeffner M, Pande S, van Oel P, Sanderson MR and Allen A (2023) Editorial: Solutions to water crises (related to actual interventions). *Front. Water* 5:1270291. doi: 10.3389/frwa.2023.1270291

Editorial: Solutions to water crises (related to actual interventions)

Jenia Mukherjee[1]*, Sara Marks[2], Melissa Haeffner[3], Saket Pande[4], Pieter van Oel[5], Matthew R. Sanderson[6,7] and Adriana Allen[8]

[1]Department of Humanities and Social Sciences, Indian Institute of Technology Kharagpur, Kharagpur, India, [2]Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland, [3]Department of Environmental Science and Management, Portland State University, Portland, OR, United States, [4]Department of Water Management, Delft University of Technology, Delft, Netherlands, [5]Water Resources Management Group, Wageningen University, Wageningen, Netherlands, [6]Department of Sociology, Anthropology, and Social Work, Kansas State University, Manhattan, KS, United States, [7]Department of Geography and Geospatial Sciences, Kansas State University, Manhattan, KS, United States, [8]The Bartlett Development Planning Unit (DPU) at University College London (UCL), London, United Kingdom

KEYWORDS

water, solutions, hydrological, social, technology, community, psychological, adaptive

Editorial on the Research Topic
Solutions to water crises (related to actual interventions)

Water science has become "pluralistic" (Evers et al., 2017) to collectively (yet differently) understand complex water systems with promising combinations of compatible and complementary disciplines. The contemporary context of water science discusses the more severe water-society challenges of the Anthropocene. Yet, the conversation is not definitive; indeed, there are unending debates between quantitative and qualitative research approaches including methodological choices and accuracies along questions of scales, themes, and politics of funding. Transdisciplinary applications and cross-sectoral engagements offer solution-oriented water just trajectories – scientists, practitioners, and user groups designing and deploying "solutions" related to actual interventions in addressing water crisis.

However, "solutions" has its own baggage. Mainstream solution designs and implementation strategies are not free from the dangers and dogmas of "path-dependence" (Mahoney and Schensul, 2006). That is, they are often heavily loaded with lineages from the past, and with limited capacities to solve problems that are "wicked" – multi-dimensional, dynamic, and recurring. The post-development era on "sustainability" (Castro, 2004) takes us through the critical "solution" route at global scales, when development agencies desperately transported and transplanted "first world" solutions on the "third world" "poor," "uncertain," and "ignorant" communities, resulting into development of underdevelopment (Frank, 1969), distinctly demonstrating the problematic aspects of universally designed prescriptive solution packages, manufactured in alienated contexts (Therkildsen, 1988). The articles in this Research Topic explore the chasm between bourgeoisie environmentalist notions and traditional river rituals (Bhattacharya et al.), how ignoring indigenous water treatment beliefs can reduce sanitation access (Daniel et al.), shadow water supply projects filling the gap left by tourism- fuelled economies (Sarkar), and other unintended consequences of top-down, large-scale water infrastructure as technological fixes.

But are "local," "small-scale," "community-based" adaptive practices effective and efficient enough to solve environmental/water crises, with far flung outcomes and impacts within and beyond situated geographies? The answer is not simple; it is unwise to fall prey to binary reductionisms, pitting "small" against "big," "cost-effective" against "costly," "ecofriendly" against "environmentally malign," and "indigenous" against "modern'. The authors have problematized "solutions" with rich, diverse, dense, and in-depth empirical investigations using transdisciplinary water-society perspectives.

Basel et al. unveils the paradoxes within the otherwise hydrologically and socially promising small- scale managed aquifer recharge (MAR), exemplifying "how such interventions play out within the complexity of the socio-hydrological system in which they are implemented" (p. 1). Here, the application of political ecology enables the authors to study the interplay between biophysical, climate, and social systems and account for both positive (drought reduction chances) and negative feedback loops (time lag between implementation and benefits reducing community willingness to act). Thus, they scientifically refrain from overestimating or oversimplifying small-scale MAR as a solution, while advocating for its practical implementation. The article underscores place-based dynamics in determining complex human-water interactions within and beyond local landscapes, emphasizing the need to critically understand climate trends using a power-sensitive approach, sensitizing us with non- linearities and complexities socially embedded in small-scale MAR.

Solutions at micro-settings with household as the unit of analysis, have been discussed by Daniel et al., manifesting how socio-economic characteristics (SECs) and psychological factors determine behavioral choices in adopting to household water treatment (HWT) as a feasible technology in improving the quality of potable water in developing economies. The authors implement the RANAS (Risk, Attitude, Norm, Ability, and Self-regulation) approach to map psychological trajectories of 377 households inhabiting East Sumba, Indonesia – one of the poorest localities with inadequate public utilities. Identifying correlation between SECs and RANAS, the study reveals how worldviews and belief systems, ability to access local infrastructures, and habituated and affective familiarity (taste of water) within situated contexts facilitate or impede solution-oriented strategies, impacting (un)just water futures. Moncaleano et al. extend the use and analysis of behavioral and human psychological variables in investigating water use efficiency (WUE). Following a systematic review of literature, the authors deliver a conceptual model integrating contextual (socioeconomic, technical, institutional, and environmental) and behavioral factors (RANAS, Values, Beliefs and Norms and trust) to represent potential WUE cause-effect relationships. Together these articles extend the application of the RANAS framework to new realms of the water supply space, while generating knowledge regarding the pathways connecting behavioral and technological concepts.

Mukherjee et al. off-loads social hierarchies in the developing and hyper-urbanizing metropolis of Asia, actuating differentiated access to utilities and unjust water trajectories. Critically analyzing primary household data from Kolkata (India), the article advocates for specifically designed inclusive water solution strategies to accommodate the most marginalized, namely gender, trans-individuals, and children, inhabiting more vulnerable and unequal (peri)urban spaces such as slums or *bastis*. In similar vein, Sarkar validates how water crises in a hill city (Shimla) of India should be understood beyond hydrological (erratic rainfall due to climate change) and other physical and socio-economic factors (urban growth and tourism), and as an outcome of infrastructural politics shaping unequal and unjust water conjectures. Sarkar also uses an urban (situated) political ecology approach to read uneven waterscapes of Shimla. The case study argues that "the water crisis, as a context, is dialectical" (p. 1). And thus, in spite of implementation of several hydraulic projects, "...the inherent fissures of inequality within the city that cause differential access to water remain" (p. 1).

Inclusive water governance frameworks are keys in making low-cost, local technologies work viz. water reuse. Frick-Trzebitzky et al. map the success of an informal municipal partnership engaging a group of interdisciplinary researchers, municipal decision-makers, engineers, and farmers in water reuse in agriculture in Namibia. They investigate complex interplays between human behavioral aspects, functioning of the institutional landscape, and physical-material configurations, and discuss the value of cross-sectoral collaboration in fostering municipal capacities toward efficient water reuse as a sustainable solution in Africa. Koehler et al. examines the knowledge to action framework, investigating interconnections between water politics and policy making, focusing on Kitui County, Kenya. The authors place a provocative proposition for readers to reflect and contemplate: "What if, instead of policy producing practice, practices produce policy?" (p. 11). Documenting detailed insights and recommendations from a knowledge co-production workshop, involving participation of (women) fishers, researchers, fishworkers" forum (partner NGO), and scientists, Ghosh et al. deploy solution- focused participatory research to capture intersecting social-ecological and socio-hydrological variables in the least explored dried fish sector of the Sundarbans delta.

Bhattacharya et al. reinforce this "transdisciplinary exigency" (Mukherjee et al., 2022), weaving together cherishable moments of collaborative governance, accommodating agencies of (more-than-human) actors on the heritage river the Adi Ganga, flowing through the Kolkata metropolis. The authors apply historical urban political ecology (HUPE) (Mukherjee, 2020) to perceive urban riverscapes as adaptive "living systems infrastructure" (Mukherjee, 2022), dotted with (a)synchronous space-time movements and flows. Thus, "solution" is imagined through nuanced interpretations of numerous "(un)successful attempts to revive the river beyond global conceptualizations of what a "river" should be."

The diverse range of spatio-empirics across different themes on water-society interactions constituting this issue complexifies "solutions," conveying its temporal, relational, and political edges, and thus offer opportunities to appreciate fluidities, beyond fixed prescriptions, standardized and strategized upon by powerful techno-environmental groups and political lobbies.

Author contributions

JM: Writing—original draft. SM: Writing—review & editing. MH: Writing—review & editing. SP: Writing—review & editing. PO: Writing—review & editing. MS: Writing—review & editing. AA: Writing—review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We would like to acknowledge the contributors of the issue for their patience in enthusiasm to work on revised drafts. We are grateful to the reviewers. Our special gratitude is to the TU Delft Conference on Socio-Hydrology. It made way to this Research Topic, assembling critical researchers and practitioners discussing and debating water-society relations toward just and equitable solutions.

Conflict of interest

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

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Castro, C. J. (2004). Sustainable development: mainstream and critical perspectives. *Org. and Environ.* 17, 195–225. doi: 10.1177/1086026604264910

Evers, M., Höllermann, B., Almoradie, A. D. S., Garcia Santos, G., and Taft, L. (2017). The pluralistic water research concept: a new human-water system research approach. *Water* 9, 933. doi: 10.3390/w9120933

Frank, A. G. (1969). "Sociology of development and the underdevelopment of sociology," in *Latin America: Underdevelopment or Revolution*, ed A. G. Frank (New York, NY: Monthly Review Press).

Mahoney, J., and Schensul, D. (2006). "Historical context and path dependence," in *The Oxford Handbook of Contextual Political Analysis*, ed R. Goodin and C. Tilly (New York, NY: Oxford University Press).

Mukherjee, J. (2020). *Blue Infrastructures of Kolkata: Natural History. Political Ecology and Urban Development in Kolkata.* Singapore: Springer Nature.

Mukherjee, J. (2022). "Living systems infrastructure" of Kolkata: exploring co-production of urban nature using historical urban political ecology (HUPE). *Environ. Urb.*. 34, 32–51. doi: 10.1177/09562478221084560

Mukherjee, J., Bhattacharya, S., Ghosh, R., Pathak, S., and Choudry, A. (2022). "Environment, society and sustainability: the transdisciplinary exigency for a desirable anthropocene," in *Social Morphology, Human Welfare and Sustainability*, ed M. I. Hassan (Cham: Springer Nature).

Therkildsen, O. (1988). *Watering White Elephants? Lessons from Donor funded Planning and Implementation of Rural Water Supplies in Tanzania.* Uppsala: Scandinavian Institute of African Studies.

frontiers in Water

ORIGINAL RESEARCH
published: 08 April 2021
doi: 10.3389/frwa.2021.649445

Socio-Economic and Psychological Determinants for Household Water Treatment Practices in Indigenous–Rural Indonesia

D. Daniel[1,2]*, *Saket Pande*[1] *and Luuk Rietveld*[1]

[1] *Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands,* [2] *Department of Health Behavior, Environment, and Social Medicine, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia*

Household water treatment (HWT) is one of the possible technologies to improve the quality of potable water in low–middle-income countries. However, many households still drink untreated water that leads to negative health consequences, highlighting the need for a behavioral study. This study explores the role of eight socio-economic characteristics (SECs) and five psychological factors on the practices of HWT, using a combination of statistical analyses and Bayesian Belief Network (BBN) modeling. The findings were based on 377 household interviews in East Sumba, Indonesia, an area where indigenous belief is still common. Self-reported answers and observed practices of HWT were combined, and 51% of the respondents were categorized as regular users of HWT. Furthermore, favorable socio-economic conditions, e.g., wealthier or more educated parents, facilitated psychological factors that led to regular use of HWT. This suggests the importance of reducing SEC inequalities to improve the HWT adoption. Mother's education was the most influential SEC ($\Delta P = 8$), and people who followed indigenous beliefs tend not to use HWT on a regular basis. Moreover, easy access to water positively influenced the household's ability to operate the HWT technology. Attitude toward the HWT practice, especially the perception of treated water's taste ($\beta = 0.277$), was the most significant psychological factor, influencing HWT adoption. An interpretation of complex interlinkages between socio-economic conditions and psychological factors that drive the practice of HWT was therefore offered, alongside recommendations for conservative interventions to change the household's behavior in a culturally unique area with difficult access to water.

Keywords: household water treatment, Bayesian belief networks, socio-economic characteristics, psychological factors, RANAS, indigenous belief

OPEN ACCESS

Edited by:
Roman Seidl,
Leibniz University Hannover, Germany

Reviewed by:
Peter Goethals,
Ghent University, Belgium
Jim Wright,
University of Southampton, United Kingdom
Anindrya Nastiti,
Bandung Institute of Technology, Indonesia

Correspondence:
D. Daniel
d.daniel@tudelft.nl

Specialty section:
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

Received: *04 January 2021*
Accepted: *02 March 2021*
Published: *08 April 2021*

Citation:
Daniel D, Pande S and Rietveld L (2021) Socio-Economic and Psychological Determinants for Household Water Treatment Practices in Indigenous–Rural Indonesia. Front. Water 3:649445. doi: 10.3389/frwa.2021.649445

INTRODUCTION

It was estimated that 2.1 billion people had no access to safely managed drinking water services in 2017 (UNICEF and WHO, 2019). Lack of access to safe drinking water leads to adverse health conditions and inhibits productive activities (Prüss-Ustün et al., 2019). Children below the age of five suffer the most from these water-related diseases, such as diarrhea, stunting, and even mortality (GBD 2016 Diarrhoeal Diseases Collaborators, 2017).

Water, sanitation, and hygiene (WASH) interventions have been conducted intensively in LMICs. Such interventions have included household water treatment (HWT), i.e., treating water oneself within a household, and includes technologies such as boiling, solar disinfection, adding chlorine, or water filtration (Sobsey et al., 2008). HWT has been effective in reducing water-related diseases in LMICs, for example, in studies conducted in Ethiopia (Mengistie et al., 2013) and Bangladesh (Pickering et al., 2019). However, previous studies have found that, in spite of its success, many households in LMICs have not extensively adopted HWT technologies or practiced it regularly (Geremew and Damtew, 2020). This can reduce the positive health effect of HWT (Enger et al., 2013).

Understanding the reasons behind adoption of HWT is essential in order to develop better WASH intervention strategies that sustain appropriate WASH behavior. RANAS, which stands for *Risk*, *Attitude*, *Norm*, *Ability*, and *Self-regulation*, is one of the psychological frameworks that has been used to understand the behavioral determinants of diverse water use practices (Mosler, 2012). It has been successful in explaining the use of HWT in developing countries such as Bangladesh (Inauen et al., 2013), Chad (Lilje et al., 2015), and Ethiopia (Sonego et al., 2013).

However, only few HWT studies have included and analyzed behavioral determinants, i.e., SEC and psychological factors (Fiebelkorn et al., 2012), which limits the understanding of such behavior. Dreibelbis et al. (2013) argue that combining the socio-economic characteristics (SECs) and psychological factors can even provide better systems-level understanding of WASH-related behavior. However, Lilje and Mosler (2017) argue that SEC is "less important" to measure because SEC explains only a small portion of the behavior and it is nested within psychological factors. Other WASH studies have similarly suggested that the strength of the influence of SEC is much smaller than psychological factors, once it is combined with psychological factors as independent variables at the same level of regression analysis. See, for e.g., Stocker and Mosler (2015) in the context of cleaning of water storage and Seimetz et al. (2016) in the context of handwashing behavior.

However, Daniel et al. (2020b) tested the hypothesis that the use of HWT is influenced by the household's SEC via psychological factors and the psychological factors are influenced by the household's SEC. The authors used mediation analysis and found statistically significant evidence for the hypothesis that the influence of SEC on HWT adoption is mediated by psychological variables, meaning that SEC and psychological factors could not be analyzed at the same level. A previous study has introduced and implemented this hierarchical causal framework using a Bayesian Belief Network (BBN) and combined SEC and psychological factors to analyze the use of HWT in Nepal (Daniel et al., 2019). RANAS psychological framework guided the analysis. However, RANAS factors have not completely been utilized, potential bias of self-reported answers existed, and limited SECs were used. The study presented in this manuscript therefore tackles the limitations in the previous work (Daniel et al., 2019). In addition, a BBN model with more SEC and a complete set of RANAS psychological factors was developed and constructed. No other study [other than Daniel et al. (2019)] has explored the influence of SEC on psychological factors in HWT or WASH context, i.e., such possible causal relationship has been ignored; see, for e.g., Stocker and Mosler (2015) and Seimetz et al. (2016).

The current study takes up the abovementioned hierarchical causal framework to understand the complex interlinkages between SEC and psychological factors behind the practice of HWT in a rural area in East Sumba, Indonesia. This approach not only is able to understand the complex system behind the practice of HWT but also potentially enables local stakeholders to design relevant interventions considering the household's psychological and SEC to facilitate behavioral change.

MATERIALS AND METHODS

A cross-sectional study was conducted on August 3–16, 2018, in the district of East Sumba, Province Nusa Tenggara Timur, Indonesia. More than 10% of the total population in the district still follow an indigenous belief, known as "Marapu," i.e., worship the forefathers (Fowler, 2003; Vel and Makambombu, 2019). Even though only a small portion of the population still officially practice Marapu, there is still a large influence of Marapu on the culture and daily life of the Sumbanese people (Vel and Makambombu, 2010). This area is known to be one of the poorest in Indonesia, where open defecation is common, and the prevalence of malnutrition among children is one of the highest in Indonesia (Picauly and Toy, 2013; Sungkar et al., 2015). The majority of the households used wells (44%) and surface water (spring or river) (32%) as their main drinking water sources (BPS Statistics of East Sumba Regency, 2018). This situation emphasizes the need to practice HWT regularly. However, local NGOs suggested that many of the households in this area still drink untreated water.

We targeted a number of household based on the methodology of Krejcie and Morgan (1970) and Wilson Van Voorhis and Morgan (2007) (see the **Supplementary Material** for more information). A total of 377 households were randomly visited during transect walk within nine villages and enrollment of every, for example, five houses (**Figure 1**). There were no exclusion criteria for the participation of households because we aimed to get overall situations in that area. A structured household interview contains the household's socio-demographic information, WASH knowledge and perceptions, and observations by hired local enumerators. The observation covered several hygiene indicators, such as conditions of the toilet and cleanliness of the house. The SECs were encoded in categorical variables, while most of the answers related to psychological factor questions were measured in a five-point Likert scale. The interview targeted a mother as a respondent on behalf of the household, wherever possible, because they are mainly responsible for the water management in the house. The Open Data Kit (ODK) platform on a smartphone was used for the interview and the data were transferred to the computer for analysis. The interviews were conducted in Bahasa Indonesia by six local enumerators. The survey results were checked daily, and if there was a doubt on the data, we confirmed it directly

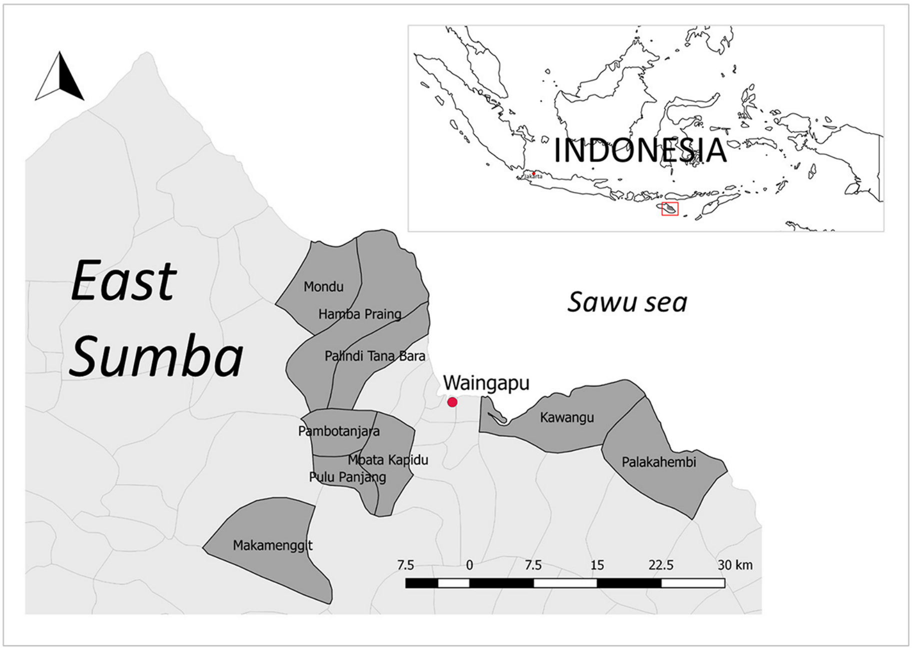


FIGURE 1 | Location of nine villages visited in district East Sumba, Indonesia; drawn using QGIS (QGIS Development Team, 2017).

with the enumerator. The Human Research Ethics Committee of Delft University of Technology and the Agency for Promotion, Investment and One-Stop Licensing Service at the province (East Nusa Tenggara) and district (East Sumba) level approved the study setting. Participation was voluntary, and written informed consents were obtained from all respondents; as well as the consent from the village's head prior to the data collection. No household visited declined to participate in the study.

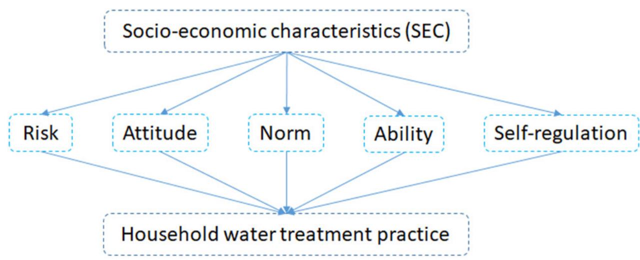


FIGURE 2 | A conceptual model of the three-level hierarchical BBN model.

Bayesian Belief Network

A BBN is a directed acyclic graph showing a hypothetical causal relationship between "causal" variables (called "parent nodes" in BBN) and an "affected" variable (child node) (Pearl, 1988). The strength of a probabilistic relationship between parents and a child node is depicted by the entries in the corresponding Conditional Probability Tables (CPTs). An introduction on BBN can be found in Cain (2001). BBN offers advantages compared to other common statistical methods used to analyze the adoption of water technology or water-related behavior, such as regression analysis. BBN is able to combine expert judgement (qualitative) with actual data to tackle data's uncertainties or unavailability and better visualization of a complex system by multiple stakeholders, while allowing for both predictive and diagnostic inference (Barton et al., 2012).

A BBN structure can be inspired through statistical inference between variables, theory, or by consensus between experts (Nadkarni and Shenoy, 2004). In this study, a three-level hierarchical model depicting how SECs influence the use of HWT via psychological factors was created (**Figure 2**). BBN has been widely used in water-related studies (Phan et al., 2016, 2019), e.g., for water management and water quality, but has been rarely used in a water-related behavioral study. To the best of our knowledge, only one study has utilized BBN modeling in the behavioral context (Daniel et al., 2019).

Socio-Economic Characteristics

Eight SECs, which were expected to influence the practice of HWT or other WASH behavior based on peer-reviewed literature, were used in this study: (1) *Wealth*, e.g., mentioned as a significant variable in WASH studies in Sub-Saharan Africa (Munamati et al., 2016) and Indonesia (Roma et al., 2014); (2) *Indigenous belief*, e.g., in studies in Ethiopia (Behailu et al., 2016) and Australia (Waterworth et al., 2015); (3) *Access to market*, e.g., in WASH studies in Kenya (Dubois et al., 2010) and Guatemala (Goldman et al., 2001); (4) *Water-related health problem*, e.g., in HWT studies in rural Bolivia (Christen et al., 2011) and India (Freeman et al., 2012); (5) *Information access* (George et al., 2016); (6) *Mother's education*, e.g., in HWT studies in Cameroon

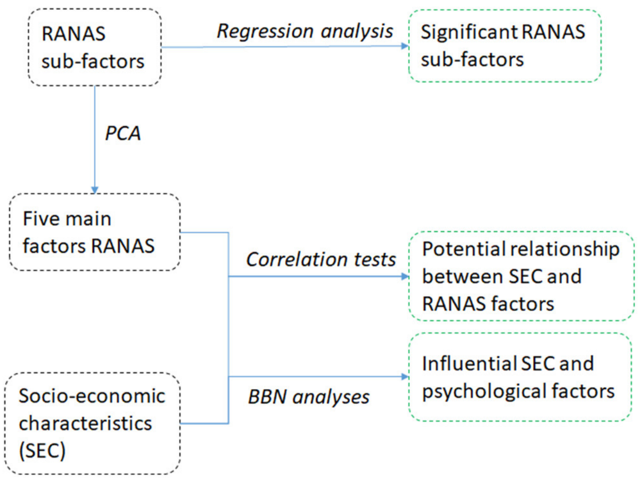


FIGURE 3 | Summary of the analyses.

(Fotue Totouom et al., 2012) and India (Freeman et al., 2012); (7) *Father's education* (Dubois et al., 2010); and (8) *Access to water* (Figueroa and Kincaid, 2010). A respondent's answer to "frequency of watching TV" was used as the proxy for variable *Information access*. The occurrence of diarrhea in the preceding 2 weeks at the time of visit among children below the age of 5 in the house was used for the variable *Water-related health problem*. Those studies found, in general, that households that have better socio-economic conditions, e.g., are wealthier, have easier access to market, or have a more educated mother, were more likely to use WASH-related technologies.

RANAS Psychological Factors

RANAS consists of five main factors (Mosler, 2012). *Risk* is related to the individual's awareness and understanding of HWT-related issues. *Attitude* represents a person's positive or negative feeling toward HWT. *Norm* represents the social pressure toward HWT. *Ability* represents a personal confidence in his or her ability to execute HWT. Finally, *Self-regulation* reflects personal attempts to self-monitor and plan HWT and deal with conflicting goals. RANAS framework inquires psychological information at the sub-factor level (Mosler, 2012); see also **Table 1**. Previous WASH studies used RANAS framework to find critical psychological factors that influence the WASH-related behavior, for example, *self-regulation* (Stocker and Mosler, 2015), *ability* (Seimetz et al., 2016), and *norm* (Lilje et al., 2015). By targeting such critical psychological factors, the behavior of a target group can be changed, e.g., toward adoption of technology (Mosler, 2012).

Data Analyses

Two sequential analyses were performed (**Figure 3**): (1) statistical analysis: regression of the RANAS psychological sub-factors on HWT practice, reduction of RANAS sub-factors to five dominant factors, and correlation tests between each SEC and the five RANAS factors; (2) hierarchical BBN modeling to assess the effect of SEC, via RANAS psycho-social characteristics, on *HWT practice*. The regression results were used to identify the significant RANAS sub-factors. Furthermore, BBN was performed using SEC and *reduced* RANAS psychological factors to predict the use of HWT.

Statistical Analyses

Principal Component Analysis (PCA) was performed to create some "latent" variables and reduce dimensionality (i.e., number of variables used in the analysis), before building the BBN model, as conducted also by Daniel et al. (2019). The "latent" variables created as a result were *wealth* and the five RANAS factors: *Risk*, *Attitude*, *Norm*, *Ability*, and *Self-regulation*, and finally *HWT practice*. *Wealth* was created from the first principal component of variables linked to the household's assets.

Using all RANAS sub-factors will make a BBN structure too complex and therefore should be avoided (Marcot et al., 2006). Thus, PCA was also used to combine the sub-factor information into one representative variable, i.e., the first principal component, for each RANAS factor. For example, the data of all *Norm* sub-factors *descriptive*, *injunctive*, and *personal norm* were combined (see **Table 1**) using PCA and obtained the first principal component as the representative variable (and its corresponding data) *Norm*. The reliability of performing PCA to represent RANAS main factors and *HWT practice* have been more extensively discussed in Daniel et al. (2019).

To assess the practice of HWT among the respondents, respondent's answers to four questions related to the use of HWT and observation of the practice by the enumerators at the time of visit, to identify whether the household practiced HWT, were combined. The four questions corresponded to percentage of water treated daily, frequency of drinking raw water daily, habit to perform HWT, and intention to treat water. The intention behind combining multiple answers was to diminish the bias of self-reported behavior, which may overestimate the practice of HWT (Schmidt and Cairncross, 2009). We again used PCA to create a variable *HWT practice*.

Forced-entry multivariate regression analysis using all RANAS sub-factors was conducted (**Table 1**) as independent variables with *HWT practice* as the dependent variable. One-to-one Pearson's correlation tests between each SEC and each of the five factors of RANAS were conducted (each of the five factors being the principal components of the corresponding sub-factors) to identify potential relationships between them. The results were considered when building the final hierarchical BBN structure. All statistical analyses were conducted using IBM SPSS Statistics 24.

BBN Analysis

Discrete BBN requires categorical or discrete information as model inputs. Thus, continuous variables, such as the output of PCA, were discretized into several categories. The respondents were categorized into three groups: (1) for the psychological factors: low (lowest one-third of scores, e.g., low *Norm*), moderate (one-third to two-thirds of the lowest scores, e.g., moderate *Norm*), and high (the remaining data); and (2) for the

TABLE 1 | Descriptive statistics of psychological factors.

Psychological factors		Example question	Scale	M (SD)	Cronbach's α
Risk	Perceived vulnerability	How high do you feel is the risk that you will get diarrhea if you drink untreated water?	1–5	2.9 (1.0)	0.846
	Health knowledge	What are the causes of diarrheal diseases?	1–5*	1.9 (0.9)	
	Perceived severity (on life)	Imagine you have diarrhea, how severe would be the impact on your daily life?	1–5	3.2 (1.1)	
	Perceived severity (on a child)	Imagine your child below 5 years has diarrhea, how severe would be the impact on his life and development?	1–5	3.6 (1.2)	
Attitude	Health benefit	How certain are you that always treating your water will prevent you from getting diarrhea?	1–5	3.4 (1.1)	0.780
	Affective belief (taste)	How much do you like the taste of treated water?	1–5	3.9 (1.1)	
	Affective belief (enjoy)	How much do you enjoy the moment when you treat your water?	1–5	3.9 (0.9)	
Norm	Descriptive	How many of your neighbors treat their water?	1–5	3.0 (1.1)	0.734
	Injunctive	People who are important to you, how do they think you should always treat your water before consumption?	1–5	3.5 (0.8)	
	Personal	How strongly do you feel an obligation to yourself to always treat your water before consumption?	1–5	3.8 (1.2)	
Ability	Confidence in performance	How certain are you that you will always be able to treat your drinking water before drinking?	1–5	3.3 (1.0)	0.905
	Confidence in recovering	Imagine that you have stopped treating your water for several days, how confident are you that you would restart treating your drinking water again)?	1–5	3.3 (1.1)	
	Confidence in continuation	Imagine that you have much work to do. How confident are you that you can always treat your water?	1–5	3.3 (1.0)	
Self-regulation	Action control	How much do you pay attention to the resources needed to treat the water?	1–5	3.6 (0.9)	0.535
	Remembering	Within the last 24 h: How often did it happen that you intended to treat your water and then forgot to do so?	1–5	3.8 (1.2)	
	Commitment	How important is it for you to treat the water?	1–5	3.8 (1.0)	
	Barrier planning	Could you tell me how do you deal with the obstacles that hinder you to treat water?	1–0*	0.5 (0.5)	

M, mean; SD, standard deviation.

**For health knowledge, the scale is based on the correct causes mentioned by the respondents; for coping planning, 1 = has clear solution, 0 = no clear solution. The Cronbach's α is for PCA.*

HWT practice: "non-user," "irregular user", and "regular user" (using the approach used for psychological factors).

Discretization was also conducted on *wealth* (after PCA), *access to water*, and *information access* for the BBN analysis. For variable *wealth* in the BBN, three categories were created based on the first principal component's score: poor (the lowest 40%), middle (the next 40%), and rich (the last 20%), as suggested by Houweling et al. (2003). For *access to water*, respondent's answer "below 5 min" (i.e., 5 min for respondent to walk to the main water source, wait in the line if there is a queue, collect the water, and come back) was coded "close," "5–30 min" was "medium," and "above 30 min was "far." For *information access*, if the respondent answered "almost never" and "seldom" to indicate the frequency to watch TV daily, then we coded "difficult" *information access*. If they answered "sometimes" and "quite often," then *information access* was coded "medium," and very often was coded as "easy" *information access*.

As mentioned previously, a BBN structure can be inspired by statistical relationships, theory, expert knowledge, or hypothetical causal relationship between variables (Nadkarni and Shenoy, 2004). The structure was created by considering statistical relationships, i.e., using the Pearson's correlation tests, and, especially, hypothetical causal relationship between each SEC and psychological factor. For example, even though the Pearson's correlation test showed that there was a significant relationship between "indigenous belief" and "ability," we did not link them in the BBN structure. That is because we argue that there cannot be a (direct) causal relationship between "indigenous belief" and "ability." Cain (2001) argues that BBN is composed by "a set of links representing causal relationships between these nodes," suggesting the hypothetical causal relationship between interconnected nodes in the BBN structure. Therefore, by not linking all significant relationships, we tried to limit the number of parent nodes on each psychological factor.

BBN was performed using Genie 2.2 (http://www.bayesfusion.com). The software uses the Expectation Maximization (EM) algorithm to estimate the entries of CPT, which maps the conditional probability between a child node and all its parent nodes (Druzdzel and Sowinski, 1995; Do and Batzoglou, 2008). The EM algorithm used the inputted data, i.e., the questionnaire results after the discretization steps as explained previously. Ten-fold cross-validation was conducted to assess the model's performance. The sample, i.e., households, is divided into 10 sub-samples and use nine sub-samples for parameter learning and the remaining one for prediction. The model's performance is indicated by the Area Under the Curve (AUC) value of the Receiver Operating Characteristics (ROC) curve in which a value close to one indicates perfect prediction of the output variable (higher sensitivity and lower false positives) (Greiner et al., 2000). Furthermore, sensitivity analysis was conducted to find the most influential variable for the output node. Predictive (forward) and diagnostic (backward) inference were also conducted using the same software.

During the sensitivity analysis, the effect of a small change in the CPT, i.e., model's parameters, of each node on the output node was calculated. The predictive (Bayesian) inference was intended to simulate the influence of specific SEC and psychological nodes, i.e., model's input, on the HWT practice. For example, by updating the node *Indigenous belief* to 100% "yes," the value in the psychological node connected to it should change and will thereafter change the value in output node *HWT practice*. In addition, diagnostic inference was performed, which is the opposite of predictive inference. In diagnostic inference, a desired distribution of states in the output node was set and infer the distribution of states in its parent nodes that could lead to the desired outcome (Zabinski et al., 2018). For example, diagnostic inference of *HWT practice* at 100% "regular" will identify distribution of states in all SEC and psychological nodes that will lead to such output; i.e., it will identify most probable causes of 100% of households to practice HWT.

RESULTS

Most of the respondents (84%) were the mother, and the rest were the household head. In terms of schooling, 33% of the respondents attended at least secondary school, while only 29% among the household's head (male). The majority of the respondents (87%) had non-permanent housing walls, i.e., wood or bamboo; 7.4% a non-permanent roof, i.e., straw; and 69% a non-permanent floor, i.e., compacted soil. Twenty-six percent of the respondents followed the indigenous belief "Marapu." Around half of the respondents mentioned that they almost never watched TV (56%). Fifty-two percent of respondents were categorized as living in relatively difficult market access.

TABLE 2 | Regression analysis of all RANAS sub-factors psychological factors on HWT practice.

Variables	B	SEB	β
Risk			
Perceived vulnerability	0.061	0.034	0.069
Health knowledge	0.037	0.040	0.033
Perceived severity (on life)	−0.077	0.036	−0.090*
Perceived severity (on a child)	0.019	0.032	0.023
Attitude			
Health benefit	0.002	0.038	0.002
Affective belief (taste)	0.246	0.034	0.277***
Affective belief (enjoy)	0.052	0.043	0.046
Norm			
Descriptive	0.058	0.029	0.065*
Injunctive	0.027	0.041	0.024
Personal norm	0.190	0.035	0.233***
Ability			
Confidence in performance	0.122	0.040	0.118**
Confidence in recovering	0.043	0.045	0.044
Confidence in continuation	0.159	0.049	0.158**
Self-Regulation			
Action control	−0.028	0.037	−0.027
Remembering	0.012	0.024	0.016
Commitment	0.017	0.028	0.018
Barrier planning	0.406	0.067	0.209***

$^*p \le 0.05$, $^{**}p \le 0.01$, $^{***}p \le 0.001$. Adjusted $R^2 = 0.842$, $n = 257$.

Additionally, 29% of the respondents said that they still practiced open defecation, while 50% of the respondents had their own toilet. Thirty-four percent of the respondents had access to a piped water scheme, while 58% still relied on river or well, and 8% bought water from commercial entities or private persons, e.g., water truck or refill water station. Fifty-one percent of the respondents had a water source nearby or in the house, i.e., below 5 min per trip to get water, while 29% of the respondents needed at least 15 min per trip to fetch water. A total of 101 respondents (27%) claimed that almost all of their drinking water was treated, i.e., self-reported answer. However, after using PCA to create the variable *HWT practice*, 51% of the respondents were categorized as "regularly" practicing HWT, 26% as irregular user, and 23% as non-users. Moreover, 85% of the respondents answered boiling as the HWT method that they often practiced. Very few households used another type of HWT, e.g., commercial water filter (five households), which is because there was no promotion of other types of HWT in that area. Diarrhea incidence among children below the age of 5 was relatively high, 32% in the preceding 2 weeks at the time of visit; i.e., the data collection was conducted in the dry period. A table of descriptive statistics of the respondents can be found in the **Supplementary Material**.

Statistical Analyses

Table 2 shows the results of the regression analysis using all RANAS sub-factors as predictors of the use of HWT. The results show that *perceived severity—on life* (risk), *affective belief—taste* (attitude), *descriptive* and *personal norm*, *confidence in performance*, and *in continuation* (ability), and *barrier planning* (self-regulation) were significantly influencing the HWT practice ($p \leq 0.05$ in **Table 2**). *Affective belief—taste* (attitude) was the most influential psychological sub-factor (the highest β-value in **Table 2**); i.e., households were more likely to practice HWT regularly if they like the taste of treated water. These 17 psychological RANAS sub-factors explained 84.2% variance in the output variable *HWT practice*.

Furthermore, Pearson's correlation analyses between each SEC and the five RANAS main factors show that *Indigenous belief, access to market, information access, father's education,* and *wealth* were correlated with all RANAS factors (**Figure 4**). Almost all SECs had positive correlations with the RANAS factors; e.g., the level of risk perception in a house is high if there is a child who frequently gets diarrhea, or the higher the education level of mother and father, the higher is the perception level of the RANAS factors. Exceptions were *Indigenous belief* and *access to water*, which had negative correlations with psychological variables. Households who followed indigenous belief and took longer to get water were inclined to have lower levels of psychological factors, e.g., have lower level of ability perception.

BBN Analyses

Figure 5 shows the complete BBN model, including the "status-quo" (baseline) condition, where 42% of the respondents were categorized as regularly practicing HWT. The average model accuracy to predict the *HWT practice* was 79%. Furthermore, the accuracy to predict the three categories, non-user, irregular user, and regular user was 79, 54, and 90%, respectively. The area under the ROC curve (AUC) was 0.94, which is categorized as "highly accurate" (Greiner et al., 2000); i.e., the model can distinguish between the three categories in node *HWT practice* based on the SEC and RANAS psychological data well.

The sensitivity analysis shows that *mother's education*, *indigenous belief*, and *information access* were the three most influential nodes (**Figure 6**). Moreover, *attitude* followed by *risk* were the most influential psychological variables.

The effect of updating individual nodes on *HWT practice*, i.e., predictive inference, is shown in **Table 3**. Overall, the better the socio-economic conditions of households, the more favorable were the psychological factors, i.e., the "level" of psychological factors that facilitate the desired behavior, and then led to higher probability of regularly practicing HWT. The predictive inference found *ability* as the most important node. If a respondent perceived his/her ability to practice HWT to be low, his/her probability of practicing HWT regularly was only 22%. However, if households were confident, then the probability of treating water regularly jumped to 53%.

Diagnostic inference shows that a higher probability of regularly practicing HWT required higher levels of all five psychological factors. For example, **Figure 7** shows that if the level of regularly practicing HWT was set to 100%, then the values in the psychological nodes changed by 4% to 14%. However, the values in all socio-economic nodes did not change much compared to the status quo as shown in **Figure 5**. Diagnostic inference also shows that *attitude* was a key psychological factor to change non-user to an irregular user, while *ability* was a key factor to change irregular to a regular user of HWT—re-affirming the conclusion based on predictive inference.

Furthermore, the effect of specific SECs on psychological factors connected to it was studied in more detail using the BBN's predictive inference. Households that followed indigenous belief had a lower probability of psychological nodes connected to it being "high," e.g., *attitude* and *norm* (46 and 31%, respectively), compared to households that did not follow the belief (69 and 34% respectively). Another example is that if someone needed to walk more than half an hour to fetch water, then the probability of *ability* and *self-regulation* being "high" was only 42 and 36%, respectively, compared to 47 and 46%, if they needed to walk <5 min. The effect of other SEC on psychological factors were in a "positive direction": higher parent's education level, easier information access, wealthier, having water-related health problem, and more accessible location all had a positive influence on the psychological factors and then on the HWT practice.

DISCUSSION

Explaining water-related behavior, such as the practice of HWT, is very complex, particularly because there are multiple factors involved (Peters, 2014). Using a system-based approach that combines SECs and psychological factors, this study found that locally rooted belief and access to water highly influence people's perceptions (psychological factors) and thus the adoption of HWT. Moreover, using complete RANAS variables in the analyses, including more relevant SECs, and minimizing the bias from respondent's self-reported answers, the model's performance of this study was better than the one in Daniel et al. (2019), as shown by the AUC value of 0.94, and also provided better interpretations of within-system interactions resulting in more confident recommendations.

The results of the sensitivity analysis and predictive (Bayesian) inference show the same pattern. For example, a more educated mother perceived a higher level of the psychological factors, i.e., a positive correlation (**Figure 4**). This is in line with the findings of Figueroa and Kincaid (2010) who mentioned that a more educated mother may have a better understanding of the health risk of untreated water and could manage and plan better about the practice of HWT. In addition, since the mother is the primary adult caretaker and usually responsible for home WASH management, the new ways of thinking obtained from the promotional activities or school are probably translated into a sustained behavior and followed by other household members (Allen et al., 2018).

The effect of other individual socio-economic and psychological characteristics are also consistent with the literature. For example, easier information access may facilitate the spread of knowledge and understanding of health risks from untreated drinking water (George et al., 2016; Daniel et al., 2019). Easier access to market also stimulates more confidence in getting the resources needed to adopt HWT while wealth represents their ability to purchase the resources (Opryszko et al.,

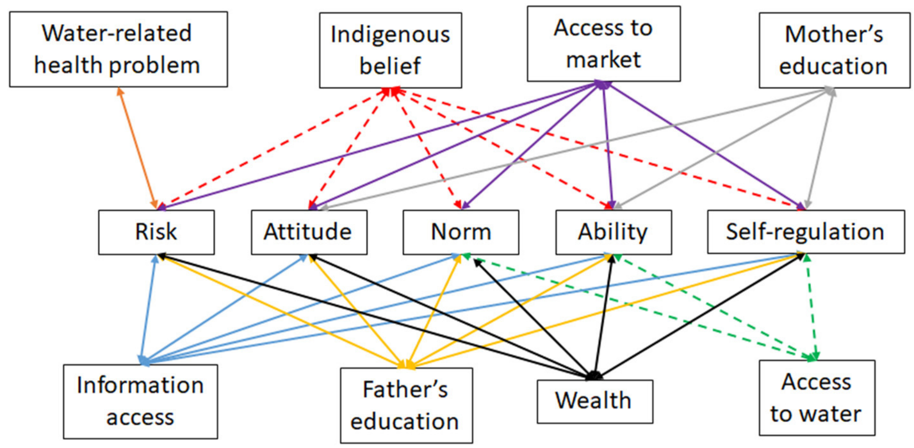


FIGURE 4 | Correlation relationship between SEC and RANAS psychological factors. Solid lines indicate positive correlation and dashed lines indicate negative correlation (Pearson correlation, $p \leq 0.05$).

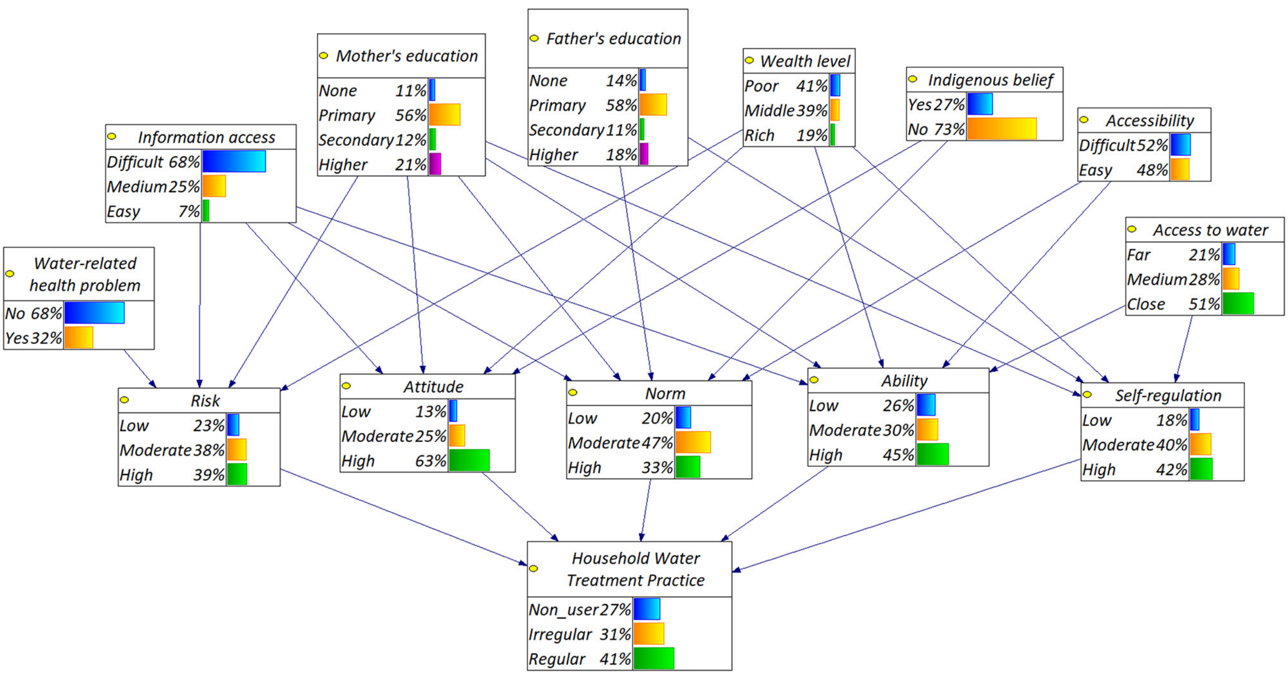


FIGURE 5 | The BBN model showing the hypothetical causal relationship between socio-economic characteristics (SECs), RANAS psychological factors, and HWT practice in rural Indonesia. The bars in each node show the probability that a node is in a certain state (status quo or existing condition).

2010; Roma et al., 2014). This suggests that "context matters" and that SECs of households play an important role in context of health-related behavior (Manstead, 2018), e.g., in the case of women's sanitation use in Africa (Winter et al., 2018). This paper argues that including SECs is essential in order to implement a system thinking approach (Dreibelbis et al., 2013) to interpret the behavior or investigate "the causes of the causes" (Braveman and Gottlieb, 2002). Since the results show that better SECs lead to regular practice of HWT, reducing disparities in SECs is essential for healthier behavior (Adler and Newman, 2002). The similar interpretation may apply to the context of technology adoption among people in developing countries.

Indigenous belief played a significant role in this study. The analysis found it to be negatively correlated with both psychological factors of households and the HWT behavior. However, how indigenous belief "Marapu" influences the psychological factors of the people is not well-understood and should be investigated in future studies. Some WASH-related behavioral studies have also highlighted that indigenous belief plays a critical role. For example, rainwater is considered to be

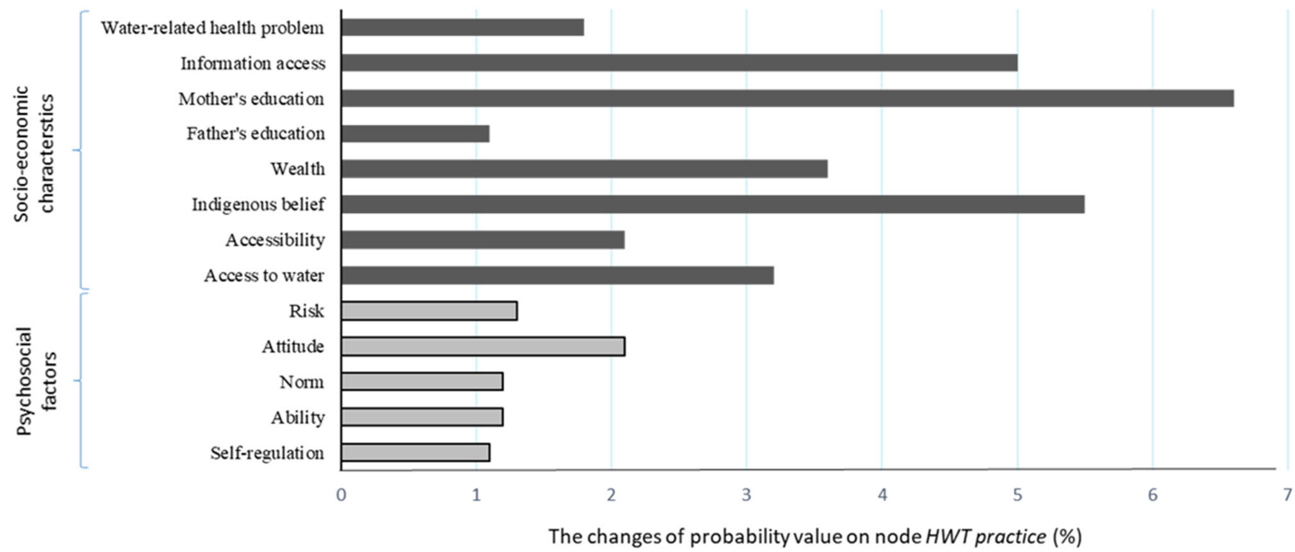


FIGURE 6 | Sensitivity analysis of individual nodes on the output node *HWT practice*.

blessed by God and therefore HWT is perceived not to be needed in some areas of Kenya (Harris, 2005). Water from rivers such as River Ganga is considered pure by religious people in India for the same reason and often consumed without treatment (Kley and Reijerkerk, 2009). Being a Christian or not has been found to be a significant predictor of using private latrine (Winter et al., 2018). In addition, indigenous belief has facilitated a high sanitation coverage in Uganda (Okurut et al., 2015) but has led to distrust in filtered water in Bangladesh (Johnston et al., 2010). Other studies have also mentioned indigenous belief as important drivers of HWT practice in Pakistan (Mahmood et al., 2011) and Nepal (Rainey and Harding, 2005).

By understanding more about the role of belief, behavioral change interventions could be better designed, without changing their unique cultural belief and practices. For example, religious leaders could be involved in the WASH promotion activities (Dwipayanti et al., 2019). This might also work in East Sumba since the religious leader is highly influential there.

Households who need more time to collect water perceived lower levels of ability and self-regulation to operate HWT technologies. That is probably because the time to treat water, e.g., to boil and cool water (Clasen T. et al., 2008), competes with the time needed to fetch water. This issue is particularly important in East Sumba where the area faces serious drought throughout the year (Messakh et al., 2018). This finding underlines the need for easier access to the water supply to facilitate a behavioral change toward the adoption of HWT, especially because ability and self-regulation are the main two factors that related to the continuation of the behavior (Mosler, 2012).

From the BBN sensitivity analysis, the psychological factor *attitude* of households toward HWT was found to be the most influential variable (**Figure 6**). In addition, psychological sub-factor *affective belief (taste)*, i.e., one of *attitude* sub-factors, was the most influential variable in the regression analysis. This suggests that if households in the area like the taste (or temperature) of the treated water, they are highly likely to regularly practice HWT. This finding could be related to another study in Pakistan where households preferred to have fresh and cold water in hot weather (Luby et al., 2001). A similar interpretation may apply to Sumba since this island is a quite hot and humid area; i.e., people prefer to have raw fresh water taken directly from tap, river, or well. Moreover, since the perception of *risk* appears as the second important psychological factor in BBN, highlighting the poor water quality of the fresh—but untreated—water is one of the important focuses to change the behavior. However, extra effort would be needed to ensure that households perceive treated water more positively, e.g., by finding opportunities where households experience the taste (freshness) of treated water. Boiling, which is common in the Sumba area, will release the dissolved oxygen in the water and make the water taste less fresh and thus may not be the preferred option. Therefore, other treatment systems, such as SODIS, could be a preferred option since it does not change the taste of water (Luzi et al., 2016).

There are some limitations to the presented study. First, 16% of the respondents were not the mother, i.e., the one responsible for the water management in the house. However, the means of five psychological factors and HWT practice were not significantly different ($p > 0.05$). Second, we only assessed the HWT practice in this study and not the safe storage practice. Safe storage is needed to prevent recontamination of treated water (Mintz et al., 1995), and, indeed, in another study in the same area, it was found that there is a "moderate" chance of recontamination due to inappropriate water storage (Daniel et al., 2020a). This implies that even though households were categorized as regularly practicing HWT in this study, the drinking water quality may not be safe to drink. Therefore,

TABLE 3 | Predictive inference that measures the effect of each state in each node on *HWT practice*.

Nodes		Updated $P_{HWT\ practice}$ = regular (%)				$\Delta P_{HWT\ practice}$ = regular (%)[a]
Socio-economic characteristics	Water-related health problem	No	Yes			2
		41	43			
	Information access	Difficult	Medium	Easy		4
		41	43	37		
	Mother's education	None	Primary	Secondary	Higher	8
		36	42	37	44	
	Father's education	None	Primary	Secondary	Higher	1
		41	42	42	41	
	Wealth	Poor	Middle	Rich		4
		40	41	44		
	Indigenous belief	Yes	No			6
		37	43			
	Access to market	Difficult	Easy			3
		40	43			
	Access water	Far	Medium	Close		4
		39	40	43		
Psychological factors	Risk	Low	Moderate	High		16
		32	40	48		
	Attitude	Low	Moderate	High		18
		30	32	48		
	Norm	Low	Moderate	High		17
		30	42	47		
	Ability	Low	Moderate	High		33
		21	40	54		
	Self-regulation	Low	Moderate	High		21
		29	38	50		

*The value under each category corresponding to a node as displayed in the first column is the updated probability of the output node being "regular" given that all households maintain this state. The baseline probability was 41% (**Figure 5**).*

[a] *The difference between the lowest and highest value of the updated probability of output node, HWT practice being "regular," in %.*

we recommend that promotion of HWT in that area must be accompanied by promotion of safe storage and hygienic conditions in the household. Future HWT studies in that area have also to include the assessment of safe storage practice in addition to the HWT practice. Third, we did not measure and include the organoleptic aspects of the water (smell, color, taste, and turbidity) in the analysis. These aspects were found to influence the perception of water quality (Doria et al., 2009) and thus should be analyzed further in the study area. Fourth, to the best of our knowledge, there is no practical method to confirm the actual practice of boiling, such as measuring the residual chlorine or observing the presence of bottles in the case of chlorination and solar disinfection, respectively. Therefore, a potential of self-reported bias in our study exists, even though we tried to minimize it by combining multiple answers. A previous study in Cambodia found that only one-third of the self-reported households had boiled water at follow-up visits (Brown and Sobsey, 2012). In addition, other studies found that boiling does not fully eliminate the water contamination (Clasen T. et al., 2008; Clasen T. F. et al., 2008). A future study should also analyze the effectiveness of boiling practice in this area.

CONCLUSION

In this study, the role of SECs of people in the indigenous Sumba area in Indonesia on the water-related perceptions and the practice of HWT were analyzed. Statistical analyses were combined with BBN models to accomplish this. It was found that SECs influenced water-related perceptions (psychological factors), resulting in higher or lower adoption of HWT. Indigenous beliefs played a significant role in influencing household perceptions, suggesting the importance of considering local culture in the dissemination of health- or environmental-related advisories and adoption of relevant technologies in developing countries. Access to water was found to be important for households to develop the ability to practice HWT. For improved adoption of HWT, attitude toward the HWT, especially the taste of treated water, also needs to be addressed to influence households to practice HWT. Finally, this paper argues that improving the aforementioned SECs of the respondents is essential to ensure the sustainable use of HWT or any environmental-related technologies in developing countries.

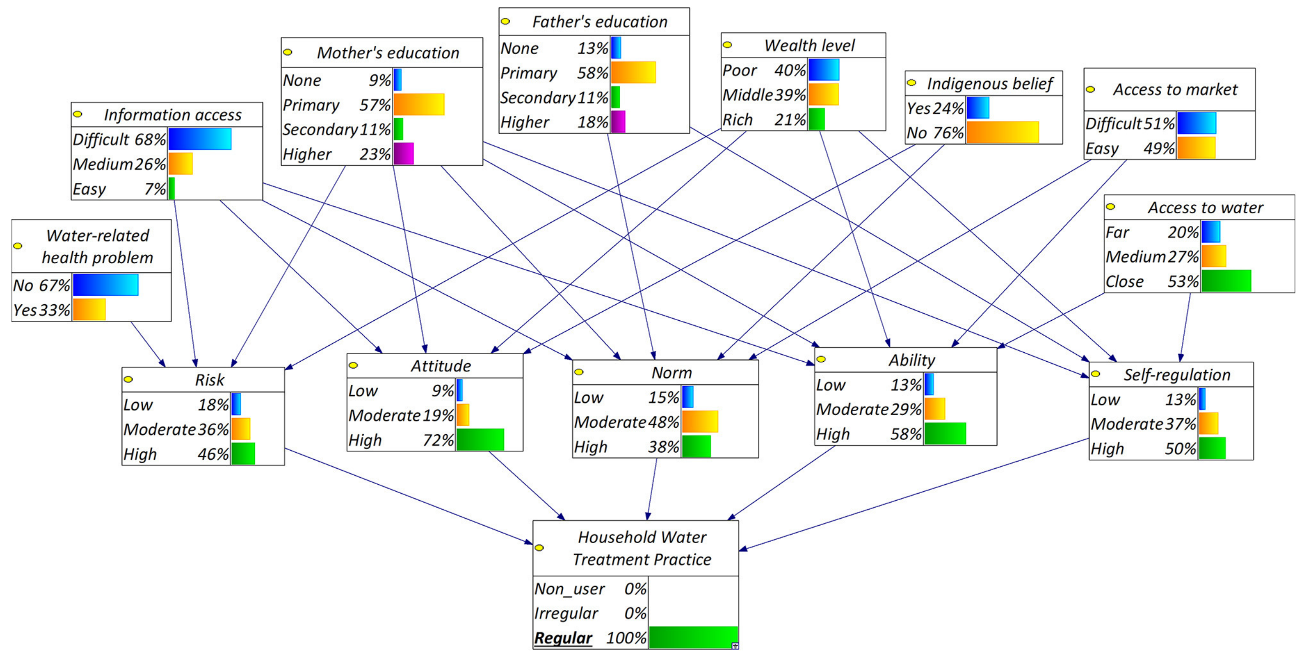


FIGURE 7 | Diagnostic inference: most probable states of all SEC and psychological factors that will lead to the probability of regularly practice HWT to 100%.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Human Research Ethics Committee of Delft University of Technology and the Agency for Promotion, Investment, and One-Stop Licensing Service at the province (East Nusa Tenggara) and district (East Sumba) level. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DD: term, methodology, software, formal analysis, investigation, resources, writing—original draft, writing—review & editing, visualization, and funding acquisition. SP: term, conceptualization, methodology, validation, writing—review & editing, supervision, and project administration. LR: term, conceptualization, validation, writing—review & editing, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

FUNDING

DD receives a Ph.D., research funding from Indonesia Endowment Fund for Education (LPDP). Delft University of Technology provided funds to support field logistics and research activities.

ACKNOWLEDGMENTS

We thank the respondents for their participation in the study; all enumerators: Antonia Djarawula, Primus Lede, Selia Nangi, Jems Ndapangadung, Dominggus Wulang, and Yemima Amah; and Yayasan Anugerah Anak Sumba for assistance during the data collection.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2021.649445/full#supplementary-material

REFERENCES

Adler, N. E., and Newman, K. (2002). Socioeconomic disparities in health: pathways and policies inequality. *Health Aff.* 2, 60–76. doi: 10.1377/hlthaff.21.2.60

Allen, E., Morazan, I. M., and Witt, E. (2018). Actively engaging women is helping solve the global water crisis. *J. Water Sanit. Hyg. Dev.* 8, 632–639. doi: 10.2166/washdev.2018.025

Barton, D. N., Kuikka, S., Varis, O., Uusitalo, L., Henriksen, H. J., Borsuk, M., et al. (2012). Bayesian networks in environmental and resource management. *Integr. Environ. Assess. Manag.* 8, 418–429. doi: 10.1002/ieam.1327

Behailu, B. M., Pietilä, P. E., and Katko, T. S. (2016). Indigenous practices of water management for sustainable services. *SAGE Open* 6, 1–11. doi: 10.1177/2158244016682292

BPS Statistics of East Sumba Regency (2018). Persentase rumah tangga menurut sumber air utama yang digunakan untuk minum di kabupaten sumba timur, 2015-2017. *Stat. Sumba Timur Regency*. Available online : https://sumbatimurkab.bps.go.id/dynamictable/2018/11/12/50/persentase-rumah-tangga-menurut-sumber-air-utama-yang-digunakan-untuk-minum-di-kabupaten-sumba-timur-2015-2017.html (accessed April 1, 2020).

Braveman, P., and Gottlieb, L. (2002). The social determinants of health : it ' s time to consider the causes of the causes. *Public Health Rep.* 129, 19–31. doi: 10.1177/00333549141291S206

Brown, J., and Sobsey, M. D. (2012). Boiling as household water treatment in Cambodia: a longitudinal study of boiling practice and microbiological effectiveness. *Am. J. Trop. Med. Hyg.* 87, 394–398. doi: 10.4269/ajtmh.2012.11-0715

Cain, J. (2001). *Planning Improvements in Natural Resources Management*. Oxfordshire: UK Centre for Ecology & Hydrology.

Christen, A., Duran Pacheco, G., Hattendorf, J., Arnold, B. F., Cevallos, M., Indergand, S., et al. (2011). Factors associated with compliance among users of solar water disinfection in rural Bolivia. *BMC Public Health* 11, 210. doi: 10.1186/1471-2458-11-210

Clasen, T., Mclaughlin, C., Nayaar, N., Boisson, S., Gupta, R., Desai, D., et al. (2008). Microbiological effectiveness and cost of disinfecting water by boiling in semi-urban India. *Am. J. Trop. Med. Hyg.* 79, 407–413. doi: 10.4269/ajtmh.2008.79.407

Clasen, T. F., Thao, D. H., Boisson, S., and Shipin, O. (2008). Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam. *Environ. Sci. Technol.* 42, 4255–4260. doi: 10.1021/es7024802

Daniel, D., Diener, A., Pande, S., Jansen, S., Marks, S., Meierhofer, R., et al. (2019). Understanding the effect of socio-economic characteristics and psychosocial factors on household water treatment practices in rural Nepal using Bayesian belief networks. *Int. J. Hyg. Environ. Health* 222, 847–855. doi: 10.1016/j.ijheh.2019.04.005

Daniel, D., Iswarani, W. P., Pande, S., and Rietveld, L. (2020a). A bayesian belief network model to link sanitary inspection data to drinking water quality in a medium resource setting in rural Indonesia. *Sci. Rep.* 10:18867. doi: 10.1038/s41598-020-75827-7

Daniel, D., Pande, S., and Rietveld, L. (2020b). The effect of socio-economic characteristics on the use of household water treatment via psychosocial factors: a mediation analysis. *Hydrol. Sci. J.* 65, 2350–2358. doi: 10.1080/02626667.2020.1807553

Do, C. B., and Batzoglou, S. (2008). What is the expectation maximization algorithm? *Nat. Biotechnol.* 26, 897–899. doi: 10.1038/nbt1406

Doria, M. F., Pidgeon, N., and Hunter, P. R. (2009). Perceptions of drinking water quality and risk and its effect on behaviour : a cross-national study. *Sci. Total Environ.* 407, 5455–5464. doi: 10.1016/j.scitotenv.2009.06.031

Dreibelbis, R., Winch, P. J., Leontsini, E., Hulland, K. R., Ram, P. K., Unicomb, L., et al. (2013). The integrated behavioural model for water, sanitation, and hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings. *BMC Public Health* 13:1015. doi: 10.1186/1471-2458-13-1015

Druzdzel, M. J., and Sowinski, T. (1995). *GeNIe Modeler*. Available online at: https://www.bayesfusion.com/

Dubois, A. E., Crump, J. A., Keswick, B. H., Slutsker, L., Quick, R. E., Vulule, J. M., et al. (2010). Determinants of use of household-level water chlorination products in rural Kenya, 2003-2005. *Int J. Env. Res. Public Health* 7, 3842–3852. doi: 10.3390/ijerph7103842

Dwipayanti, N. M. U., Rutherford, S., and Chu, C. (2019). Cultural determinants of sanitation uptake and sustainability: local values and traditional roles in rural Bali, Indonesia. *J. Water Sanit. Hyg. Dev.* 9, 438–449. doi: 10.2166/washdev.2019.178

Enger, K. S., Nelson, K. L., Rose, J. B., and Eisenberg, J. N. S. (2013). The joint effects of efficacy and compliance: a study of household water treatment effectiveness against childhood diarrhea. *Water Res.* 47, 1181–1190. doi: 10.1016/j.watres.2012.11.034

Fiebelkorn, A. P., Person, B., Quick, R. E., Vindigni, S. M., Jhung, M., Bowen, A., et al. (2012). Systematic review of behavior change research on point-of-use water treatment interventions in countries categorized as low- to medium-development on the human development index. *Soc Sci Med.* 75, 622–633. doi: 10.1016/j.socscimed.2012.02.011

Figueroa, M., and Kincaid, D. (2010). *Social, Cultural and Behavioral Correlates of Household Water Treatment and Storage.* Center of Communication Programs. Available online at: http://ccp.jhu.edu/wp-content/uploads/Household-Water-Treatment-and-Storage-2010.pdf

Fotue Totouom, A. L., Sikod, F., and Abba, I. (2012). Household choice of purifying drinking water in cameroon. *Environ. Manag. Sustain. Dev.* 1, 101–115. doi: 10.5296/emsd.v1i2.1642

Fowler, C. T. (2003). The ecological implications of ancestral religion and reciprocal exchange in a sacred forest in Karendi (Sumba, Indonesia). *Worldviews Environ. Cult. Relig.* 7, 303–329. doi: 10.1163/156853503322709155

Freeman, M. C., Trinies, V., Boisson, S., Mak, G., and Clasen, T. (2012). Promoting household water treatment through women's self help groups in rural india: assessing impact on drinking water quality and equity. *PLoS ONE* 7:e44068. doi: 10.1371/journal.pone.0044068

GBD 2016 Diarrhoeal Diseases Collaborators (2017). Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the global burden of disease study 2015. *Lancet. Infect. Dis.* 17, 909–948. doi: 10.1016/S1473-3099(17)30276-1

George, C. M., Jung, D. S., Saif-Ur-Rahman, K. M., Monira, S., Sack, D. A., Rashid, M. U., et al. (2016). Sustained uptake of a hospital-based handwashing with soap and water treatment intervention (cholera-hospital-based intervention for 7 days [CHoBI7]): a randomized controlled trial. *Am. J. Trop. Med. Hyg.* 94, 428–436. doi: 10.4269/ajtmh.15-0502

Geremew, A., and Damtew, Y. T. (2020). Household water treatment using adequate methods in sub-saharan countries: evidence from 2013–2016 demographic and health surveys. *J. Water Sanit. Hyg. Dev.* 10, 66–75. doi: 10.2166/washdev.2019.107

Goldman, N., Pebley, A. R., and Beckett, M. (2001). Diffusion of ideas about personal hygiene and contamination in poor countries: evidence from Guatemala. *Soc. Sic. Med.* 52, 53–69. doi: 10.1016/S0277-9536(00)00122-2

Greiner, M., Pfeiffer, D., and Smith, R. D. (2000). Principles and practical application of the receiver-operating characteristic analysis for diagnostic tests. *Prev. Vet. Med.* 45, 23–41. doi: 10.1016/S0167-5877(00)00115-X

Harris, J. (2005). *Challenges to the Commercial Viability of Point-of-Use (POU) Water Treatment Systems in Low-Income Settings*. Master's thesis. Oxford: Oxford School of Geography and the Environment Oxford University.

Houweling, T. A. J., Kunst, A. E., and Mackenbach, J. P. (2003). Measuring health inequality among children in developing countries: does the choice of the indicator of economic status matter? *Int. J. Equity Health* 2, 1–12. doi: 10.1186/1475-9276-2-8

Inauen, J., Hossain, M. M., Johnston, R. B., and Mosler, H. J. (2013). Acceptance and use of eight arsenic-safe drinking water options in Bangladesh. *PLoS ONE* 8:e53640. doi: 10.1371/journal.pone.0053640

Johnston, R. B., Hanchett, S., and Khan, M. H. (2010). The socio-economics of arsenic removal. *Nat. Geosci.* 3, 2–3. doi: 10.1038/ngeo735

Kley, L. S., and Reijerkerk, L. (2009). *Water a Way of Life*. Leiden: CRC Press/Balkema. doi: 10.1201/9780203872369

Krejcie, R. V., and Morgan, D. W. (1970). Determining sample size for research activities. *Educ. Psychol. Meas.* 30, 607–610. doi: 10.1177/001316447003000308

Lilje, J., Kessely, H., and Mosler, H. J. (2015). Factors determining water treatment behavior for the prevention of cholera in Chad. *Am. J. Trop. Med. Hyg.* 93, 57–65. doi: 10.4269/ajtmh.14-0613

Lilje, J., and Mosler, H.-J. (2017). Socio-psychological determinants for safe drinking water consumption behaviors: a multi-country review. *J. Water Sanit. Hyg. Dev.* 7, 13–24. doi: 10.2166/washdev.2017.080

Luby, S., Agboatwalla, M., Raza, A., Sobel, J., Mintz, E., Baier, K., et al. (2001). A low-cost intervention for cleaner drinking water in Karachi, Pakistan. *Int. J. Infect. Dis.* 5, 144–150. doi: 10.1016/S1201-9712(01)90089-X

Luzi, S., Tobler, M., Suter, F., and Meierhofer, R. (2016). *SODIS manual Guidance on Solar Water Disinfection*. Du: Eawag, Swiss Federal Institute of Aquatic Science and Technology. Available online at: www.sodis.ch

Mahmood, Q., Baig, S. A., Nawab, B., Shafqat, M. N., Pervez, A., and Zeb, B. S. (2011). Development of low cost household drinking water treatment system for the earthquake affected communities in Northern Pakistan. *Desalination* 273, 316–320. doi: 10.1016/j.desal.2011.01.052

Manstead, A. S. R. (2018). The psychology of social class : how socioeconomic status impacts thought, feelings, and behaviour. *Br. J. Soc. Psychol.* 57, 267–291. doi: 10.1111/bjso.12251

Marcot, B. G., Steventon, J. D., Sutherland, G. D., and McCann, R. K. (2006). Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. *Can. J. For. Res.* 36, 3063–3074. doi: 10.1139/x06-135

Mengistie, B., Berhane, Y., and Worku, A. (2013). Household water chlorination reduces incidence of diarrhea among under-five children in rural ethiopia: a cluster randomized controlled trial. *PLoS ONE* 8:e77887. doi: 10.1371/journal.pone.0077887

Messakh, J. J., Moy, D. L., Mojo, D., and Maliti, Y. (2018). The linkage between household water consumption and rainfall in the semi-arid region of East Nusa Tenggara, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* 106:012084. doi: 10.1088/1755-1315/106/1/012084

Mintz, E. D., Reiff, F. M., and Tauxe, R. V (1995). Safe water treatment and storage in the home: a practical new strategy to prevent waterborne Disease. *JAMA* 273, 948–953. doi: 10.1001/jama.1995.03520360062040

Mosler, H.-J. (2012). A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: a conceptual model, a review, and a guideline. *Int. J. Environ. Health Res.* 22, 431–449. doi: 10.1080/09603123.2011.650156

Munamati, M., Nhapi, I., and Misi, S. (2016). Exploring the determinants of sanitation success in Sub-Saharan Africa. *Water Res.* 103, 435–443. doi: 10.1016/j.watres.2016.07.030

Nadkarni, S., and Shenoy, P. P. (2004). A causal mapping approach to constructing Bayesian networks. *Decis. Support Syst.* 38, 259–281. doi: 10.1016/S0167-9236(03)00095-2

Okurut, K., Kulabako, R. N., Chenoweth, J., and Charles, K. (2015). Assessing demand for improved sustainable sanitation in low-income informal settlements of urban areas: a critical review. *Int. J. Environ. Health Res.* 25, 81–95. doi: 10.1080/09603123.2014.893570

Opryszko, M. C., Majeed, S. W., Hansen, P. M., Myers, J. A., Baba, D., Thompson, R. E., et al. (2010). Water and hygiene interventions to reduce diarrhoea in rural Afghanistan: a randomized controlled study. *J. Water Health* 8, 687–702. doi: 10.2166/wh.2010.121

Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. San Francisco, CA: Morgan Kaufmann Publishers Inc.

Peters, D. H. (2014). The application of systems thinking in health : why use systems thinking? *Heal. Res. Policy Syst.* 12, 1–6. doi: 10.1186/1478-4505-12-51

Phan, T. D., Smart, J. C. R., Capon, S. J., Hadwen, W. L., and Sahin, O. (2016). Applications of Bayesian belief networks in water resource management: a systematic review. *Environ. Model. Softw.* 85, 98–111. doi: 10.1016/j.envsoft.2016.08.006

Phan, T. D., Smart, J. C. R., Stewart-Koster, B., Sahin, O., Hadwen, W. L., Dinh, L. T., et al. (2019). Applications of bayesian networks as decision support tools for water resource management under climate change and socio-economic stressors: a critical appraisal. *Water* 11:2642. doi: 10.3390/w11122642

Picauly, I., and Toy, S. M. (2013). Analisis determinan dan pengaruh stunting terhadap prestasi belajar anak sekolah di kupang dan sumba timur, ntt. *J. Gizi Dan Pangan* 8:55. doi: 10.25182/jgp.2013.8.1.55-62

Pickering, A. J., Crider, Y., Sultana, S., Swarthout, J., Goddard, F. G., Anjerul Islam, S., et al. (2019). Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial. *Lancet Glob. Health* 7, e1247–e1256. doi: 10.1016/S2214-109X(19)30315-8

Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M. C., et al. (2019). Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low- and middle-income countries. *Int. J. Hyg. Environ. Health* 222, 765–777. doi: 10.1016/j.ijheh.2019.05.004

QGIS Development Team (2017). *QGIS Geographic Information System Ver. 2.18.4.* Available online at: https://download.qgis.org/

Rainey, R. C., and Harding, A. K. (2005). Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *Int. J. Environ. Health Res.* 15, 361–372. doi: 10.1080/09603120500289168

Roma, E., Bond, T., and Jeffrey, P. (2014). Factors involved in sustained use of point-of-use water disinfection methods: a field study from Flores Island, Indonesia. *J. Water Health* 12, 573–583. doi: 10.2166/wh.2014.109

Schmidt, W., and Cairncross, S. (2009). Household water treatment in poor populations : is there enough evidence for scaling up now? *Environ. Sci. Technol.* 43, 9–10. doi: 10.1021/es802232w

Seimetz, E., Boyayo, A. M., and Mosler, H. J. (2016). The influence of contextual and psychosocial factors on handwashing. *Am. J. Trop. Med. Hyg.* 94, 1407–1417. doi: 10.4269/ajtmh.15-0657

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M., and Elliott, M. A. (2008). Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ. Sci. Technol.* 42, 4261–4267. doi: 10.1021/es702746n

Sonego, I. L., Huber, A. C., and Mosler, H. (2013). Does the Implementation of Hardware Need Software? A longitudinal study on fluoride-removal filter use in Ethiopia. *Environ. Sci. Technol.* 47, 12661–12668. doi: 10.1021/es402787s

Stocker, A., and Mosler, H. J. (2015). Contextual and sociopsychological factors in predicting habitual cleaning of water storage containers in rural Benin. *Water Resour. Res.* 51, 2000–2008. doi: 10.1002/2014WR016005

Sungkar, S., Pohan, A. P. N., Ramadani, A., Albar, N., Azizah, F., Nugraha, A. R. A., et al. (2015). Heavy burden of intestinal parasite infections in Kalena Rongo village, a rural area in South West Sumba, eastern part of Indonesia: a cross sectional study. *BMC Public Health* 15:1296. doi: 10.1186/s12889-015-2619-z

UNICEF and WHO (2019). *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017: Special Focus on Inequalities*. New York, NY: UNICEF and WHO.

Vel, J., and Makambombu, S. (2019). Strategic Framing of Adat in Land-Acquisition Politics in East Sumba. *Asia Pacific J. Anthropol.* 20, 435–452. doi: 10.1080/14442213.2019.1670239

Vel, J. A. C., and Makambombu, S. (2010). Access to agrarian justice in sumba, Eastern Indonesia. *Law Soc. Justice Glob. Dev.* 2010, 1–22. Available online at: https://warwick.ac.uk/fac/soc/law/elj/lgd/2010_1/vel_makambombu

Waterworth, P., Pescud, M., Braham, R., Dimmock, J., and Rosenberg, M. (2015). Factors influencing the health behaviour of indigenous Australians: perspectives from support people. *PLoS ONE* 10, 1–17. doi: 10.1371/journal.pone.0142323

Wilson Van Voorhis, C. R., and Morgan, B. L. (2007). Understanding power and rules of thumb for determining sample sizes. *Tutor. Quant. Methods Psychol.* 3, 43–50. doi: 10.20982/tqmp.03.2.p043

Winter, S., Dreibelbis, R., and Barchi, F. (2018). Context matters : a multicountry analysis of individual- and neighbourhood-level factors associated with women's sanitation use in sub-Saharan Africa. *Trop. Med. Int. Health* 23, 173–192. doi: 10.1111/tmi.13016

Zabinski, J. W., Pieper, K. J., and Gibson, J. M. (2018). A bayesian belief network model assessing the risk to wastewater workers of contracting ebola virus disease during an outbreak. *Risk Anal.* 38, 376–391. doi: 10.1111/risa.12827

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

frontiers in Water

REVIEW
published: 05 August 2021
doi: 10.3389/frwa.2021.685650

Water Use Efficiency: A Review of Contextual and Behavioral Factors

Diana Carolina Callejas Moncaleano, Saket Pande and Luuk Rietveld*

Department of Water Management, Faculty of Civil Engineering and Geosciencies, Delft University of Technology, Delft, Netherlands

Water withdrawals around the world have increased almost twice as fast as the population during the last century. Higher than expected water demand is leading to water scarcity and causing rapid depletion of water tables around the world. One reason behind the higher than expected demand is the inefficient use of water. Inefficient use of water affects the well-being of society, the economic stability of countries, and environmental health. Indeed, water use efficiency (WUE) is one of the pillars of sustainable development goals (SDG 6.4.1). However, progress toward achieving WUE is slow, especially for many developing countries where the degradation of natural resources is critical, economic growth is slow, and there are few strong institutions to coordinate actions. One reason behind inefficient water use is human behavior. A variety of contextual and psychological factors underlie the behavior. The contextual factors include socioeconomic, technical, institutional, and environmental factors and the behavioral factors include factors associated with the perception of risk, attitudes, norms, etc. Yet, few studies consider an integrated view of these factors in shaping water use behavior. This paper consolidates contextual and behavioral factors which influence water use, studies the gaps in our understanding of human water behavior underlying WUE and highlights the need to comprehensive assess and consistently measure such factors and their relationships. Based on the gaps identified, it proposes a conceptual model that connects contextual and behavioral factors and represents potential cause-effect relationships as supported by various environmental behavior approaches and psychological theories. Based on the literature review of water use, and conservation behavior, environmental psychology, and water use models, this model proposes an institutional factor to assess the relationship between institutions and stakeholders, and study contextual factors linked not only for individual water users but also studying these factors for individuals of water supply organizations.

Keywords: water use efficiency, human behavior, contextual factors, psychological factors, behavioral factors

OPEN ACCESS

Edited by:
Yizi Shang,
China Institute of Water Resources and Hydropower Research, China

Reviewed by:
Carly Maynard,
Scotland's Rural College, United Kingdom
Paria Shojaei,
Isfahan University of Technology, Iran

****Correspondence:***
Diana Carolina Callejas Moncaleano
d.c.callejasmoncaleano-1@tudelft.nl

Specialty section:
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

Received: *25 March 2021*
Accepted: *12 July 2021*
Published: *05 August 2021*

Citation:
Callejas Moncaleano DC, Pande S and Rietveld L (2021) Water Use Efficiency: A Review of Contextual and Behavioral Factors. Front. Water 3:685650. doi: 10.3389/frwa.2021.685650

INTRODUCTION

Every day large amounts of water are extracted from inland surface water bodies (e.g., rivers, lakes, wetlands, and reservoirs) and aquifers for diverse uses such as for agriculture, domestic, electricity, and industrial purposes. Water withdrawal around the world has increased almost twice as fast as the world population (FAO, n.d.). Agriculture is the largest water using sector, accounting for approximately 69% of global water withdrawals, whereas municipal withdrawals contribute to 12% of total withdrawals (FAO, 2018b). Withdrawing water faster than it is recharged has led to water scarcity in countries such as Qatar, Saudi Arabia, and Pakistan, which are suffering from extremely high water stress conditions (Hofste et al., 2019). This, when combined with weak control of water permissions and concession rights, has exasperated water scarcity.

The difference between global water withdrawals and real water demand is significant and is steadily increasing. One of the reasons behind this difference is the inefficient use of water, leading to consumption that can otherwise be lower (Wang et al., 2015; Nazari et al., 2018; Ding et al., 2019; Ghanim, 2019). The resulting over-extraction poses considerable risks to water sustainability as rivers and groundwater resources around the world are running dry (Jorgensen et al., 2009; Graymore and Wallis, 2010; Arto et al., 2016; Bhaduri et al., 2016; Mekonnen and Hoekstra, 2016; Lund et al., 2018).

Driven by unconstrained consumption, water scarcity could occur even under average climate conditions. Inefficient use of water also affects the provision of environmental flows and contributes to environmental degradation and economic instability (Mekonnen and Hoekstra, 2016; Vieira et al., 2017; Piedra-Muñoz et al., 2018). Efficient use of water has therefore often been proposed as a measure by policymakers and water managers to reduce the inflated gap between water extractions and water demand.

Efficient use of water conserves water and reduces pressure over natural sources. By reducing water consumption, water flows in water treatment plants and irrigation systems diminish (Tang et al., 2013; Jorgensen and Martin, 2015), leading subsequently to reductions in effluent discharges (Hoekstra, 2014). It thus also contributes to environmental and economic benefits (Rad et al., 2019) such as water protection, and reduction in operational costs (See, 2015; Jabari, 2017).

Therefore, water users and institutions have taken actions toward improving water use efficiency (WUE) (Bruneau et al., 2013). Global and local policies, aiming at reducing water demand, have focused mainly on two sectors with a relatively high number of users and relevant for water security: households (Attari, 2014; Manouseli et al., 2019), and farmers (Bruneau et al., 2013; Tang et al., 2013; Chang et al., 2016; Roobavannan et al., 2017; Benito et al., 2019; Ghanim, 2019; Xiao et al., 2019), farmers being the biggest water user. Actions include installation of water-saving devices, leakage control, water re-use, water harvesting, implementation of indicators like non-revenue water (NRW), and the extension of economic incentives to users, such as increasing water price, and subsidies to water savers (Wang et al., 2015; Chang et al., 2016).

Increasing WUE is also one of the pillars of those global and local policies, such as the SDGs of the United Nations (Cole et al., 2018; Ortigara et al., 2018). In addition, the strategy of the European Commission (EU, 2014) is to move from a linear economy to a sustainable, circular economy by 2050. Moreover, the national water initiative of Australia (Department of Agriculture, 2019) is pursuing WUE to conserve rivers and groundwater systems, Colombia's Government has established plans to improve WUE in their policy plan (Minambiente, 2010), and the United States Environmental Protection Agency (USEPA) is implementing WUE strategies to mitigate water stress and prevent water conflicts (GAO-14-430, 2014; EPA, 2018).

Despite such efforts, the slow progress of the application of WUE principles remains a matter of concern for many developing countries where natural resources are being critically degraded, and the economic growth is slow compared to developed countries (Sánchez et al., 2004; Carrus et al., 2010; Russell and Fielding, 2010; Bruneau et al., 2013; Jorge et al., 2015; Mekonnen and Hoekstra, 2016; Rad et al., 2019). Often WUE is only associated with technical factors that affect the performance of water utilities, e.g., water leakages in water distribution systems, poor management, and maintenance of irrigation systems (European Environment Agency, EEA, 2007). Other factors such as those linked to the psychology of water use, influencing behavior, and decisions of relevant water users, are frequently ignored by policymakers. Mosler (2012) defines behavior as the result of the psychological processing of factors within the individual. Therefore, a comprehensive assessment of these factors and their relationships is needed to provide insights into the causes of over-extraction, the interdependence between stakeholders, and the effects on WUE.

A holistic view of how various such factors influence WUE behavior is currently not available. Therefore, this contribution aims to identify challenges in understanding water use behavior, especially underlying WUE, while considering various contextual and behavioral factors. Based on gaps that are identified, a conceptual model is proposed to capture the relationship between institutions and stakeholders, and studies contextual factors linked not only of individual water users but also studying these factors for individuals of water supply organizations to understand (in)efficient water use.

WATER USE EFFICIENCY CONCEPT

Definition of Water Use Efficiency

The WUE concept has been extended to environmental sustainability, sustainable development, and water management frameworks. As summarized in **Table 1**, WUE is interpreted differently in different uses of water (e.g., agriculture, industry, and service sectors). Activities linked to water use, therefore, pursue different WUE targets. However, only few frameworks have focused on WUE as an alternative to water protection and conservation.

Approaches to Achieve WUE

Since the concept of WUE involves various definitions, approaches, and indicators, it has implications on water literacy (Dean et al., 2016), specifically WUE knowledge. It means how WUE is interpreted and implemented by various water users.

There are numerous approaches available to achieve WUE (Gleick et al., 2011). Each such approach depends on specific objectives, **Table 2** summarizes the most important approaches that refer to WUE. For example, water conservation and mitigation of scarcity can motivate efficient water use practices to meet specific environmental goals. Expanding existing production, profit maximization, and costs minimization efforts prompt producers to use water

TABLE 1 | Diverse interpretations of WUE.

Domain	Interpretation	Reference
Agronomy	Crop production per unit volume used.	Stanhill, 1986; Howell, 2005
	The water efficiency is the ratio between water used and water withdrawals.	UN, 2015; FAO, 2018a
Sustainability	WUE in any activity is related to using the resource in a better way, doing more or the same with less quantity.	Sánchez et al., 2004
	Resource efficiency refers to water consumption per unit of process or product.	Hoekstra et al., 2017
	Actions focus on reducing water consumption, and leakages, or optimizing water usage. These actions include water reuse, recycling, rain usage, controlling leakages, and moving to saving technologies.	Minambiente, 2018
	Using the Earth's limited resources sustainably while minimizing the impacts on the environment.	European Union, 2019
Water management	It is a term used to measure the productivity of water used for specific purposes.	Brooks, 2006
Technical	Innovation based, moving to water saving systems, e.g., moving from flood irrigation to sprinkler systems, and from high to low-pressure systems.	Bruneau et al., 2013

TABLE 2 | Approaches toward improving WUE.

Domain	Principles guiding water use	Definition of/approach toward WUE	Motivation	Reference
Sustainable development goals (SDG)	Economic, Sustainability	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.	Economic viability Protection of the environment Social and ethical acceptance	Hens et al., 2018
		Goal 6.4.: Increasing water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater. Improving water efficiency means water-saving and making water available for other purposes.	Addressing water scarcity Increasing water availability for people and the economy	UN, 2015; Ortigara et al., 2018
Cleaner production (CP)	Economic	Integrate preventive environmental strategies to processes, products, and services to increase efficiency and reduce the risk to humans and the environment.	Environmental sustainability Maximization of water reduction Recycling Reuse	Hens et al., 2018
		Resource use minimization, improved eco-efficiency, environmental protection.	Doing more with less	Glavič and Lukman, 2007
Circular Economy (CE)	Economic	Minimizing the intake of fresh raw materials.	3Rs (reduce, reuse, recycle) Closing the loop of use of resources	Winans et al., 2017; Varbanov and Walmsley, 2019
Sustainable water management (SWM) efficiency	Social, Environmental, Economic, Technical	Balancing water resources supply with demands from society, economy, and the environment.	Sustainable water management (SWM)	Zhang and Xu, 2019
Water footprint	Sustainability, Economic	Analyzing water usage along supply chains, and assessing the sustainability, efficiency, and fairness of its water use.	Reduction of water consumption	Hoekstra, 2014
Blue water footprint	Sustainability, Economic	Measuring the consumption of groundwater or surface water.	The assessment of freshwater use and its relation to consumption, production, and trade	Hoekstra et al., 2017

more efficiently (Bruneau et al., 2013). It may also be motivated by consumer or regulators demands for cleaner production, lower water footprint (Mekonnen et al., 2015), and circular economy (Winans et al., 2017; Varbanov and Walmsley, 2019).

Reduction of water footprint implicitly measures the effect of reducing water usage on water scarcity (Hoekstra, 2014). In the context of sustainable water management, efficient water use aims at finding a balance between water resources availability and demands from society, the economy, and the environment (Zhang and Xu, 2019). The circular economy, on the other hand, involves the reduction of water use, water reuse, and recycling schemes and implies closing the loop of resource usage (Winans et al., 2017).

Therefore, calculating WUE for a particular use depends on how WUE is interpreted, how specific variables are used, availability of reliable data, and if data tally with the variables. Experts who have developed a methodology to compute indicator 6.4.1. of SDGs, related to water-use efficiency, mention that "different sectors require their definition of water-use efficiency" (FAO, 2018a).

TABLE 3 | Indicators related to WUE.

Indicator/Index	Description	Reference
WUE 6.4.1. (SDG)	Change in water-use efficiency over time. It is an economic component of SDG target 6.4. and evaluates to what extent a country's economic growth is dependent on the use of water resources. It can be calculated at national and basin scales.	UN, 2015; FAO, 2018a
Blue water footprint	It is an indicator of direct and indirect freshwater use by a consumer or producer. It gives information about how much water is being consumed by a particular country at river or catchment scale. It can be calculated for a particular process, product, and company. It is computed as the volume of water abstracted from natural sources minus the water returned to the system.	Hoekstra, 2014; Water footprint, n.d.
Water exploitation index (WEI)	Measuring the ratio between the mean annual total freshwater abstraction and the long-term average of available freshwater resources. The unit of measure is a percentage.	European Union, 2019
Water productivity index (WPI)	Measuring the amount of economic output produced (EUR) in terms of gross domestic product (GDP) per unit of water abstracted (m^3). The WEI and WPI indices aim at monitoring WUE at national scale through sustainable water usage and reduced pressure over natural water sources.	European Union, 2019
WUE evaluation index system	It is a method used in sustainable water management efficiency (SWM) evaluation, and it aims to evaluate regional sustainable water utilization. The index considers the experts' psychological factors in the decision-making processes, and uses six indicators.	Zhang and Xu, 2019

The indicators used to estimate WUE vary with temporal and spatial scales of water use and users, depending on the variables and methodology used for its estimation, and the target stakeholders (FAO, 2018a). **Table 3** presents various indicators that have been used to analyze water usage related to WUE.

Hoekstra et al. (2017) state that "looking at efficiency from the production perspective is limited because most of the reduction of water consumption can be achieved by changing consumption patterns." In the assessment of WUE indicator 6.4.1. of SDGs, institutions play an essential role in coordinating various stakeholders who are involved in monitoring the indicator (FAO, 2018a).

Details on how various variables are measured and its effects estimated are often not clear. Bhaduri et al. (2016) state that "the level of allowable withdrawal rates from freshwater bodies is not well established scientifically;" Hák et al. (2016) and Miola and Schiltz (2019) show there is no clear link between methods and indicators used to measure the performance of SDGs. Zhang and Xu (2019) claim that "the absence of an effective, scientific evaluation method may lead to a lack of awareness of sustainable water usage."

Approaches to assess and achieve WUE influence and is influenced by, the knowledge and capacity of water users to adopt best practices. These, in turn, affect behavioral factors such as attitudes and perceptions of individuals and influence their decisions about water use.

FACTORS UNDERLYING WATER USE BEHAVIOR

In the context of water use, water use behavior is defined as an environmental behavior. Steg and de Groot (2018) define environmental behavior as "any behavior that has a good or bad impact on the environment" (p. 164). This behavior is influenced by contextual and behavioral factors (Carrus et al., 2010; Graymore et al., 2010; Russell and Fielding, 2010).

Contextual factors refer to the background characteristics of individuals and their physical environment (Dreibelbis et al., 2013). These influence behavioral factors in different ways (Contzen and Mosler, 2012) and may facilitate or constrain behaviors. The contextual factors encompass social, economic, technical, environmental, and institutional backgrounds, acquired skills, immediate personal conditions, economic resources, capabilities, regulations, etc. The first three factors have been shown to be important in predicting water use (Russell et al., 2020). Here, the environmental factors refer to geographical experiences which are connected with associative learning (Dean et al., 2016), and institutional factors involve institutional relationships (Kapetas et al., 2019) between water users and the water supply systems and regulations (Khair et al., 2019).

Behavioral factors are referred to as determinants (Jager and Joachim Mosler, 2007; Dreibelbis et al., 2013) that may immediately influence individual behavior. These are also actions and habits that can be observed directly and factors that influence the mindset of individuals.

Contextual Factors

Several studies have examined the domain large number of contextual factors (Russell and Fielding, 2010). Stern (2000) finds contextual factors as the second major type of causal variables of environmentally significant behavior after attitude related factors. Contzen and Mosler (2012) state that contextual factors can affect behavior by influencing behavioral factors. In fact various contextual factors influence behavior and individual motivations (Steg and Vlek, 2009; Dietz, 2014) (see **Table 4**).

In the context of WUE, the contextual factors that have been studied are social, economic, environmental, technical

TABLE 4 | Examples of contextual factors that influence environmental behavior.

Approach	Factors	Reference
Theory of environmentally significant behavior	Interpersonal influences; community expectations; advertising; government regulations; legal and institutional factors; monetary incentives and costs; the physical difficulty of specific actions; capabilities and constraints provided by technology and the built environment; the availability of public policies to support behavior; social, economic, and political context	Stern, 2000
Environmental psychology	Physical infrastructure, technical facilities, the availability of products, and product characteristics	Steg and Vlek, 2009
Water, sanitation, and hygiene behavior (WASH)	Social, physical, and personal	Contzen and Mosler, 2012

(Jorgensen et al., 2009; Millock and Nauges, 2010; Russell and Fielding, 2010; Lee et al., 2011; Willis et al., 2013; Scott et al., 2014; Jorge et al., 2015; Wang et al., 2015; Hussien and Memon, 2016; Vieira et al., 2017; Kneebone et al., 2018; Nazari et al., 2018; Benedict and Hussein, 2019; Kapetas et al., 2019; Koh, 2020) and, in some cases institutional factors.

Socioeconomic Factors

Factors such as age (Beal et al., 2013; Tang et al., 2013; Attari, 2014; Chang et al., 2016; Dean et al., 2016; Piedra-Muñoz et al., 2018; Khair et al., 2019), gender (Beal et al., 2013; Attari, 2014; Piedra-Muñoz et al., 2018), education level (Beal et al., 2013; Chang et al., 2016; Dean et al., 2016; Piedra-Muñoz et al., 2018; Khair et al., 2019), information (Dean et al., 2016), networking (Tang et al., 2013; Dean et al., 2016), household characteristics (Russell and Fielding, 2010; Dreibelbis et al., 2013), and population density (Benito et al., 2019; Zhang and Xu, 2019) are the key socio-demographic factors that contextualize water use.

Age, education level, information, and networking are strongly associated with knowledge (Dean et al., 2016) about water use, which is a core component of solving water-related problems.

Some authors have shown that men and women differ in terms of environmental awareness (Piedra-Muñoz et al., 2018), and risk perception (Attari, 2014). Meanwhile, cultural factors involve beliefs and traditions that influence water use practices. For instance, Kadibadiba et al. (2018) observed that high levels of domestic consumption are associated with the daily desire for cleanness, comfort, and convenience in certain cultures. Household size and composition are linked with economic capability to make investments, e.g., on water saving devices; while population density influences the operation and performance of water utilities due to economies of scale, resulting from consequent size of utilities (Benito et al., 2019).

Financial incentives include subsidies that may have positive or negative effects on WUE. There are subsidies to conserve water, investments in technology and infrastructure; others such as subsidized energy mainly has promoted groundwater overuse (Nazari et al., 2018; Khair et al., 2019). This incentive has thus had the opposite effect, known as the rebound effect (Freire-González, 2019).

Water pricing is a relevant determinant since it affects perceptions (Tang et al., 2013), willingness (Bruneau et al., 2013), awareness, and attitudes (Nazari et al., 2018) of water users such as farmers and households. This together with other factors signals people to use water efficiently. The regional economy also influences technical factors, such as training, investment in infrastructure or ability to acquire water savings devices (Bruneau et al., 2013). Several economic activities, such as agriculture, depend on water to produce goods, and its productivity is often associated with average income of the producers (Graymore et al., 2010; Khair et al., 2019; Xiao et al., 2019), and diversification of the economy. For instance, if irrigated agriculture is the only source of livelihood (i.e., lack of diversification), water users will focus solely on increasing production to increase profits (Roobavannan et al., 2017; Khair et al., 2019), leading to a higher water demand (Ghanim, 2019; Xiao et al., 2019). In such cases, users may not adopt techniques to increase WUE if water is not appropriately priced, or may adopt low flow high-efficiency faucets like drip irrigation but still consume more water (so called efficiency paradox), since their perception of well-being is driven by profit maximization.

Technical Factors

Frequently examined technical factors include training, data availability, elaboration of WUE plans, infrastructure and technology readiness, and the performance of utilities in terms of financial and NRW indicators, and capacity to supply water demand. Training facilitates a better understanding of water usage and knowledge of good water management practices (Dean et al., 2016; Nazari et al., 2018) and better informed decisions. The metering and monitoring of water use are often overlooked. Also, flawed estimations of water requirements, water balance, and allocation (Manouseli et al., 2019), and management of water systems (Benito et al., 2019) can lead to water use inefficiency. Timely and accurate information is therefore required to plan and implement efficient use of water (Manouseli et al., 2019).

The infrastructure of a water system also impacts WUE. Proper pricing and financial sustainability can lead to more capacity for investments (Ding et al., 2019; Manouseli et al., 2019), and proper operation (Nazari et al., 2018), and maintenance. In some water systems, the operations have to be stopped because of reasons such as water scarcity, and water contamination. As a result, there are water restrictions, e.g., shortages and intermittent supply. Such circumstances can motivate users to adopt water savings measures (Graymore et al., 2010) but can also have serious implications for efficient operations and water use (Charalambous and Laspidou, 2017).

Institutional and Environmental Factors

There are three groups of functions that water related institutions are generally responsible for. First concerns the goals to guide, enable, and constrain the actions of individuals (Greif, as cited in Vitola and Senfelde, 2015), firms, households, and other decision-making units (Lynne et al., 1991), and shaping human interactions around water use (North as cited in Vitola and Senfelde, 2015). These may activate values and shape beliefs of individuals and can change the behavior of many toward water use (Stern, 2000). The second group of functions focuses on coordinating activities (Geels, 2004), and designing, and implementing policies systematically (Kapetas et al., 2019). The third group of functions facilitates information and promotes incentives to encourage people to use water appropriately (Ostrom, 1990; Aligica, 2006; Koehler et al., 2018).

Individual staff members are crucial stakeholders along the chain of water use decisions and actions (Meglino and Ravlin, 1998). The structure of institutions itself (Ortigara et al., 2018) determines the progress and implementation of regulations. For example, populist agendas rarely prioritize WUE. At the same time, unstable water governance (Ortigara et al., 2018) interrupts planning activities, and lack of environmental awareness policies becomes a hurdle to implement WUE measures promptly.

The influence of institutions on behavior has been often highlighted (Markey-towler, 2018). Jorgensen et al. (2009). Graymore et al. (2010) argue that trust in institutions is linked to water-saving by water users. If water users do not trust the institutions, they are less likely to use water efficiently. Additionally, weak institutions produce ineffective regulations and subsequently do not encourage users to use water efficiently (Khair et al., 2019).

Regulations often lag behind the understanding of current and future water challenges (Nazari et al., 2018) with little participation of stakeholders (Chang et al., 2016). The involvement of communities is important, but often ignored, in the design and application of rules and regulations (Horinkova and Abdullaev, 2003), because it influences their attitudes toward the implemented regulations, awareness of beneficial consequences, and willingness to obey (Chang et al., 2016).

Behavioral Factors

Behavioral factors consist of perceptions, thoughts, feelings, and beliefs that affect the practice of behavior. These factors as a whole characterize the mindset of an individual linked to behavior (Contzen and Mosler, 2012).

Several theories and models have been used to analyze environmental behavior such as the norm activation model (NAM) (Steg and de Groot, 2018); the new environmental paradigm (NEP) (Dunlap et al., 2000); the theory of planned behavior (TPB) (Ajzen, 1991); the theory of values (Steg and de Groot, 2018); the values, beliefs, and norms theory (VBN) (Stern, 2000; Yildirim and Semiz, 2019); the theory of environmentally significant behavior (Stern, 2000); and the risk, attitude, norms, abilities, and self-regulation (RANAS) model (Contzen and Mosler, 2012) (see **Table 5**).

The RANAS model combines the most important behavioral theories to explain and change behavior (Contzen and Mosler, 2012). It has two main advantages, firstly, it can be adapted to a range of behaviors in a variety of settings and populations, and it provides a standard template of questions to quantify behavioral factors and analyze the behavior. This further allows the comparison of multiple sites or scenarios (Dreibelbis et al., 2013). Risk, attitude, norms, abilities, and self-regulation has been used to evaluate behaviors linked to water, sanitation, and hygiene (WASH) practices, such as handwashing and adoption of household water treatment technology (Contzen and Mosler, 2012; Mosler, 2012; Dreibelbis et al., 2013; Lilje and Mosler, 2018; Daniel et al., 2019; Nunbogu et al., 2019). In the context of water use, RANAS factors such as knowledge, beliefs, and emotions are linked to an individual's psychology of water use and influence the practice of a behavior (Mosler and Contzen, 2016). Indeed, this model includes behavioral factors such as risk, and self-regulation that are crucial to regulate and understand different behaviors.

One of the theories that has been integrated in the RANAS is the TPB, which has also been widely used to investigate and understand environmental behaviors, including water use and its associated factors (Harland et al., 1999; Stern, 2000; Steg and Vlek, 2009; Russell and Fielding, 2010; Mosler, 2012; Fu and Wu, 2014; Yuriev et al., 2020).

Values are defined as "concepts or beliefs about desirable end states or behaviors that transcend specific situations and guide the evaluation of behavior and are ordered by relative importance" (Dietz et al., 2005, p. 345–346). Values may directly affect beliefs, norms and behavior. Beliefs have a direct effect on norms and norms influence behavior (Roobavannan et al., 2018). In the domain of environmental behavior, values are factors that are linked with concern about the environment and may affect individual decisions. These are altruism, biospheric, egoistic, and hedonistic values (Stern, 2000; Dietz et al., 2005; Steg and de Groot, 2018). Personal norms are a solid base for predispositions of individuals to pro-environmental action (Stern, 2000).

Stern (2000) integrated the values theory, NEP and NAM to developed the VBN theory of environmentalism. It is represented by a causal chain that includes values, beliefs and norms and its variables (Stern, 2000; Dietz et al., 2005) (see **Figure 1**).

Since individual behavior is essential to analyse the psychology of why people use water efficiently or not, behavioral studies have mainly focused on individual users, e.g., how consumers react to WUE measures and regulations (Graymore and Wallis, 2010; Lee et al., 2011; Scott et al., 2014; Jorge et al., 2015; Wang et al., 2015; Vieira et al., 2017; Kneebone et al., 2018; Nazari et al., 2018; Benedict and Hussein, 2019; Kapetas et al., 2019; Koh, 2020). Several stakeholders, including farmers and households from rural communities have been considered.

KNOWLEDGE GAPS IN UNDERSTANDING WUE

Limited number of studies (Cortner et al., 1998; Chai and Schoon, 2016; Nazari et al., 2018; Kapetas et al., 2019) have considered stakeholders such as the institutions and their staff in assessing WUE. The determinants of individual behavior

TABLE 5 | Models and theories and factors to understand environmental behavior.

Model or theory	Approach	Factors
The norm activation model (NAM) [1]	The pro-environmental actions follow from the activation of personal norms, reflecting feelings of moral obligation to perform actions. Experimental studies have showed that NAM variables are causally related.	Personal norms are activated by: problem awareness; ascription of responsibility; outcome efficacy; self-efficacy
The new environmental paradigm (NEP) [2, 3]	The NEP focused on beliefs about humanity's ability to upset the balance of nature, the existence of limits to growth for human societies, and humanity's right to rule over the rest of nature.	Beliefs
Theory of planned behavior (TPB) [1]	Behavior results from the intention to engage in specific behavior. The TPB assumes that socio-demographics and values influence behavior indirectly via attitudes, subjective norms, and perceived behavioral. Attitudes express a positive or negative stance toward a behavior; subjective norms, normative factors represent convictions about the incidence of a behavior and how the social network thinks about the behavior; perceived behavioral control ability factors represent the aptitudes and individual beliefs.	Attitudes, subjective norms, and perceived behavioral
Theory of values [1]	Values include beliefs about desirability or undesirability of certain end-states that transcend specific situations. Values serve as guideline principles for the evaluation of people and for behaviors.	Key values for pro-environmental behavior. These are separated in two dimensions: Self-transcendence: altruistic; biospheric. Self-enhancement; egoistic and hedonic.
The theory of environmentally significant behavior [4]	This theory assesses the definitions, classifies the precursors of environmental behavior, evaluates the links between environmental concern and behavior and identifies the factors that determine environmentally significant behavior.	Causal variables: attitudinal; personal capabilities; contextual factors; habit and routine.
The value-belief-norm theory (VBN) [1, 3, 4, 5, 6]	This theory is an extension of the NAM and links the values theory, the norm activation theory (NAM) and new environmental paradigm (NEP). A causal chain of values (biospheric, altruistic, and egoistic), beliefs, and personal norms triggers the behavior. Beliefs consist of personal worldview of concerns or perceptions about the consequences of human actions that may harm the environment; norms relate to moral obligations to engage in an environmental behavior; values are central to any decision making process, and guide behavior and attitudes.	Values; beliefs on relationships between humans and the natural environment reflected by ecological worldview; norms
Risk, attitude, norm, abilities, self-regulation (RANAS) [1,5]	This model systematically identifies, measures, and integrates behavioral and contextual factors to assess behavior at an individual scale. The RANAS model derives the factors on the basis of quantitative data. Behavioral outcomes: behavior; intention and habit. Risk: perceived vulnerability. Attitude: instrumental beliefs, affective beliefs. Normative: descriptive, injunctive, and personal norms. Ability: action knowledge, self-efficacy, maintenance efficacy, recovery efficacy. Self-regulation: action control/planning, coping planning, remembering, commitment.	Risk; attitude; ability; self-regulation.

[1] (Steg and de Groot, 2018); [2] (Dunlap and Van Liere, 2010); [3] (Russell and Fielding, 2010); [4] (Stern, 2000); [5] (Contzen and Mosler, 2012); [6] (Dietz, 2014).

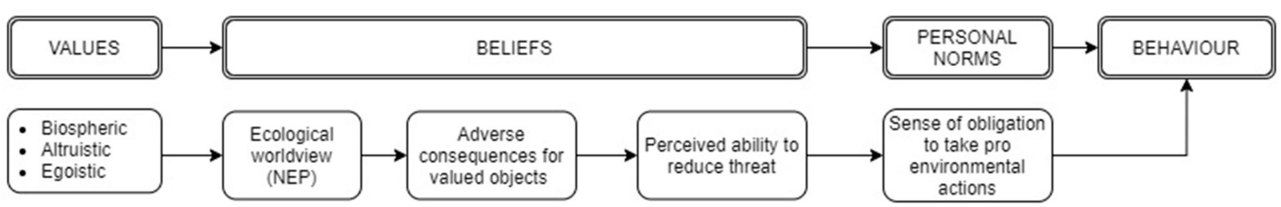


FIGURE 1 | Representation of the VBN theory of environmentalism. Arrows represent direct effects. Adapted from Dietz et al. (2005) and Stern (2000).

within organizations are different from those of household behaviors and the behavior of organizations has a huge environmental impact. All stakeholders may ignore it. But the disregard for environmental criteria by institutions can have more adverse consequences. For example, institutions may ignore environmental criteria or make decisions regarding the use of water that lead to unknown adverse environmental impacts (Stern, 2000). Such decisions may drive individual behavior (Stern, 2000) within organizations (Meglino and Ravlin, 1998). Moreover, environmental behavior of individuals may be influenced by the actions of organization to which they belong (Stern, 2000).

Few studies have highlighted and incorporated the role of users' trust in institutions and their influence on environmental

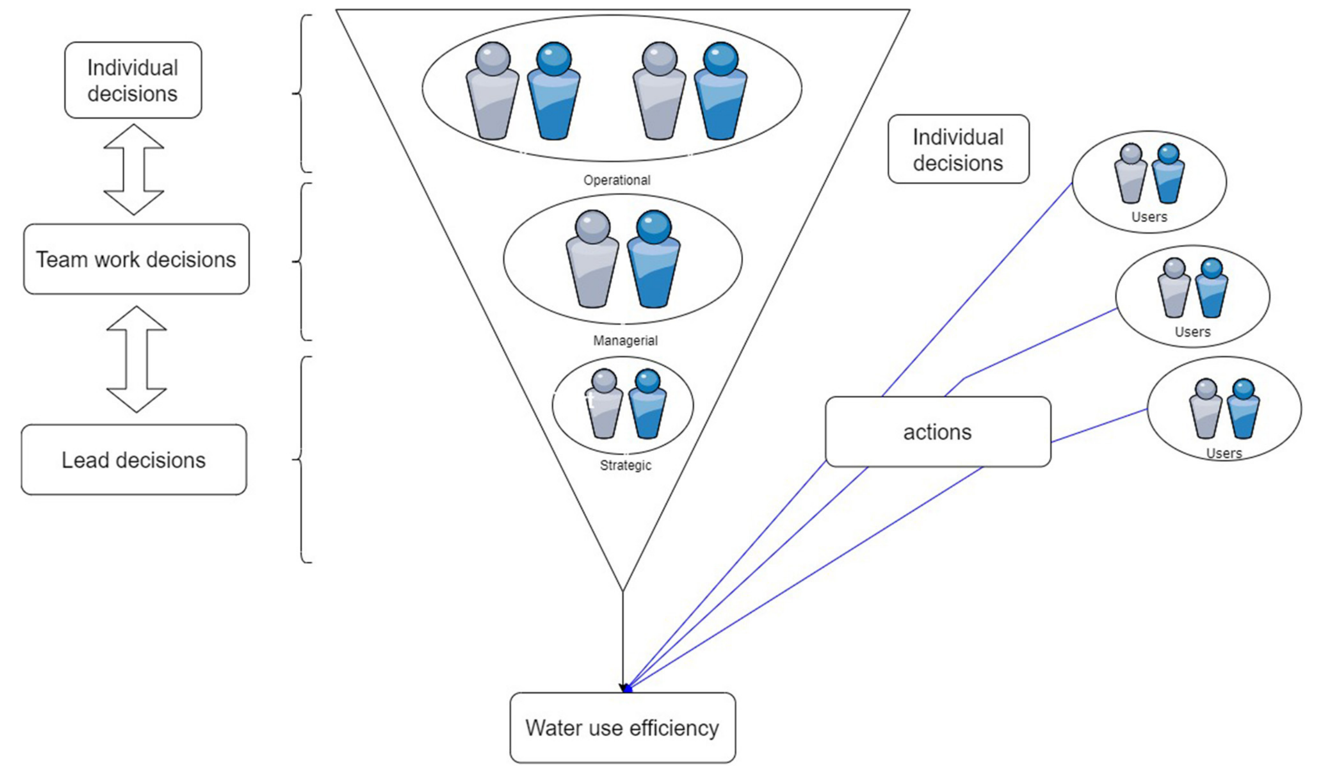


FIGURE 2 | Actors involved in using water (in)efficiently for domestic purposes.

behavior. The specific role that trust plays in determining water efficiency behavior remains unclear (Jorgensen et al., 2009). The actions taken by institutions are a result of a chain of decisions taken by relevant individuals. Subsequently, the psychology and consequent actions of such individuals also alter water use related decisions and measures that institutions take up as a whole.

Assessment of individual perceptions (Meglino and Ravlin, 1998) and the relationships between engaged stakeholders can unravel the influence of institutions over users, and how institutions can work toward WUE targets. This is illustrated in **Figure 2**. Note that the users can also be influenced by the individuals of institutions given that they frequently interact with each other.

The variables that influence sustainable water use have been widely studied, such as age and incentives (Brown and Keath, 2008; González-Gómez et al., 2011; Wang et al., 2015; Khair et al., 2019). Most of the variables are assumed to independently influence the behavior of water use. Yet many studies have highlighted the need for an integrated view of WUE, indicating its links with the underlying human behavior and institutions (Graymore and Wallis, 2010; Lee et al., 2011; Scott et al., 2014; Jorge et al., 2015; Wang et al., 2015; Vieira et al., 2017; Kneebone et al., 2018; Nazari et al., 2018; Benedict and Hussein, 2019; Kapetas et al., 2019; Koh, 2020).

Therefore, there are three main gaps in our understanding of WUE concerning to human behavior. First, an integrated assessment of behavioral and contextual factors and its relationships in relation to WUE is lacking. Second, the influence of institutions on WUE has not been evaluated completely. Only end users such as households and farmers are acknowledged for their roles in using water (in)efficiently. All other stakeholders in the supply chain of water use are mostly ignored. The influence of institutional stakeholders is neither fully known nor documented. Consumers' trust in institutions is however important to implement WUE measures (Graymore et al., 2010; 2009; Beal et al., 2013; Fu and Wu, 2014; Caspers, 2020). Further, decisions within an institution involve actions of multiple staff members and, therefore, staff dynamics within institutions also play a role in proposing regulations about WUE, of which little is known about its effect on WUE. Finally, a standardized method to understand WUE practices in terms of contextual and behavioral factors is missing.

An integrated approach of stakeholders is therefore needed to move from the current assessment that focuses solely on the behavior of individuals and households as water users to include others stakeholders, especially institutions and how they behave (Stern and Dietz, 2020).

To do that we propose an extension of the RANAS model and integrate it with the VBN theory. The extension consists of including institutions (the organization responsible for water supply system) as an additional contextual factor, and trust as an additional behavioral factor.

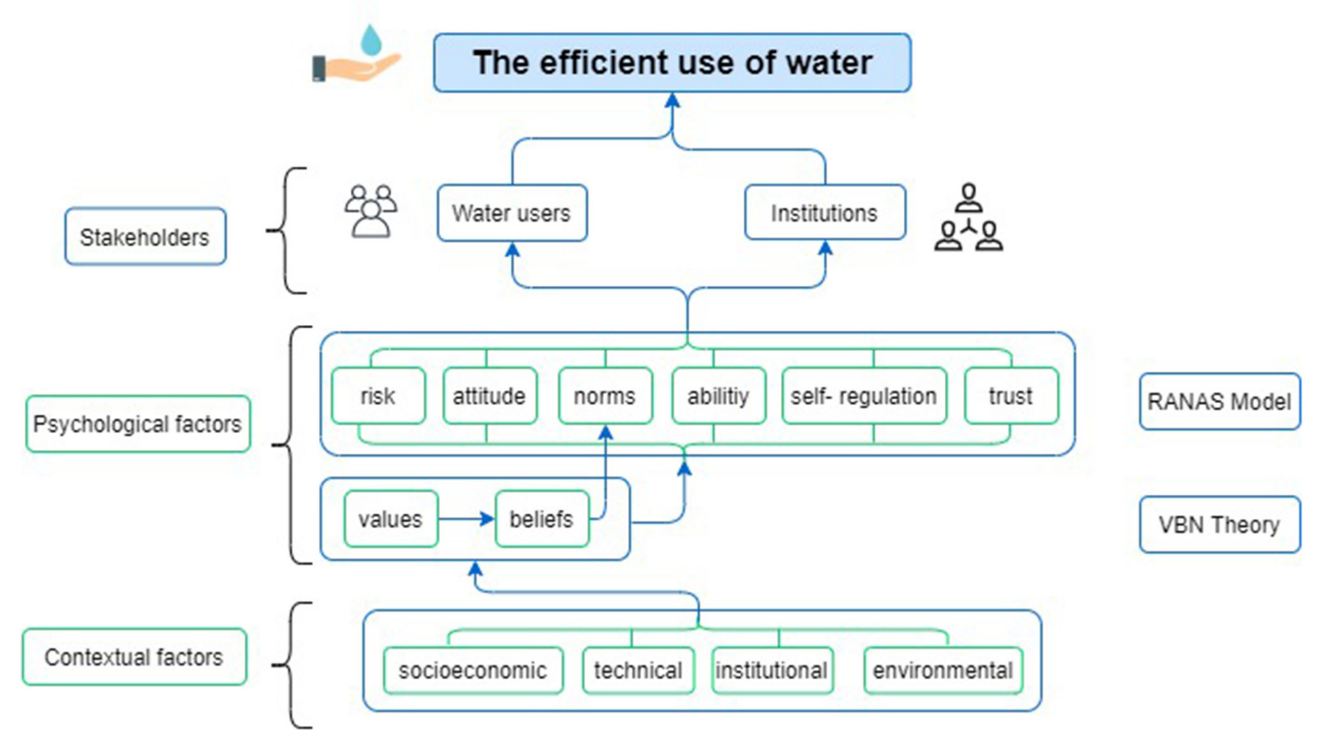


FIGURE 3 | Elaboration of contextual and psychological factors within the conceptual model.

A CONCEPTUAL MODEL TO UNDERSTAND WUE BEHAVIOR

Existing approaches for measuring and understanding environmental behavior are used as guide and source of inspiration. These include the model of behavior change (Contzen and Mosler, 2012) that has been used for the water and sanitation sector in developing countries (Mosler, 2012); the framework of Steg and Vlek (2009) for understanding and promoting pro-environmental behavior; the research of Carrus et al. (2010) for studying the socio-psychological and contextual predictors to assess sustainable water consumption and the causal chain of factors across the environmental significant behavior (Stern, 2000).

A causal hierarchy of contextual and behavioral factors is assumed, in order to suggest that context affect the psychology and the behavioral factors, which in turn influence the environmental behavior of individuals. All factors together determine the behavioral outcome with respect to efficient use of water. The model has three main components: contextual factors, behavioral (or psychological) factors, and water users, including institutions who are the stakeholders (see **Figure 3**).

The target behavior is the efficient use of water (WUE). It is a result of psychological processing of factors intrinsic to an individual (Steg and Vlek, 2009; Mosler, 2012), and involves the execution of responsible pro-environmental actions (Hines et al., 1987; Steg and de Groot, 2018). The WUE behavior involves curtailment actions that are associated to resource conservation and efficiency actions that are related with the installation of water efficiency technology (Russell and Fielding, 2010; Beal et al., 2013). These actions can be shorter showers or harvest water by using rain barrels, both having positive impacts on water use due to less water consumption and withdrawals.

The conceptual model provides a structure to construct a quantitative model to measure factors that are based on social science experiments (Voinov and Bousquet, 2010) or are informed by local observations such as social surveys (Argent et al., 2016).

This conceptual model offers to fill the identified gaps in several ways. Based on existing psychological models and theories, such as RANAS and VBN, the model interprets behavior underlying WUE with an extension of the RANAS model to include factors linked to institutions. The model concept also offers a "flexible" method that can be used, modified, or expanded to other water use contexts, e.g., drinking water treatment by rural communities, reuse of water, or harvesting of rain water. Finally, the inclusion of institutional factor also allows the interpretation of water use behavior of individuals of water supply organizations and the relationships between water users and water supply organizations.

To explain and identify the relationships within the conceptual model between factors and their influence on (in)efficient water use, the factors and WUE need to be quantified. For this a group of variables are identified for each factor, e.g., socio-demographic variables, attitude, and perception variables, and water use and availability. These variables can then be quantified using RANAS inspired questionnaires (Daniel et al., 2019), interviews, and field measurements of water use and supply (e.g., rainfall) fluxes.

CONCLUSIONS

The success of various efforts at implementing WUE measures has been limited by several related reasons. One cause behind higher than expected demand and inefficient use of water is human behavior and therefore related to the lack of an integrated assessment of behavioral and contextual factors that influence water use behavior.

Based on an extensive review, the paper identified a variety of contextual and psychological factors underlying the behavior. A conceptual model, based on existing models and theories, was proposed that integrates both groups of factors and proposes relationships between water users and institutions to understand (in)efficient water use. Involving water managers facilitates the assessment of institutional relationships between water users and water managers. This will unravel the influence of institutions or organizations on the behavior of water users, and vice versa.

Local observations and social surveys should provide the data that are needed to populate the model and test factors influencing the behavior.

The paper further highlighted that water users and institutions involved in the water use chain have an important role to play in making decisions and taking actions that affect WUE. Often the focus on end users such as households means that other stakeholders in the supply chain of water use are mostly ignored, such as institutional stakeholders (organizations/water managers). Linking the knowledge of WUE with stakeholder's perceptions, would, as a result, contribute to a more comprehensive assessment of WUE.

AUTHOR CONTRIBUTIONS

DC drafted, revised, and finalized the paper. SP and LR edited the paper. All authors contributed to the ideas in the paper and agreed to the submitted form.

FUNDING

DC is funded by Pasaporte a la Ciencia programme of Instituto Colombiano de Crédito Educativo y Estudios Técnicos en el Exterior—ICETEX.

ACKNOWLEDGMENTS

The authors would like to thank D. Daniel, Melissa Haeffner, Juan Pablo Rodriguez, and Anjana Ekka, and for their insights and comments on earlier drafts of the paper.

REFERENCES

Ajzen, I. (1991). The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* 50, 179–211. doi: 10.4135/9781446249215.n22

Aligica, P. D. (2006). Institutional and stakeholder mapping: frameworks for policy analysis and institutional change. *Publ. Organ. Rev.* 6, 79–90. doi: 10.1007/s11115-006-6833-0

Argent, R. M., Sojda, R. S., Guipponi, C., McIntosh, B., Voinov, A. A., and Maier, H. R. (2016). Best practices for conceptual modelling in environmental planning and management. *Environ. Model. Softw.* 80, 113–121. doi: 10.1016/j.envsoft.2016.02.023

Arto, I., Andreoni, V., and Rueda-cantuche, J. M. (2016). Global use of water resources : a multiregional analysis of water use, water footprint and water trade balance. *Water Resour. Econ.* 15, 1–14. doi: 10.1016/j.wre.2016.04.002

Attari, S. Z. (2014). Perceptions of water use. *Proc. Natl. Acad. Sci. U.S.A.* 111, 5129–5134. doi: 10.1073/pnas.1316402111

Beal, C. D., Stewart, R. A., and Fielding, K. (2013). A novel mixed method smart metering approach to reconciling differences between perceived and actual residential end use water consumption. *J. Clean. Prod.* 60, 116–128. doi: 10.1016/j.jclepro.2011.09.007

Benedict, S., and Hussein, H. (2019). An analysis of water awareness campaign messaging in the case of Jordan: water conservation for state security. *Water* 11:1156. doi: 10.3390/w11061156

Benito, B., Faura, Ú., Guillamón, M. D., and Ríos, A. M. (2019). Empirical evidence for efficiency in provision of drinking water. *J. Water Resour. Plann. Manage.* 145, 1–10. doi: 10.1061/(ASCE)WR.1943-5452.0001049

Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., et al. (2016). Achieving sustainable development goals from a water perspective. *Front. Environ. Sci.* 4:64. doi: 10.3389/fenvs.2016.00064

Brooks, D. B. (2006). An operational definition of water demand management. *Int. J. Water Resour. Dev.* 22, 521–528. doi: 10.1080/07900620600779699

Brown, R. R., and Keath, N. A. (2008). Drawing on social theory for transitioning to sustainable urban water management: turning the institutional supertanker. *Aust. J. Water Resour.* 12, 73–83. doi: 10.1080/13241583.2008.11465336

Bruneau, J., Dupont, D., and Renzetti, S. (2013). Economic instruments, innovation, and efficient water use. *Canad. Publ. Policy* 39, S11–S22. doi: 10.3138/CPP.39.Supplement2.S11

Carrus, G., Bonnes, M., Corral-verdugo, V., Moser, G., and Sinha, J. (2010). "Social-psychological and contextual predictors of sustainable water consumption," in *Psychological Approaches to Sustainability: Current Trends in Theory, Research and Applications*, 415. Available online at: https://www.scopus.com/inward/record.uri?partnerID=HzOxMe3b&scp=84892019381&origin=inward (Retrieved March 10, 2021).

Caspers, C. G. W. (2020). Role of trust in adopting consumer social responsible behaviour in the context of water use in domestic households. *South East Eur. J. Econ. Bus.* 15, 1–13. doi: 10.2478/jeb-2020-0001

Chai, Y., and Schoon, M. (2016). Institutions and government efficiency: decentralized irrigation management in China. *Int. J. Commons* 10, 21–44. doi: 10.18352/ijc.555

Chang, G., Wang, L., Meng, L., and Zhang, W. (2016). Farmers' attitudes toward mandatory water-saving policies: a case study in two basins in northwest China. *J. Environ. Manage.* 181, 455–464. doi: 10.1016/j.jenvman.2016.07.007

Charalambous, B., and Laspidou, C. (2017). *Dealing with the Complex Interrelation of Intermittent Supply and Water Losses.* Scientific and Technical Report. London: IWA Publishing.

Cole, M. J., Bailey, R. M., Cullis, J. D. S., and New, M. G. (2018). Water for sustainable development in the Berg Water Management Area, South Africa. *South Afr. J. Sci.* 114, 1–10. doi: 10.17159/sajs.2018/20170134

Contzen, N., and Mosler, H.-J. (2012). "The Risks, Attitudes, Norms, Abilities, and Self-regulation (RANAS) approach to systematic behavior change," in *Eawag*. Available online at: https://www.eawag.ch/en/department/ess/ (Retrieved April 20, 2020).

Cortner, H. J., Wallace, M. G., Burke, S., and Moote, M. A. (1998). Institutions matter: the need to address the institutional challenges of ecosystem management. *Landsc. Urban Plan.* 40, 159–166. doi: 10.1016/S0169-2046(97)00108-4

Daniel, D., Diener, A., Pande, S., Jansen, S., Marks, S., Meierhofer, R., et al. (2019). Understanding the effect of socio-economic characteristics and psychosocial factors on household water treatment practices in rural Nepal using Bayesian Belief Networks. *Int. J. Hyg. Environ. Health* 222, 847–855. doi: 10.1016/j.ijheh.2019.04.005

Dean, A. J., Fielding, K. S., and Newton, F. J. (2016). Community knowledge about water: who has better knowledge and is this associated with water-related behaviors and support for water-related policies? *PLoS ONE* 11:e0159063. doi: 10.1371/journal.pone.0159063

Department of Agriculture, Water and the Environment (2019). *National Water Initiative (NWI)*. Retrieved from Department of Agriculture, Water and the Environment. Available online at: https://www.agriculture.gov.au/water/policy/nwi

Dietz, T. (2014). Understanding environmentally significant consumption. *Proc. Natl. Acad. Sci. U.S.A.* 111, 5067–5068. doi: 10.1073/pnas.1403169111

Dietz, T., Fitzgerald, A., and Shwom, R. (2005). Environmental values. *Annu. Rev. Environ. Resour.* 30, 335–372. doi: 10.1146/annurev.energy.30.050504.144444

Ding, X., Zhang, Z., Wu, F., and Xu, X. (2019). Study on the evolution ofwater resource utilization efficiency in Tibet autonomous region and four provinces in Tibetan areas under double control action. *Sustainability* 11:3396. doi: 10.3390/SU11123396

Dreibelbis, R., Winch, P., Leontsini, E., Hulland, K. R., Ram, P. K., Unicomb, L., et al. (2013). The integrated behavioural model for water, sanitation, and hygiene: a systematic review of behavioural models and a framework for designing and evaluating. *BMC Public Health* 13:1015. doi: 10.1186/1471-2458-13-1015

Dunlap, R. E., and Van Liere, K. D. (2010). The "new environmental paradigm." *J. Environ. Educ.* 49, 19–28. doi: 10.3200/JOEE.40.1.19-28

Dunlap, R. E., Van Liere, K. D., Mertig, A. G., and Jones, R. E. (2000). New trends in measuring environmental attitudes: measuring endorsement of the new ecological paradigm: a revised NEP scale. *J. Soc. Issues* 56, 425–442. doi: 10.1111/0022-4537.00176

EEA (2007). *Towards Efficient Use of Water Resources in Europe 212*. European Environment Agency.

EPA (2018). *WaterSense*. United States Environmental Protection Agency. Available online at: https://www.epa.gov/watersense/how-we-use-water#Daily%20Life

EU (2014). *EU Resource Efficiency Scoreboard, 2014 Highlights. European Union. Enviroment European Commission*.

European Union (2019). *Water Exploitation Index-Eurostat - Productos Datasets*. Available online at: https://ec.europa.eu/eurostat/web/main/home

FAO (2018a). *Step by Step Monitoring of Change in Water Use Efficiency Over Time. Progress on Water Use Efficiency - Global Baseline for SDG 6 Indicator 6.4.1*. Available online at: https://www.unwater.org/publications/progress-on-water-use-efficiency-641/ (accessed August 22, 2019).

FAO (2018b). *Food and Agriculture Organization of the United Nations. Sustainable Development Goals*. Available online at: http://www.fao.org/3/CA1588EN/ca1588en.pdf

FAO (n.d.). *AQUASTAT - FAO's Global Information System on Water and Agriculture*. Available online at: http://www.fao.org/aquastat/en/overview/methodology/water-use

Freire-González, J. (2019). Does water efficiency reduce water consumption? The economy-wide water rebound effect. *Water Resour. Manage.* 33, 2191–2202. doi: 10.1007/s11269-019-02249-0

Fu, Y., and Wu, W. (2014). "Behaviour interventions for water end use: an integrated model," in *ICAC 2014 - Proceedings of the 20th International Conference on Automation and Computing: Future Automation, Computing and Manufacturing. ICAC, 14. University of Strathclyde Press* (Strathclyde).

GAO-14-430 (2014). *Supply Concerns Continue, and Uncertainties Complicate Planning. Report to Congressional Requesters*. Available online at: https://www.gao.gov/assets/gao-14-430.pdf

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. *Res. Policy* 33, 897–920. doi: 10.1016/j.respol.2004.01.015

Ghanim, A. A. (2019). Water resources crisis in Saudi Arabia, challenges and possible management options: an analytic review. *World Acad Sci. Eng. Technol.* 13, 51–56. doi: 10.5281/ZENODO.2571928

Glavič, P., and Lukman, R. (2007). Review of sustainability terms and their definitions. *J. Clean. Prod.* 15, 1875–1885. doi: 10.1016/j.jclepro.2006.12.006

Gleick, P. H., Christian-Smith, J., and Cooley, H. (2011). Water-use efficiency and productivity: rethinking the basin approach. *Water Int.* 36, 784–798. doi: 10.1080/02508060.2011.631873

González-Gómez, F., García-Rubio, M. A., and Guardiola, J. (2011). Why is non-revenue water so high in so many cities? *Int. J. Water Resour. Dev.* 27, 345–360. doi: 10.1080/07900627.2010.548317

Graymore, M., Wallis, A., and O'Toole, K. (2010). Understanding drivers and barriers: the key to water use behaviour change. *Water Sci. Technol.* 10, 679–688. doi: 10.2166/ws.2010.125

Graymore, M. L. M., and Wallis, A. M. (2010). Water savings or water efficiency? Water-use attitudes and behaviour in rural and regional areas. *Int. J. Sustain. Dev. World Ecol.* 17, 84–93. doi: 10.1080/13504500903497249

Hák, T., Janoušková, S., and Moldan, B. (2016). Sustainable development goals: a need for relevant indicators. *Ecol. Indic.* 60, 565–573. doi: 10.1016/j.ecolind.2015.08.003

Harland, P., Staats, H., and Wilke, H. A. M. (1999). Explaining proenvironmental intention and behavior by personal norms and the theory of planned behavior. *J. Appl. Soc. Psychol.* 29, 2505–2528. doi: 10.1111/j.1559-1816.1999.tb00123.x

Hens, L., Block, C., Cabello-Eras, J. J., Sagastume-Gutierez, A., Garcia-Lorenzo, D., Chamorro, C., et al. (2018). On the evolution of "Cleaner Production" as a concept and a practice. *J. Clean. Prod.* 172, 3323–3333. doi: 10.1016/j.jclepro.2017.11.082

Hines, J. M., Hungerford, H. R., and Tomera, A. N. (1987). Analysis and synthesis of research on responsible environmental behavior: a meta-analysis. *J. Environ. Educ.* 18, 1–18. doi: 10.1080/00958964.1987.9943482

Hoekstra, A. Y. (2014). Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation. *Wiley Interdisciplin. Rev. Water* 1, 31–40. doi: 10.1002/wat2.1000

Hoekstra, A. Y., Chapagain, A. K., and van Oel, P. R. (2017). Advancing water footprint assessment research: challenges in monitoring progress towards sustainable development goal 6. *Water* 9:438. doi: 10.3390/w9060438

Hofste, R. W., Reig, P., and Schleifer, L. (2019). *17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress [World Resources Institute]*. Available online at: https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress (Retrieved November 1, 2019).

Horinkova, V., and Abdullaev, I. (2003). Institutional aspects of water management in Central Asia: water users associations. *Water Int.* 28, 237–245. doi: 10.1080/02508060308691689

Howell, T. A. (2005). "Enhancing WUE in irrigated agriculture," in *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005 World Water and Environmental Resources Congress* (Anchorage, AK), p. 524. doi: 10.1061/40792(173)524

Hussien, W. A., and Memon, F. A. (2016). Assessing and modelling the influence of household characteristics on per capita water consumption. *Water Resour. Manage.* 30, 2931–2955. doi: 10.1007/s11269-016-1314-x

Jabari, S. J. (2017). Non-revenue water management in Palestine. *World Acad. Sci. Eng. Technol.* 11, 953–959. doi: 10.5281/zenodo.1131505

Jager, W., and Joachim Mosler, H. (2007). Simulating human behavior for understanding. *J. Soc. Issues* 63, 97–116. doi: 10.1111/j.1540-4560.2007.00498.x

Jorge, C., Vieira, P., Rebelo, M., and Covas, D. (2015). Assessment of water use efficiency in the household using cluster analysis. *Proc. Eng.* 119, 820–827. doi: 10.1016/j.proeng.2015.08.945

Jorgensen, B., Graymore, M., and O'Toole, K. (2009). Household water use behavior: an integrated model. *J. Environ. Manage.* 91, 227–236. doi: 10.1016/j.jenvman.2009.08.009

Jorgensen, B. S., and Martin, J. F. (2015). Understanding farmer intentions to connect to a modernised delivery system in an Australian irrigation district: a reasoned action approach. *J. Environ. Plann. Manage.* 58, 513–536. doi: 10.1080/09640568.2013.864620

Kadibadiba, T., Roberts, L., and Duncan, R. (2018). Living in a city without water: a social practice theory analysis of resource disruption in Gaborone, Botswana. *Global Environ. Change* 53, 273–285. doi: 10.1016/j.gloenvcha.2018.10.005

Kapetas, L., Kazakis, N., Voudouris, K., and McNicholl, D. (2019). Water allocation and governance in multi-stakeholder environments: insight from Axios Delta, Greece. *Sci. Total Environ.* 695:133831. doi: 10.1016/j.scitotenv.2019.133831

Khair, S. M., Mushtaq, S., Reardon-Smith, K., and Ostini, J. (2019). Diverse drivers of unsustainable groundwater extraction behaviour operate in an unregulated water scarce region. *J. Environ. Manage.* 236, 340–350. doi: 10.1016/j.jenvman.2018.12.077

Kneebone, S., Fielding, K., and Smith, L. (2018). It's what you do and where you do it: perceived similarity in household water saving behaviours. *J. Environ. Psychol.* 55, 1–10. doi: 10.1016/j.jenvp.2017.10.007

Koehler, J., Rayner, S., Katuva, J., Thomson, P., and Hope, R. (2018). A cultural theory of drinking water risks, values and institutional change. *Global Environ. Change* 50, 268–277. doi: 10.1016/j.gloenvcha.2018.03.006

Koh, Y. T. R. (2020). Attitude, behaviour and choice: the role of psychosocial drivers in water demand management in Singapore. *Int. J. Water Resour. Dev.* 36, 69–87. doi: 10.1080/07900627.2019.1617114

Lee, M., Tansel, B., and Balbin, M. (2011). Influence of residential water use efficiency measures on household water demand: a four year longitudinal study. *Resour. Conserv. Recycl.* 56, 1–6. doi: 10.1016/j.resconrec.2011.08.006

Lilje, J., and Mosler, H. J. (2018). Effects of a behavior change campaign on household drinking water disinfection in the Lake Chad basin using the RANAS approach. *Sci. Total Environ.* 619–620, 1599–1607. doi: 10.1016/j.scitotenv.2017.10.142

Lund, J., Medellin-Azuara, J., Durand, J., and Stone, K. (2018). Lessons from California's 2012-2016 drought. *J. Water Resour. Plann. Manage.* 144, 1–13. doi: 10.1061/(ASCE)WR.1943-5452.0000984

Lynne, G. D., Shonkwiler, J. S., and Wilson, M. E. (1991). Water permitting behavior under the 1972 Florida Water Resources Act. *Land Econ.* 67, 340–351. doi: 10.2307/3146429

Manouseli, D., Kayaga, S. M., and Kalawsky, R. (2019). Evaluating the effectiveness of residential water efficiency initiatives in england: influencing factors and policy implications. *Water Resourc. Manage.* 33, 2219–2238. doi: 10.1007/s11269-018-2176-1

Markey-towler, B. (2018). Rules, perception and emotion. *J. Instit. Econ.*15, 381–396. doi: 10.13140/RG.2.2.10321.43363

Meglino, B. M., and Ravlin, E. C. (1998). Individual values in organizations: concepts, controversies, and research. *J. Manage.* 24, 351–389. doi: 10.1177/014920639802400304

Mekonnen, M. M., and Hoekstra, A. Y. (2016). Sustainability: four billion people facing severe water scarcity. *Sci. Adv.* 2:e1500323. doi: 10.1126/sciadv.1500323

Mekonnen, M. M., Pahlow, M., Aldaya, M. M., Zarate, E., and Hoekstra, A. Y. (2015). Sustainability, efficiency and equitability of water consumption and pollution in latin America and the Caribbean. *Sustainability* 7, 2086–2112. doi: 10.3390/su7022086

Millock, K., and Nauges, C. (2010). *Household Adoption of Water-Efficient Equipment : The Role of Socio-economic Factors, Environmental To cite this version : HAL Id : halshs-00492291*. Centre d' Economie de la Sorbonne Documents de Travail du.

Minambiente (2010). *Política Nacional para la Gestión Integral del Recurso Hídrico*. Available online at: https://www.minambiente.gov.co/

Minambiente (2018). *Guía para el uso eficiente y ahorro del agua*. Available online at: https://www.minambiente.gov.co/

Miola, A., and Schiltz, F. (2019). Measuring sustainable development goals performance: how to monitor policy action in the 2030 Agenda implementation? *Ecol. Econ.* 164:106373. doi: 10.1016/j.ecolecon.2019.106373

Mosler, H.-J., and Contzen, N. (2016). "Systematic behavior change in water sanitation and hygiene a practical guide using the RANAS approach," in *Eawag*. Available online at: https://www.eawag.ch/en/department/ess/ (Retrieved April 20, 2020).

Mosler, H. J. (2012). A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: a conceptual model, a review, and a guideline. *Int. J. Environ. Health Res.* 22, 431–449. doi: 10.1080/09603123.2011.650156

Nazari, B., Liaghat, A., Akbari, M. R., and Keshavarz, M. (2018). Irrigation water management in Iran: implications for water use efficiency improvement. *Agric. Water Manage.* 208, 7–18. doi: 10.1016/j.agwat.2018.06.003

Nunbogu, A. M., Harter, M., and Mosler, H. J. (2019). Factors associated with levels of latrine completion and consequent latrine use in northern Ghana. *Int. J. Environ. Res. Public Health* 16:920. doi: 10.3390/ijerph16060920

Ortigara, A. R. C., Kay, M., and Uhlenbrook, S. (2018). A review of the SDG 6 synthesis report 2018 from an education, training, and research perspective. *Water* 10:1353. doi: 10.3390/w10101353

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge: Cambridge University Press. doi: 10.2307/3146384

Piedra-Muñoz, L., Vega-López, L. L., Galdeano-Gómez, E., and Zepeda-Zepeda, J. A. (2018). Drivers for efficient water use in agriculture: an empirical analysis of family farms in Almería, Spain. *Exp. Agric.* 54, 31–44. doi: 10.1017/S0014479716000661

Rad, M. H., Sarkheil, H., and Khojastehpour, R. (2019). Analysing water use efficiency and productivity in Iran's metropolises. *Proc. Institut. Civil Eng. Water Manage.* 172, 102–108. doi: 10.1680/jwama.17.00025

Roobavannan, M., Kandasamy, J., Pande, S., Vigneswaran, S., and Sivapalan, M. (2017). Allocating environmental water and impact on basin unemployment: role of a diversified economy. *Ecol. Econ.* 136, 178–188. doi: 10.1016/j.ecolecon.2017.02.006

Roobavannan, M.ahendran, Van Emmerik, T. H. M., Elshafei, Y., Kandasamy, J., Sanderson, M. R., Vigneswaran, S., Pande, S., et al. (2018). Norms and values in sociohydrological models. *Hydrol. Earth Syst. Sci.* 22, 1337–1349. doi: 10.5194/hess-22-1337-2018

Russell, S., and Fielding, K. (2010). Water demand management research: a psychological perspective. *Water Resour. Res.* 46, 1–12. doi: 10.1029/2009WR008408

Russell, S. V., Knoeri, C., and Russell, S. V. (2020). Exploring the psychosocial and behavioural determinants of household water conservation and intention household water conservation and intention. *Int. J. Water Resour. Dev.* 36, 940–955. doi: 10.1080/07900627.2019.1638230

Sánchez, T., Luis, D., and Sánchez, T. A. (2004). Uso Eficiente del Agua Agua. *Ponencias Sobre Una Perspectiva General Temática*. Instituto de Investigación y Desarrollo en Agua Potable, Saneamiento Básico y Conservación del Recurso Hídrico.

Scott, C. A., Vicuña, S., Blanco-Gutiérrez, I., Meza, F., and Varela-Ortega, C. (2014). Irrigation efficiency and water-policy implications for river basin resilience. *Hydrol. Earth Syst. Sci.* 18, 1339–1348. doi: 10.5194/hess-18-1339-2014

See, K. F. (2015). Exploring and analysing sources of technical efficiency in water supply services: Some evidence from Southeast Asian public water utilities. *Water Resour. Econ.* 9, 23–44. doi: 10.1016/j.wre.2014.11.002

Stanhill, G. (1986). Water use efficiency. *Adv. Agron.* 39, 53–85. doi: 10.1016/S0065-2113(08)60465-4

Steg, L., and de Groot, J. I. M. (2018). "Environmental psychology: history, scope, and methods," in *Environmental Psychology: An Introduction, 2nd Edn*., eds E. M. Steg, and J. I. M. de Groot (Oxford: Wiley-Blackwell), 1–12.

Steg, L., and Vlek, C. (2009). Encouraging pro-environmental behaviour: an integrative review and research agenda. *J. Environ. Psychol.* 29, 309–317. doi: 10.1016/j.jenvp.2008.10.004

Stern, P. C. (2000). New Environmental theories: toward a coherent theory of environmentally significant behavior. *J. Soc. Issues* 56, 407–424. doi: 10.1111/0022-4537.00175

Stern, P. C., and Dietz, T. (2020). A broader social science research agenda on sustainability: nongovernmental influences on climate footprints. *Energy Res. Soc. Sci.* 60:101401. doi: 10.1016/j.erss.2019.101401

Tang, J., Folmer, H., and Xue, J. (2013). Estimation of awareness and perception of water scarcity among farmers in the Guanzhong Plain, China, by means of a structural equation model. *J. Environ. Manage.* 126, 55–62. doi: 10.1016/j.jenvman.2013.03.051

UN (2015). *UN WATER. Water Scarcity*. United Nations. Available online at: https://www.unwater.org/water-facts/scarcity/ (accessed August 31, 2020).

Varbanov, P. S., and Walmsley, T. G. (2019). Circular economy and engineering concepts for technology and policy development. *Clean Technol. Environ. Policy* 21, 479–480. doi: 10.1007/s10098-019-01683-3

Vieira, P., Jorge, C., and Covas, D. (2017). Assessment of household water use efficiency using performance indices. *Resour. Conserv. Recycl.* 116, 94–106. doi: 10.1016/j.resconrec.2016.09.007

Vitola, A., and Senfelde, M. (2015). The role of institutions in economic performance. *Bus. Theory Pract.* 16, 271–279. doi: 10.3846/btp.2015.498

Voinov, A., and Bousquet, F. (2010). Modelling with stakeholders. *Environ. Model. Softw.* 25, 1268–1281. doi: 10.1016/j.envsoft.2010.03.007

Wang, T., Park, S. C., and Jin, H. (2015). Will farmers save water? A theoretical analysis of groundwater conservation policies. *Water Resour. Econ.* 12, 27–39. doi: 10.1016/j.wre.2015.10.002

Water footprint (n.d.) *What Is a Water Footprint? [Water Footprint Network]*. Available online at: https://waterfootprint.org/en/water-footprint/what-is-water-footprint/ (April 2020).

Willis, R. M., Stewart, R. A., Giurco, D. P., Talebpour, M. R., and Mousavinejad, A. (2013). End use water consumption in households: impact of socio-demographic factors and efficient devices. *J. Clean. Prod.* 60, 107–115. doi: 10.1016/j.jclepro.2011.08.006

Winans, K., Kendall, A., and Deng, H. (2017). The history and current applications of the circular economy concept. *Renew. Sustain. Energy Rev.* 68, 825–833. doi: 10.1016/j.rser.2016.09.123

Xiao, X., Fan, L., Li, X., Tan, M., Jiang, T., Zheng, L., et al. (2019). Water-use efficiency of crops in the arid area of the middle reaches of the Heihe River: taking Zhangye City as an example. *Water* 11:1541. doi: 10.3390/w11081541

Yildirim, B. Ç., and Semiz, G. K. (2019). Future teachers' sustainablewater consumption behavior: a test of the value-belief-norm theory. *Sustainability* 11:1558. doi: 10.3390/su11061558

Yuriev, A., Dahmen, M., Paillé, P., Boiral, O., and Guillaumie, L. (2020). Pro-environmental behaviors through the lens of the theory of planned behavior: a scoping review. *Resour. Conserv. Recycl.* 155:104660. doi: 10.1016/j.resconrec.2019.104660

Zhang, Y., and Xu, Z. (2019). Efficiency evaluation of sustainable water management using the HF-TODIM method. *Int. Trans. Operat. Res.* 26, 747–764. doi: 10.1111/itor.12318

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

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

ORIGINAL RESEARCH
published: 15 February 2022
doi: 10.3389/frwa.2022.834239

An Integrated Quantitative Assessment of Urban Water Security of a Megacity in the Global South

Subham Mukherjee[1], Trude Sundberg[2], Pradip Kumar Sikdar[3] and Brigitta Schütt[1]*

[1] Institute of Geographical Sciences, Physical Geography, Freie Universität Berlin, Berlin, Germany, [2] Q-Step Centre, School of Social Policy, Sociology and Social Research (SSPSSR), University of Kent, Canterbury, United Kingdom, [3] Department of Environment Management, Indian Institute of Social Welfare and Business Management, Kolkata, India

Water security, the access to adequate amounts of water of adequate quality, is and will remain a hugely important issue over the next decades as climate change and related hazards, food insecurity, and social instability will exacerbate insecurities. Despite attempts made by researchers and water professionals to study different dimensions of water security in urban areas, there is still an absence of comprehensive water security measurement tools. This study aims to untangle the interrelationship between biophysical and socio-economic dimensions that shape water security in a megacity in the Global South—Kolkata, India. It provides an interdisciplinary understanding of urban water security by extracting and integrating relevant empirical knowledge on urban water issues in the city from physical, environmental, and social sciences approaches. To do so we use intersectional perspectives to analyze urban water security at a micro (respondent) level and associated challenges across and between areas within the city. The study concludes with the recommendation that future studies should make use of comprehensive and inclusive approaches so we can ensure that we leave no one behind.

Keywords: water scarcity, water access, water quality, governance, intersectionality

OPEN ACCESS

Edited by:
*Jenia Mukherjee,
Indian Institute of Technology
Kharagpur, India*

Reviewed by:
*Mahalaya Chatterjee,
University of Calcutta, India
Gopa Samanta,
University of Burdwan, India*

****Correspondence:***
*Subham Mukherjee
subham.m@fu-berlin.de*

Specialty section:
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

Received: *13 December 2021*
Accepted: *20 January 2022*
Published: *15 February 2022*

Citation:
Mukherjee S, Sundberg T, Sikdar PK and Schütt B (2022) An Integrated Quantitative Assessment of Urban Water Security of a Megacity in the Global South. Front. Water 4:834239. doi: 10.3389/frwa.2022.834239

INTRODUCTION

Water security is defined as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments, and economies" (Grey and Sadoff, 2007, p. 548), which embodies a complex, multi-dimensional, and interdependent set of issues (Wheater, 2015). Water Security represents multiple challenges to twenty first century water management and crucial to achieve Sustainable Development (Cook and Bakker, 2012; UN, 2015). As a Sustainable Development Goal, water security has three primary dimensions: environmental, economic, and social (Giddings et al., 2002). To achieve "sustainability and security" within water security, each of these three dimensions should be addressed. While water scarcity has historically been more severe in rural areas, emerging research has shown a worsening availability and quality of water in urban areas and thus, urban areas are the focus of this study (Maiti and Agrawal, 2005; Mohan et al., 2011; Cook and Bakker, 2012; Mukherjee et al., 2020, 2021). From the rapidly changing urban perspective, the dimension of water security includes a focus ons the need for organizational and institutional flexibility and capabilities to address increasing uncertainty and change, a need for social capital and adaptive governance, and the need for engagement with stakeholders in knowledge exchange (Wheater, 2015). Thus, the interface between the scholars, practitioners and stakeholder communities has been increasingly important for the measurement and management of Urban Water Security (UWS) (Wheater and Gober, 2014). To address and better capture the multidimensional issues related to and driving water security, this study creates a quantitative index based on social, economic, cultural, and bio-physical dimensions of water security, specifically focusing on water availability, water accessibility, water quality, and risks associated with water.

UWS issues are particularly pertinent and show insufficient conditions in megacities in the developing world due to rapid and unplanned demographic and economic growth. India is one of the emerging economies where UWS issues are non-satisfying (Shaban and Sattar, 2011; Shaban et al., 2020; Chatterjee and Roy, 2021). In urban India, the rapid population growth combined with increasing levels of consumption and pollution has increased water insecurities (Shaban and Sattar, 2011; Mukherjee et al., 2018). UWS here relates to both the physical-environmental and societal barriers to access, availability, and quality of water for drinking, food production, hygiene, and sanitation (Obani and Gupta, 2016). Among the megacities in India, we chose Kolkata (under jurisdiction of Kolkata Municipal Corporation or KMC) as our study area. Kolkata is a growing megacity that faces rising pressures on water-environmental provision due to the rapid population growth coupled with sporadic urbanization and resultant governance and infrastructural issues despite of having enough water resources (Mukherjee et al., 2018, 2020, 2021).

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 in Kolkata (Mukherjee et al., 2018). 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, within the city or in fringe areas (Kundu, 2003; Mukherjee et al., 2020). Despite of the fact that the right to water and sanitation was recognized as a human right by the United Nations General Assembly on 28 July 2010 (UN, 2010) and recognized by UN's sustainable development goal 6 (SDG) (Mukherjee et al., 2020), social inequities in (mega)cities like Kolkata play an important role in water and sanitation-related risks. With informal settlements and socially deprived areas generally having lower levels of UWS than other parts of the city (WHO, 2020). Marginalized groups, which include women, children, refugees, indigenous people, disabled people, and many others, are often overlooked, and sometimes face discrimination, as they try to access and manage the safe water they need (Mukherjee et al., 2020). For example, gender roles and relations can be important as an explanatory factor to analyze how access, needs, and use of water are shaped in every society (Wallace and Coles, 2005; Ray, 2007). Risks associated with water are higher among women and transgender people in comparison to their male counterpart (Denton, 2002; MacGregor, 2009; Demetriades and Esplen, 2010). Insecurity related to water includes vulnerability due to natural disasters like floods and droughts. In addition, it influences and is influenced by socio-economic pressures—which leads to increased water insecurity for marginalized groups, including women, girls, and trans individuals (Saravanan, 2010). The transgender and other gendered communities, despite of accordion of the Supreme Court of India in 2014, the community is still waiting for gender-neutral public toilets (Gopalakrishnan, 2016). Pangare (2016) argues that water security for the poor cannot be achieved without considering socio-economic factors as a determining issue (Pangare, 2016; WWAP, 2019).

Urban Water Security Assessment so Far

Previous studies in different disciplines have highlighted that vulnerabilities and experiences of UWS vary according to a range of bio-physical and socio-economic factors (Mukherjee et al., 2021). UWS in relation to population size and growth has been the focus of many studies from the 1990s (Vörösmarty et al., 2000; Cook and Bakker, 2012). Most recent studies have demonstrated the development of numerous definitions and assessment frameworks for UWS over the past decade (Denton, 2002; Lundqvist et al., 2003; MacGregor, 2009; Demetriades and Esplen, 2010; Vorosmarty et al., 2010; Sullivan, 2011; Truelove, 2011; Aihara et al., 2015; Muller, 2016; Pangare, 2016; Romero-Lankao and Gnatz, 2016; Thompson, 2016; Harris et al., 2017; Hellberg, 2017; Allan et al., 2018; Castán Broto and Neves Alves, 2018; Shrestha et al., 2018; van Ginkel et al., 2018; Aboelnga et al., 2019, 2020; Sultana, 2020). It is proven that UWS is driven by a complex set of biophysical and social factors—which needs to be dealt with together, rather than independently. However, there is still no agreed-upon understanding of how to hypothesize and quantify an assessment framework to measure the current state and the complex dynamics of UWS particularly at the urban level (Mukherjee et al., 2021). This research tries to fill this gap.

The existing measurement frameworks of UWS have been conceptualized in various ways; some focus on risks, while others have adopted broader aspects with a focus on the management of water as a resource for fulfilling human needs only (Clement, 2013; Garrick and Hall, 2014; Giordano, 2017). Several studies have stressed the lack of quantitative and comprehensive assessments of UWS and applications that can be used at the micro level (Grey and Sadoff, 2007; Cook and Bakker, 2012; Srinivasan et al., 2017; Mukherjee et al., 2021). Moreover, some studies show that given the difficulties and shortcomings, such as lack of updated legal tenures, socio-cultural exclusion, and inadequate survey reports, associated with accurately measuring the proportion of the population without access to clean and safe water, it is probable that the proportion thought to have access is grossly overestimated (Nganyanyuka et al., 2014; Satterthwaite, 2016; Adams, 2017). This lack of accurate data on access to clean and safe water indicate the considerable disparity in dynamics of UWS to address urban water challenges effectively and provide decision-makers with robust policy instruments and measures to achieve UWS from the bottom-up approach (Rouse, 2013; Allan et al., 2018). It is therefore important to improve the assessment frameworks to better understand disparities in everyday water-access and practices across different scales especially for all in an urban setup.

The approaches of quantitative index-based assessment and the corresponding dimensions and issues of urban water mentioned in the previous studies are summarized in **Appendix A** of the electronic Supplementary Material. This list shows that any attempt to assess UWS needs to consider the intersecting characteristics of bio-physical environment, society, and communities together along with social, economic, ethnic, religious, caste, gender sexuality characteristics—to ensure inclusion across divisions and levels of insecurity (Sullivan, 2011; Truelove, 2011; Thompson, 2016; Harris et al., 2017; Hellberg, 2017; Castán Broto and Neves Alves, 2018; Sultana, 2020).

Aims and Objectives of the Study

This study aims to assess UWS from a quantitative bottom-up approach. We will include the factors behind the multiple intersections in Kolkatas, India, covering one of the world's most densely populated areas, characterized by complex inherited social structures characterized by diverging communities and religious groups (Mukherjee et al., 2018, 2020). The approach sheds lights on the complexity and interconnectedness of water security issues. For example, we want to carve out, how water access issues for multiple social identities at the micro level (i.e., intersections of caste, gender, and socio-economic status) correspond with macrolevel structural factors (i.e., poverty, racism, and sexism) to produce unequal accessibility to water in Kolkata. Therefore, the objective of this study is to develop a quantitative assessment index within the framework of water (in)security in urban areas that can capture the complex interrelationships present between bio-physical and social dimensions (for details see Mukherjee et al., 2021) within water security.

STUDY AREA

Kolkata city (22°28′00″-22°37′30″ N and 88°17′30″-88°25′00″ E) is the capital of the state of West Bengal (**Figures 1**, **2**) situated on the east bank of River Hugli in the deltaic Bengal Basin developed by the action of the Ganga-Brahmaputra River system and nearly 120 km away from the Bay of Bengal. The city area as governed under Kolkata Municipal Corporation (KMC) covers about 205 km^2 and is divided into 16 boroughs or administrative blocks, having 21 assemblies and 3 parliamentary constituencies and 144 wards. Population counts 4,496,694 inhabitants and a population density of 24,760 km^{-2}. The ratio of the population is 956 females for every thousand males; the literacy rate is 81.31%. Every day, about 6 million people (floating population) come to Kolkata for work, business, and other purposes (Mukherjee et al., 2021). Within the KMC area, there are little more than 1 million households (KMC report, 2012a). The Census-2011 of India shows that one third of the total population of KMC live in semi-permanent houses within 5,600 (c. 1.141 million residents) deprived areas often referred to as slums (officially known as "basti") comprising a total area of 25.95 km^2 (Mukherjee et al., 2020). We have carried out in depth analysis focusing socially excluded areas, often defined as "slums," elsewhere (see Mukherjee et al., 2020). Hence, we exclude the repetition in this research article. In this paper, we aim to have an inclusive approach for which we took the entire survey sample across various socio-economic (i.e., gender, religion, caste etc.) and spatial demographic variations within the study area (i.e., KMC area) as representative population, where "slums" and other "non-slums" households were given equal priorities for analyses. Most of these houses do not have direct piped water supply or toilets (Mukherjee et al., 2020). The number of public toilets in whole KMC area totals 375 of which. The statistics of boroughs of KMC are given in **Appendices B, C**. Mukherjee et al. (2018) documented detailed bio-physical and social characteristics of Kolkata city and its water security issues. **Figure 2** emphasizes the importance of looking at intra city variations when it comes to analyzing water security issues, exemplified by variations of gender inclusive public toilets and the number of basti in the different wards of the city. These maps outline the background and a starting point for our analysis as we see how social issues, like population density and the existence of WaSH facilities, for example, are related.

METHODS

Data

Primary Data: Household Survey

The primary data is based on a household survey using Stratified Random Sampling method. Data were collected from 45 households from each of the Boroughs of Kolkata Municipal Corporation (KMC) area. Altogether 720 households were surveyed within November-December 2018.

Based on the definition of "Water Security" by Grey and Sadoff (2007), this study constructs an Urban Water Security assessment framework to score 4 major components of water security: water availability, water accessibility, water quality and water risks and hazards. The details of each variable are given in the **Appendix D**.

The Survey questionnaire (**Appendix D**) forming the basis of the household survey consists of 47 questions divided into 5 segments. The first four segments cover different components of water security (*Water Availability*: 11 questions, *Water Accessibility*: 8 questions, *Water Quality*: 2 questions, and *Water Risks and Hazards*: 11 questions). The last segment includes 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.

The four components of water security cover all relevant aspects of the integrated urban water security index (Grey and Sadoff, 2007; Mukherjee et al., 2021) as well as, together with socio-demographic indicators form the assessment framework of urban water security within Kolkata Municipal Corporation area. We combined environmental (bio-physical) and socioeconomic indicators (Hoekstra, 2000; OECD, 2016) for each of the water security components, which grouped first into the water security component-scores (at the respondent level) and then aggregated into ward level scores and finally averaged into brough level scores to create the Urban Water Security Index at the borough level.

Due to the ethnic and linguistic diversity of Kolkata, interviewers with a range of language spoken, socio-economic, and ethnic background were recruited, allowing us access and

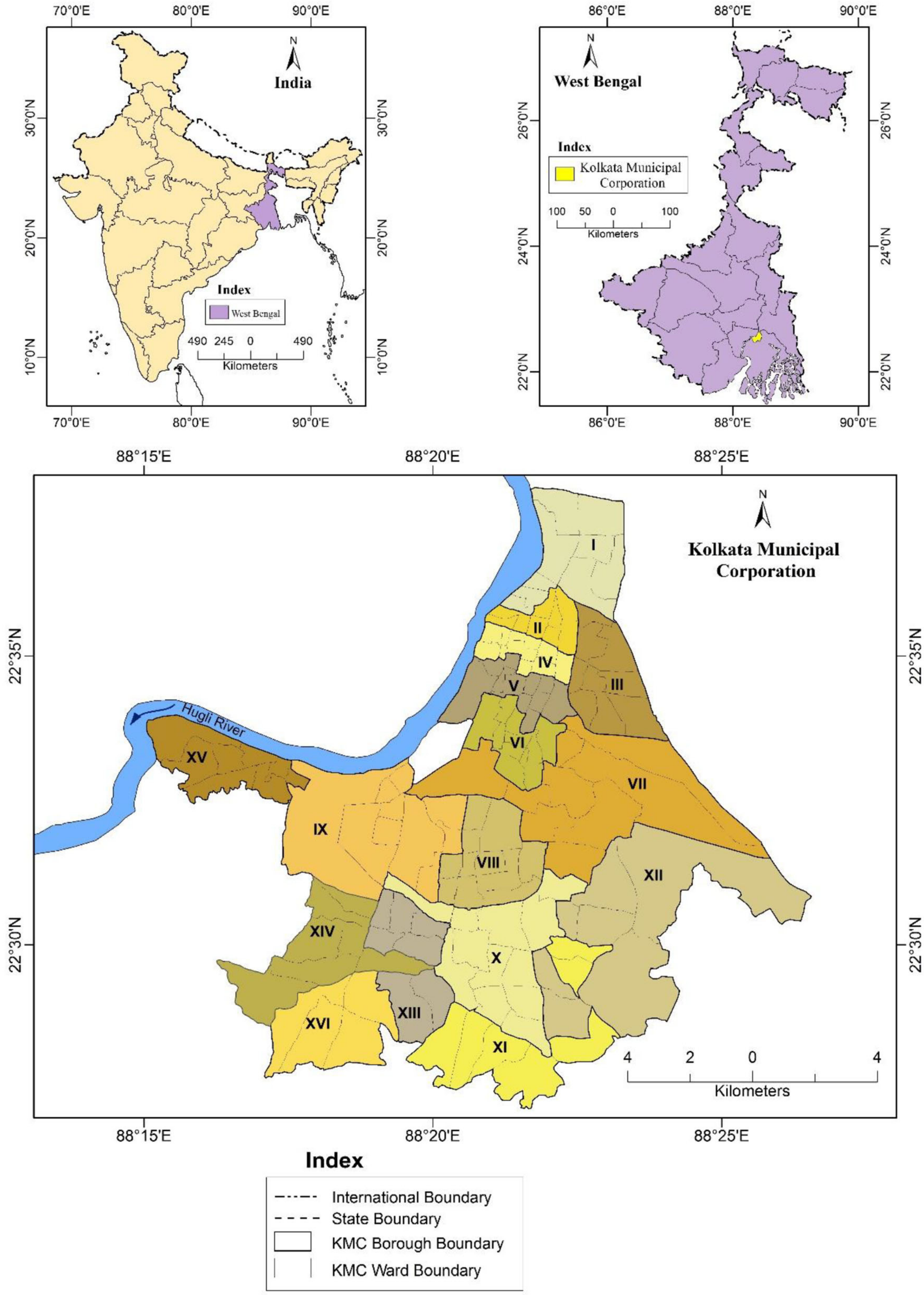


FIGURE 1 | Location of Kolkata Municipal Corporation (KMC) boroughs (featuring the wards associated in a borough) within West Bengal, India. Roman numbers mark the borough numbers and darker tones represent higher values (Source: Mukherjee et al., 2018).

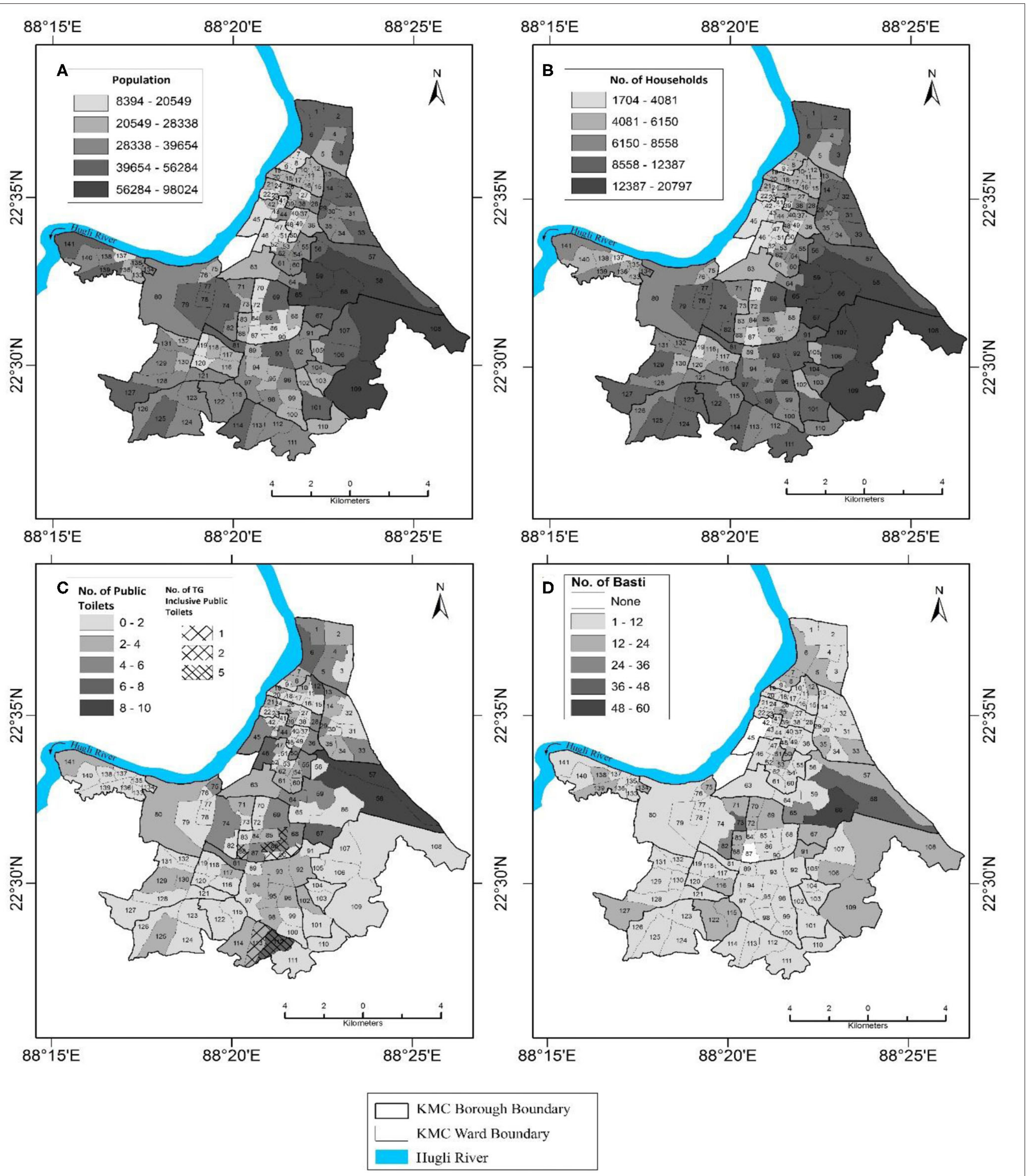


FIGURE 2 | Demographic features of the Kolkata Municipal Corporation (KMC) area (Wardwise). **(A)** Population, **(B)** Number of Households, **(C)** Number of Public Toilets along with number of Transgender (TG) inclusive Public Toilets, and **(D)** Number of basti (Sources: Census of India, 2011; Department of Slum Development and Department of Water Engineering, Kolkata Municipal Corporation, India).

higher levels of rapport with respondents who we otherwise would not have been able to interview due to distrust with members of higher caste/different ethnicity etc. Any time a suitable sample is used, it may confound the analysis because subjects were chosen based on availability rather than being representative of the full population. The interviewers undertook training to ensure they learnt about the crucial (both bio-physical and social) dimensions of water security. Further, they were trained how to avoid biased language as well as ethical issues that may arise during an interview. Survey training activities were particularly important to maintain survey quality and gender sensitization because our survey included the entire gender spectrum to be notified on record. Interviews were conducted based on the availability of respondents, which might affect how representative the sample is. The average survey response rate across the city was about 80% which varied across the study area.

Secondary Data

Secondary data were collected from the Department of Water Investigation and Department of Urban Development of Government of West Bengal (data on amount of treated water, urban water supply, distribution, and infrastructures). Additionally, the data from the Kolkata Municipal Corporation (KMC) (Department of Slum Development, Department of Water Engineering) (data on "Slum" population, housing and public toilets), West Bengal Pollution Control Board (WBPCB) (data on surface water quality) and Kolkata Municipal Development Authority (KMDA) were also collected (data on groundwater quality, urban water supply and distribution network at the boundary areas of Kolkata Municipal Corporation). These data contained information on the components of water security within Kolkata Municipal Corporation (KMC) area.

Data Processing

Initial Data Processing

We assigned variables' scores on a 0–10-point scale of water security, where 0–2 denotes "Very Insecure," 2–4 denotes "Insecure," 4–6 denotes "Around acceptable threshold" and 8–10 denotes "Very Secure" state of UWS). These categories and cut off values for *security status* were based on the "urban water security dashboard" proposed by van Ginkel et al. (2018). Here, 5 (median value between 0 and 10) is considered as the "threshold" point. Therefore, score higher than 5 denotes *secure* status of UWS and lower than 5 indicates *insecure* status of UWS. Aggregation from each level to the next was done by calculating the arithmetic mean. Finally, the borough level scores of the four components of water security were further combined into one water security index (borough level), which determined the final ranking of the KMC boroughs.

Principal Component Analysis

Principal Component Analysis (PCA) allows us to identify patterns and components that enhance our understanding of water security (Raschka, 2015). In this case, it helps us to identify which factors come together to create the crucial components of water security, and then allowing us to create an index to measure it (Aihara et al., 2015; Shrestha et al., 2018). Each of the PC axis or factors (with high loadings on one or more variables) may be representing an independent source of variation in the data (Vyas and Kumaranayake, 2006). 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 (Filmer and Pritchett, 2001). This approach allows the determination of the most appropriate weightings for each variable to derive an index which captures maximum variation (Filmer and Pritchett, 2001; Vyas and Kumaranayake, 2006; Raschka, 2015; Shrestha et al., 2018).

Calculation of Urban Water Security Index

Urban Water Security Index (UWSI) scores have been calculated integrating scores of variables of *Water Availability, Water Accessibility, Water Quality*, and *Water Risk and Hazards* variables from the survey data collected across the city. Here the objective is to analyse the interrelationship between UWSI scores and socio-demographic parameters (such as gender, religion, monthly income, caste, ethnicity, occupation, education, and household type) within boroughs across the city.

The Urban water security index (UWSI) at the borough level was calculated as:

$$\text{UWSI} = (\text{Avl}^{*}\text{w1}) + (\text{Acs}^{*}\text{w2}) + (\text{Wqt}^{*}\text{w3}) + (\text{Wrh}^{*}\text{w4}) \quad (1)$$

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 1) for each variable.

Finally, the UWSI scores were used to categorize each borough on the 0–10-point scale (Status of security status as discussed earlier) classifying the status of urban water security.

Interrelationships Between UWSI and Socio-Demographic Variables

Indicator scores were aggregated to an Urban Water Security Index (UWSI) at the borough level, (we preferred borough level index to be able to access to government data at the borough level than that of 144 wards). We then studied the coherence between UWSI's scores and the sociodemographic characteristics of the Kolkata Municipal Corporation area, through statistical analyses (Pearson's correlation and crosstabs-contingency tables) using SPSS.

RESULTS

Principal Component Analysis

The aggregated values of the four water security components were analyzed using Principal Component Analysis (PCA), and four principal components (PCs) were identified. The choice of 4 components was based on each of the PCs explaining data variation between 13.02 and 36.23% and accounting for 100% of the total variance (**Table 1**). In the analysis of the variables

TABLE 1 | Total variance explained.

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	1.45	36.23	36.23	1.45	36.23	36.23	1.43	35.72	35.72
2	1.10	27.58	63.82	1.10	27.58	63.82	1.12	28.10	63.82
3	0.93	23.16	86.98						
4	0.52	13.02	100.00						

Extraction method: principal component analysis.

TABLE 2 | Communalities.

	Initial	Extraction
Water availability	1.000	0.742
Water accessibility	1.000	0.738
Water quality	1.000	0.614
Water risk and hazards	1.000	0.458

Extraction method: principal component analysis.

TABLE 3 | Factors loadings (rotated component matrix) of the first and second principal components.

	Principal component	
	1	2
Water availability	0.837	0.204
Water risk and hazards	0.667	−0.113
Water accessibility	0.332	0.792
Water quality	−0.416	0.664

Extraction method: principal component analysis. rotation method: varimax with kaiser normalization[a].

[a]Rotation converged in 3 iterations.

studied, the resulting first principal component PC1 explained 36.23% of the data variability, while PC2 explained 27.58% of the variance. The remaining principal components PC3 and PC4 accounted for 10–20% of the variance. Communalities statistics revealed that >70% of the variance can be explained by the factor *Water Availability* and *Water Accessibility*, >60% of the variance by the factor *Water Quality* and >45% of the variance can be explained by the factor *Water Risk and Hazards* (**Table 2**). This analysis confirms the assumptions of our study that these dimensions are the crucial dimensions of water security, and we go on to look at what social and bio-physical dimensions are associated with higher or lower levels of security along these dimensions.

The UWSI aggregates the components of water security into a single index which represents the set of information collected through survey, and we argue, that this index improves assessment of the multidimensional issues affecting water security. The factors loadings (**Table 3**) associated with the variables indicate which are the most important of the different water security components in terms of distinguishing between different levels of wellbeing and so which variables the index is most sensitive to Filmer and Pritchett (2001), Vyas and Kumaranayake (2006), Raschka (2015), Shrestha et al. (2018). These factor loadings are the weights assigned to each variable in Equation 1 to calculate UWSI values. *Water Availability* (0.837) and *Water Risk and Hazards* (0.667) show the highest factor loadings and are the highly correlated with the first principal component PC1; correspondingly, they are the best single-dimensional descriptors of the dataset. As the data have been scaled and centered, the resulting principal components and index of values based on this component are all relative values enabling comparisons, however their absolute values without validity (**Tables 1–3**). In contrast, the variables which were less important in the index still contributed to the distinction, including *Water Accessibility* (0.332) and *Water Quality* (−0.416), which is why we still include them.

Spatial Distribution of UWSI Values

After calculating UWSI values using the weights of PC1, the results were tallied with individual water security component scores to compare with UWSI. Distribution of scores of UWSI values in comparison to scores of the components of water security within Kolkata Municipal Corporation (KMC) area at the respondent level (**Figure 3**) shows the scores of UWSI (mean = 7.33; median = 7.33; Interquartile Range IQR = 8.56–6.20); data are normally distributed without skew and fall into the range of status of water security within Kolkata Municipal Corporation area. Skewed data distribution occurs for the UWS components: For *Water Availability*, data is right-skewed (mean = 4.60; median = 4.43; IQR = 5.33–4.08), whereas *Water Quality* data has the highest variability in scores among all the water security components and is potentially left-skewed (mean = 6.72, median = 7.37; IQR = 5.65–7.70). *Water Accessibility* (mean = 4.88; median = 4.91; IQR = 5.34–4.50) has a low variability and falls into the range of "Around acceptable threshold." *Water Risk and Hazards* (mean = 6.99; median = 7.11; IQR=6.55–7.70) ranges within the "Secured" status of water security and having almost identical mean and median. From this we can see the importance of disaggregating the index to understand which component is driving and influencing the overall averages, here we see the overall higher mean of *Water Risk and Hazard,*

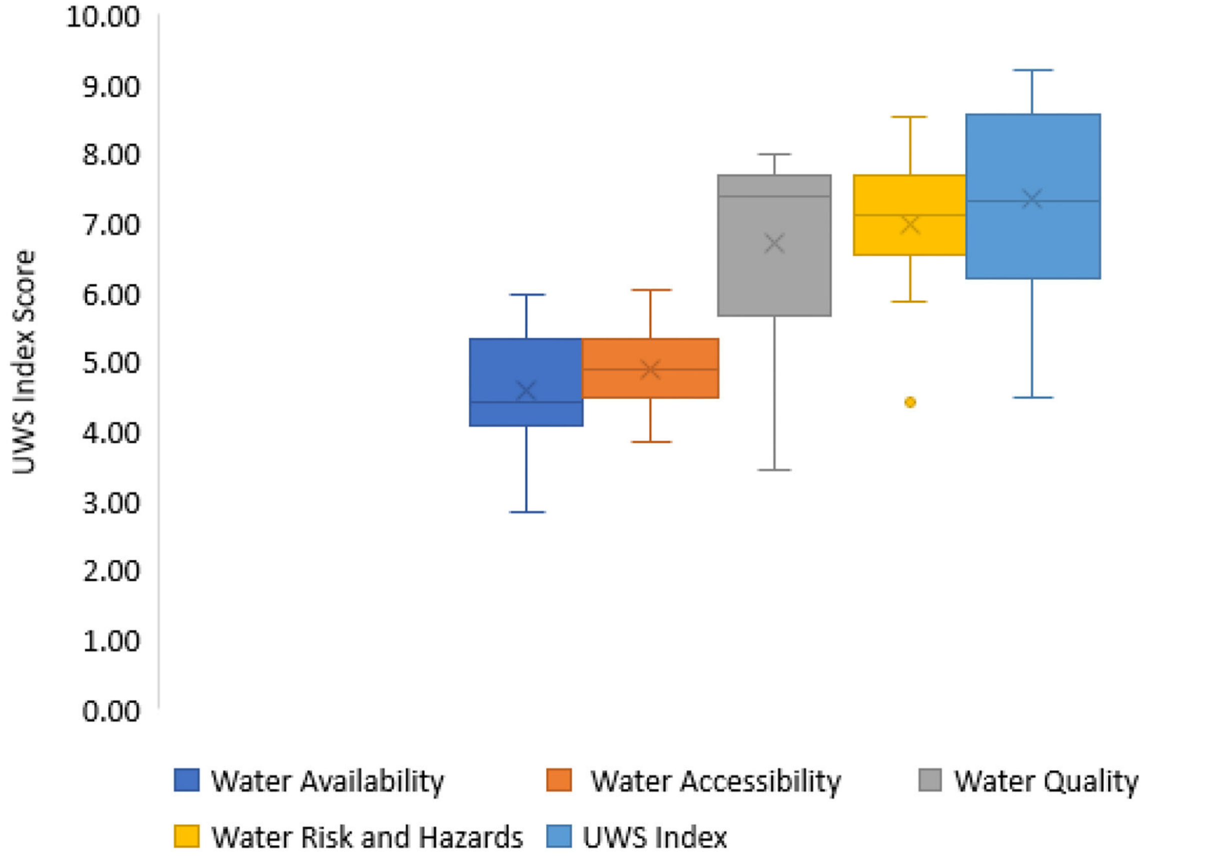


FIGURE 3 | Distribution of scores of Urban Water Security (UWS) Index (along the Y-axis) and Components of Urban Water Security (*Water Availability, Water Accessibility, Water Quality,* and *Water Risks and Hazards*) (along the X-axis) within Kolkata Municipal Corporation (KMC) area at the respondent level. Data source: Survey data.

compared to lower overall "security" along *Water Accessibility and Water availability*.

Further delving into the components of the UWSI index, we find that (*Water Availability, Water Accessibility, Water Quality,* and *Water Risks and Hazards*) (**Figure 4**) the scores for *Water Availability* and *Water Risks and Hazards* played a major role in the overall status of the UWS of the boroughs, thus explaining the overall high mean and median for the UWSI. High values of *Water Risks and Hazards* component dominate the final index scores for all the boroughs. **Figure 4** highlights the intra city variations across the components and underlines the need for researchers to take intra city variation into account when studying water security. For the *Water Risks and Hazards* component, boroughs VIII and XV show highest UWSI scores within Kolkata Municipal Corporation (KMC) area (borough VIII = 9.21, borough XV = 9.05). For borough VIII, both *Water Risks and Hazards* and UWSI score are >8. For borough XV, UWSI score is higher than 9 despites of the score for *Water Quality* amounts 3.44 which means "Insecure." Scores of Water *Quality* component have no impact on the total UWSI scores for boroughs IX and X. These boroughs show the lowest scores in *Water Quality* within Kolkata Municipal Corporation (KMC) area (boroughs IX = 5.11 boroughs X = 3.66), but the urban water security status for borough IX and X are still "secured" because of the higher scores in *Water Risks and Hazards*. In borough VI the value for the *Water Quality* component totals 7.89, however, due to its low score in *Water Availability* (3.65), it only receives an "Around acceptable threshold" status of UWS. For borough XIII UWSI score (4.48) is ranked as the lowest within Kolkata Municipal Corporation (KMC) area, coinciding with the lowest score in *Water Availability* (2.85).

Figure 5 shows borough wise distribution of % of respondents with different status of Urban Water Security (UWS) across the Kolkata Municipal Corporation (KMC) area. The highest percentage of respondents projected as "Very Secured" status of UWS are in borough VIII (>86%). Borough I has the maximum respondents with "Secured" status. No respondent in borough VI and XIII is falling within "Very Secured" status of UWS. More than 2% of respondents within borough XIII are falling into "Very Insecure" status of UWS and this is the only borough which has respondents with "Very Insecure" status of UWS. Most respondents (39.16%) within the whole survey dataset are falling within "Very Secured" status of UWS. Boroughs I, IV, VIII, IX,

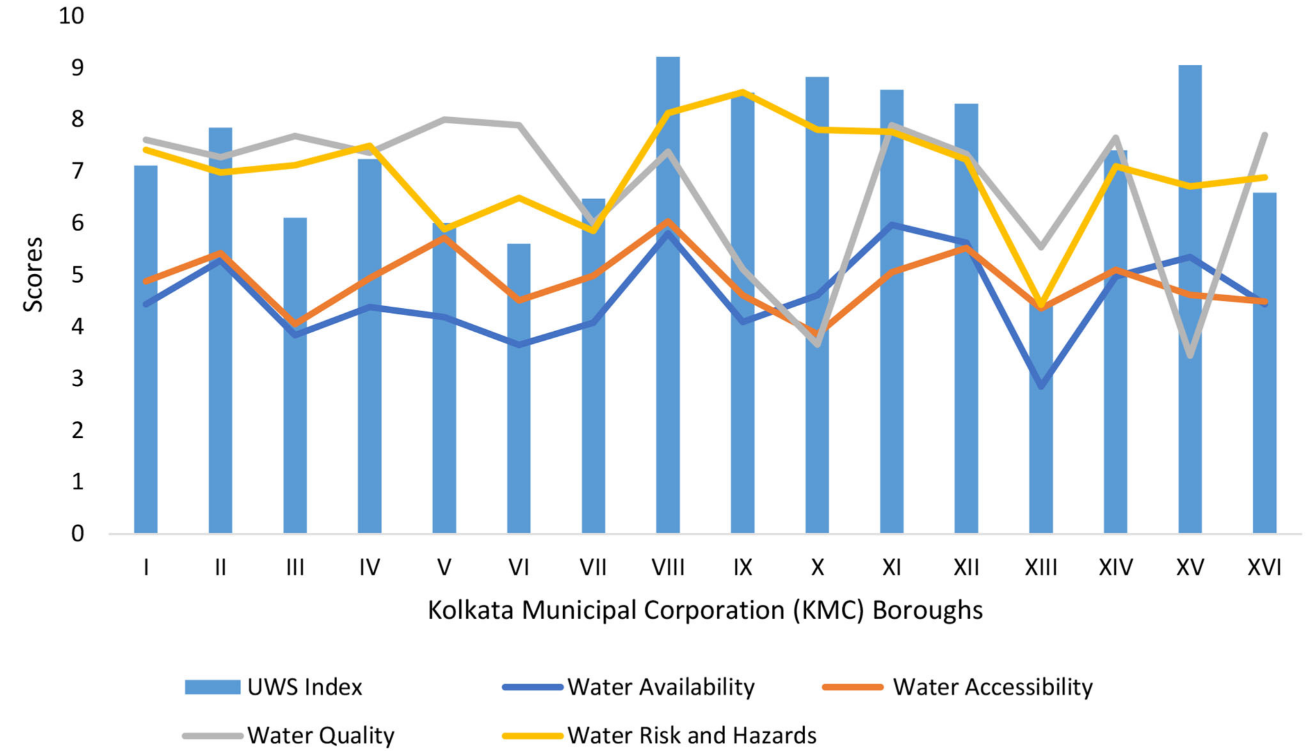


FIGURE 4 | Borough wise distribution of average scores of Urban Water Security (UWS) Index and Components of Urban Water Security (*Water Availability, Water Accessibility, Water Quality, and Water Risks and Hazards*) within Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Data source: Survey data.

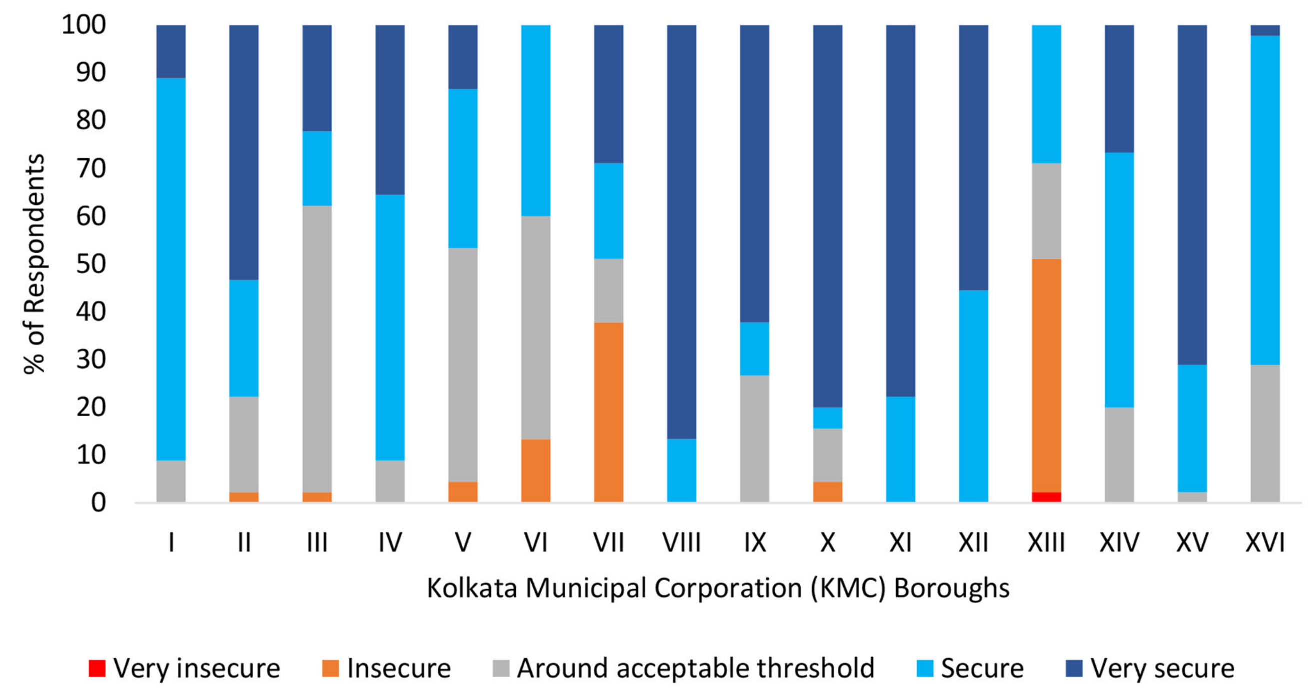


FIGURE 5 | Borough wise distribution of % of respondents with different status of Urban Water Security (UWS) across Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Data source: Survey data.

XI, XII, and XV–XVI have no respondent with either "Very Insecure" or "Insecure" status of UWS.

As seen in **Figure 5**, another crucial factor to take into account is highlighted when we look at intra borough variation of the UWS components.

Looking at the geographical distribution of the components of UWS (*Water Availability, Water Accessibility, Water Quality,* and *Water Risks and Hazards*) we can better appreciate how they vary across boroughs in the KMC area (**Figure 6**). For *Water Availability*, no borough has entirely either "Very Secure" or "Very Insecure" status of UWS. Most boroughs have "Secure" status, except boroughs IX, XIV, and XV where the UWS status is limited to "Around acceptable threshold." Borough XV has the same "Around accepted threshold" status of UWS for *Water Accessibility* scores, where borough I is in the "Very Secured" status. The rest of the boroughs are "Secured" with *Water Accessibility*. Variations are also less for *Water Risks and Hazards* component of UWS across KMC. In this case, boroughs XIV and XVI are within "Around accepted threshold" status and broughs I, II, and III are in "Very Secure" status of UWS, where rest of the boroughs are having "Secure" status for *Water Risks and Hazards*. Borough wise scores for *Water Quality* vary more than other components of UWS across the entire KMC area. Boroughs IV and XIII are within "Very Secure" status, boroughs II, III, and VII are within "Around accepted threshold" status and the rest are in "Secure" status of UWS.

By using borough wise UWS index scores we can observe the combined effect all component of UWS across the KMC area (**Figure 7**). The UWS index scores appear to be within "Secure" status for the boroughs I–V and VII in the north-central part of KMC area and boroughs XIV and XVI in the southern part of KMC area. For boroughs VI and XIII, the UWS index scores fall within the "Around accepted threshold" status. However, boroughs VIII-XII and XV in the southern part of KMC fall within "Very Secure" status of UWS.

Interrelationships Between Index Values and Socio-Demographic Variables

Pearson's r

We calculated Pearson correlation coefficients to assess the strength and direction of correlations between socio-demographic variables (Independent variables), urban water security (UWS) components (*Water Availability, Water Accessibility, Water Quality, and Water Risks and Hazards*) and the UWS Index (Dependent variables) (**Table 2**) within the Kolkata Municipal Corporation (KMC) area. There are statistically significant correlations in the data between the UWSI values with all the components of water security variables along with type of households, number of members in the households, caste, and employment status of the respondents ($\alpha < 0.01$) (**Table 4**). UWSI values also correlate with *Ethnicity* ($\alpha < 0.05$). *Water Availability* component of UWS shows statistically significant correlations with other UWS components and types of households, monthly household income, caste, ethnicity, occupation, gender, and the education levels of the respondent and other family members. Gender of the respondent also correlates with the *Water Quality* and *Water Risks and Hazards* components of UWS ($\alpha < 0.01$). Employment status and religion of the respondent only correlate with *Accessibility* component of UWS ($\alpha < 0.01$). There are statistically significant relationships between *Accessibilit*y component of UWS and education level of the respondent, *Water Quality* variables and types of households, education levels of both the respondents and their family members ($\alpha < 0.05$). Castes of the respondents statistically corelate with all the components of UWS. Number of members in the household and *Water Risks and Hazards* also have a statistically significant relationship ($\alpha < 0.01$). The survey data do not provide statistically significant relationships between the dependent variable UWSI scores and the independent variables such as monthly household income, religion, occupation, employment status, gender, and the education levels of the respondents ($\alpha > 0.05$). High income, caste, education, and occupational level correlate with higher levels of UWS. Furthermore, religion, ethnicity and gender also matter as being a Hindu, Bengali speaker and cis-man is associated with higher UWS.

Cross Tabulation

The Cross tabulation of survey data (**Appendix E**) reveals the percentages of respondents based on its different socio-demographic characteristics (such as caste, ethnicity etc.) within different categories of UWSI scores (*Very Insecure* to *Very Secure*) as shown by the bivariate analysis in the previous section (chapter 4.3.1). The main findings from the cross-tabulation analysis are as follows:

Household Types

Respondents having their own house constitute the majority in the *Very Secure* status of UWS. In contrast, respondents dwelling in semipermanent houses in deprived areas are found in the *Very Insecure* status of UWS.

Monthly Household Income

Forty seven percentage of the respondents from the higher income group (monthly income >25,000 INR), 33.3% of the respondents from the middle income (monthly income 10,000–25,000 INR), and 16.7% of the respondents from the lower income group are within the *Very Secure* status of UWS. However, the remaining respondents from the lower income group are within the *Very Insecure* status of UWS.

Caste

86.2% of the respondents from general (upper) caste and 13.8% of the respondents from scheduled caste/scheduled tribes/other backward castes (SC/ST/OBC) are within the *Very Secure* status of UWS. Respondents from general caste are the majority (86.2%) in the *Secure* status of UWS than the SC/ST/OBC (12.9%) respondents.

Ethnicity Based on Languages Spoken

81.9% of Bengali speaking respondents and 17.4% of Other Indian languages speakers are in the *Very Secured* status of UWS. Conversely, 0.3% of Bengali speakers, and 0.8% of total *Other*

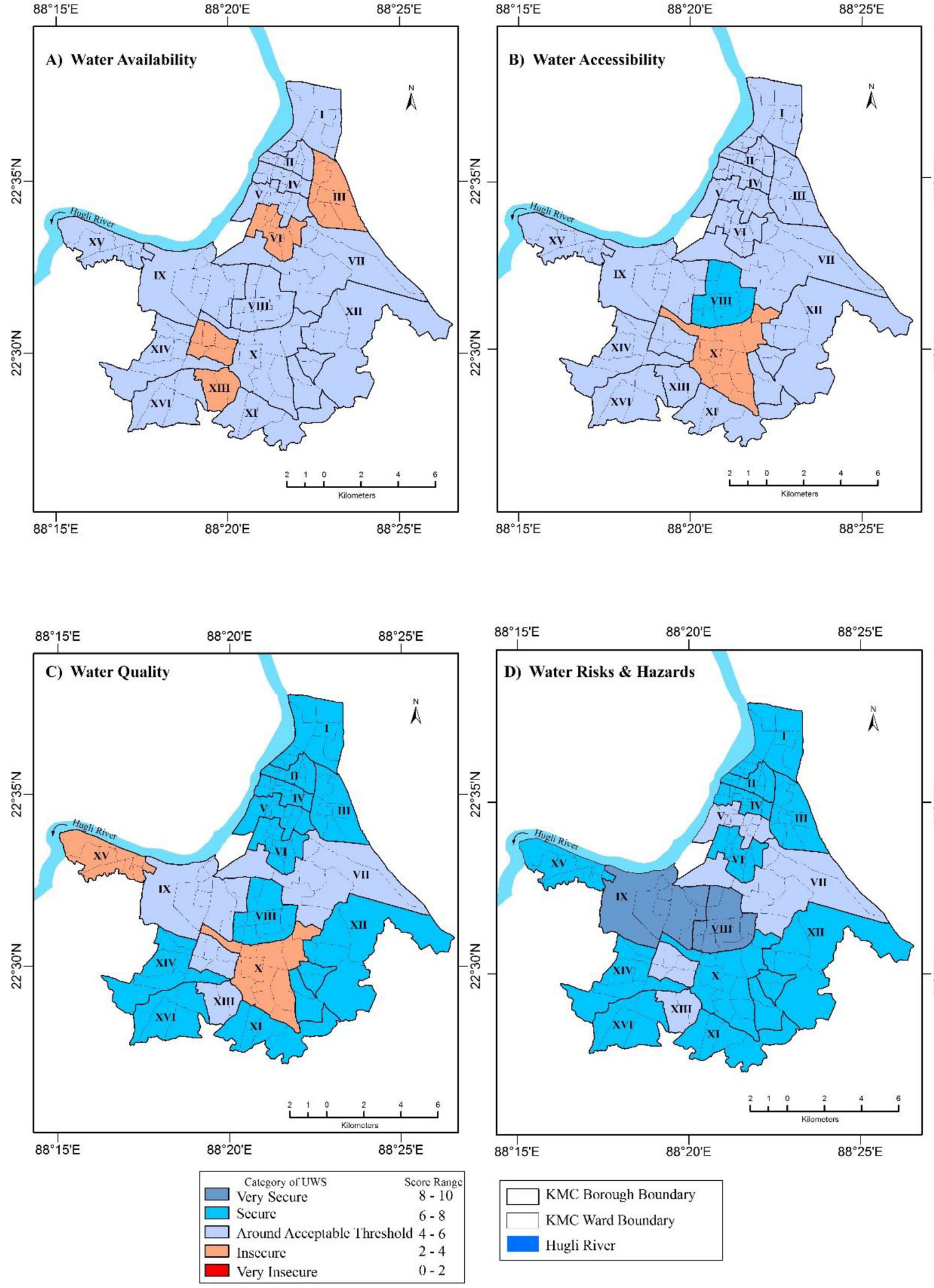


FIGURE 6 | Urban Water Security (UWS) status associated with each component [**(A)** *Water Availability*, **(B)** *Water Accessibility*, **(C)** *Water Quality*, and **(D)** *Water Risks and Hazards*] of UWS within each borough of Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Data source: Survey data.

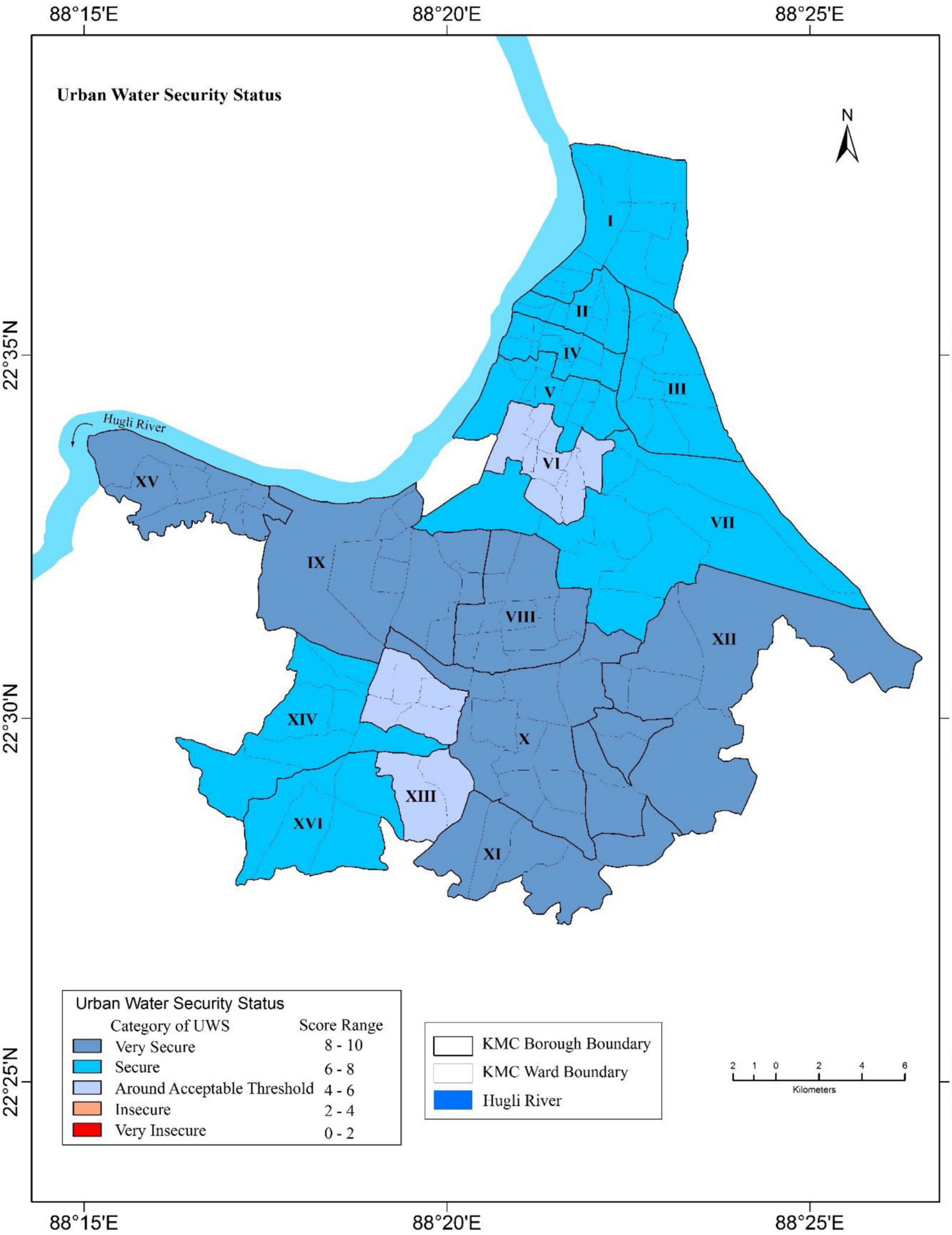


FIGURE 7 | Borough wise distribution of UWS Index status within Kolkata Municipal Corporation (KMC) area. Roman numbers mark the borough numbers. Data source: Survey data.

TABLE 4 | Pearson correlation coefficient (*r*) to assess the linear correlation between urban water security index scores, the components of urban water security (*Water Availability, Water Accessibility, Water Quality, Water Risks and Hazards*) and Socio-demography within Kolkata Municipal Corporation (KMC) area (*n* = 720).

		Availability	Accessibility	Water quality	Water risks and hazards	Type of household	Number of members in the house	Monthly household income	Caste	Ethnicity	Religion	Employment status	Occupation	Employment status of the family members	Highest level of education in the family	Education level of the respondent	Gender
Components of urban water security	Water availability	1	0.271**	−0.128**	0.303**	0.384**	–	0.269**	0.148**	0.125**	–	0.205**	0.162**	–	0.346**	0.107**	−0.114**
	Water accessibility	0.271**	1	0.290**	–	0.261**	–	0.221**	−0.086*	–	0.180**	0.220**	–	0.093**	0.136**	0.074*	–
	Water quality factor	−0.128**	0.290**	1	–	−0.084*		0.105**	−0.074*	−0.130**	–	–	−0.128**	–	−0.090*	0.082*	−0.145**
	Water risks and hazards	0.303**	–	–	1	0.169**	−0.104**	0.195**	0.128**	–	–	–	0.134**	–	0.194**	0.100**	0.124**
UWS index scores		0.801**	0.722**	−515**	0.642**	−0.074 **	−0.110**	–	−0.098**	−0.088*	–	−0.123**	–	–	–	–	–

*Data source: Survey (2018–2019). *Marking 95% confidence level, **marking 99% confidence level.*

Indian language speakers are within the *Very Insecure* status of UWS.

Religion

83.3% of Hindu respondents and 11.6% Muslim respondents are having *Very Secure* status of UWS. In contrast, *Insecure* status of UWS is higher among Muslim respondents (40%) than Hindu respondents (10%).

Occupation

Respondents who do household works are the most water secured ones, while students and those working in unorganized business/jobs are the least water secured respondents.

Level of Education

34.7% of the respondents with a college/bachelor's degree have the *Very Secure* status of UWS, while only 2.9% of the Postgraduate degree holders are the least water secured.

Gender

Within the *Very Secure* status of UWS, 37.7% of cis-males build the majority. Simultaneously, 9.6% of cis-female, 5% of intersex, 13.2% of cis-male, and 13.7% of trans(gender) respondents are within the *Insecure* status of UWS, while 0.8% of the cis-male respondents and 0.9% of the trans(gender) respondents are within the *Very Insecure* status *of UWS*.

DISCUSSION

This research quantifies the spatial distribution of urban water security (UWS) of Kolkata city through a novel index-based assessment framework that encapsulates both bio-physical and social dimensions. In this discussion section, we discuss the explanations and factors driving the spatial variations of UWS index scores, based on the individual components as well as the overall scores of the quantified UWS index and their interrelationships. This section also discusses the study area specific findings from the UWS index, despite of the current limitations of the quantitative assessment framework, how megacities in emerging economies such as Kolkata suffer from intrinsic water insecurity even when their advantageous location and resource-abundance (Basu, 2016; Mukherjee et al., 2018) in terms of water seem to be "secure" (van Ginkel et al., 2018). Variations in individual components of Urban Water Security (UWS) are discussed in the following sections: water availability, water accessibility, water quality, and water security.

Water Availability

Water Availability corresponds to sufficient and continuous water supply for personal and domestic uses, including drinking and other domestic purposes (Gleick, 2004; Mukherjee et al., 2020). Based on our findings *Water* Availability varies across boroughs and wards in KMC and is varying around what has been set as an "acceptable" threshold. The lower range of *Water Availability* indicates that there is a demand for supply of potable water, in particular in some areas of KMC, namely the southern peripheral boroughs such as boroughs XIII–XIV (**Figures 1**, **2**; **Appendices B, C**).

The water supply system of KMC has been in operation since 1865. The average per capita supply is 134 *liters per capita per day* (lpcd), which is near to desired supply of 150 lpcd (for metropolitan cities). Nevertheless, the supply is very uneven, ranging from 310 to 40 lpcd with an average supply period of 8 h a day. The water supply system for KMC area is mainly based on water of River Hugli after treatment, where 92% of the total households within the whole KMC area are connected with direct piped supply (Mukherjee et al., 2018). This estimation does not include the semi-permanent households of the deprived areas of KMC, where around 35% of KMC's population lives without having direct piped supply of potable water. The daily water demand is estimated as 293 million liters per day as per 2012, where the total daily treated water supply capacity of the 4 treatment plants of Kolkata is 271 million liters per day. Nevertheless, age-old water pipelines cause high water loss in distribution (ADB, 2011; KMC report, 2012b; Mukherjee et al., 2018). It is also accounted that 35% of the water is wasted everyday due to the leakage in pipes (Basu, 2016; Mukherjee et al., 2018). As a result, there are gaps in demand-supply which we see as one of the drivers for the low scores of *Water Availability* component. Another issue is disparity of distribution of piped supply throughout the entire KMC area. Most of the direct supply of treated water is seized by middle and upper strata of the society which also include bigger commercial establishments. Therefore, disparity can be evident in *Water Availability* of water among different sections of society within KMC.

The resultant effect of urbanization within and around KMC area increased demand of water put pressure on groundwater resources. Around, 10–15% of KMC's potable water supply is sourced from groundwater which covers up to 30% of the potable water used in households (KMC report, 2018). There are around 439 big diameter tubewells fitted with motor-pump and 10,050 small diameters tubewells fitted with handpump within KMC area, which exclude the numbers of "unaccounted" tubewells installed and used by the large housing complexes (Chatterjee, 2014). Issues associated with unplanned, excessive, and "unaccountable" groundwater extractions are land subsidence, depletion of groundwater level, and aquifer contamination (Sahu et al., 2013; McArthur et al., 2018; Hati et al., 2020). Absence of water meters or penalty system also encourage this unaccountable groundwater extraction (Mukherjee et al., 2018; Hati et al., 2020).

Other important aspect of urban water availability is the declining inland surface waterbodies (urban wetlands such as canals, ponds, or constructed inland fresh waterbodies) and their littoral zones due to urbanization (Vörösmarty et al., 2000; Moss, 2008; Feng et al., 2010; Veldkamp et al., 2017; Chen et al., 2020). Mukherjee et al. (2018, 2020) showed that borough wise declining rate of wetlands was higher in the main city areas whereas the peripheral areas lost comparatively less. Nevertheless, the gross reduction of wetlands in Kolkata and its suburban areas impacted the direct availability (and, accessibility) of freshwater for other household purposes except drinking. These waterbodies were one of the major sources of water for household purposes for the residents of deprived areas (slums) as well as for the lower income groups living in semi-permanent squatters near /on the bank of these waterbodies (Mukherjee et al., 2020). Apart from the human dimension of water supply and groundwater recharge issues (Young, 2015), urban wetlands are also vital for managing the environmental functions, such as controlling flood, pollution and soil erosion and managing microclimate of the surroundings with the relative cooling impact (Forman, 2014; Manteghi et al., 2015; Neelakantan and Ramakrishnan, 2017).

Furthermore, our survey data show that only 67% households ($n = 720$) within KMC have a toilet inside. According to KMC's report (2012) for Asian Development Bank (ADB), only 44% of all households within KMC are having toilet facilities. In the derived areas, according to the Census of India (2011), more than 50% of the total households, 14 to 25 people are having access to only one community toilet (Mukherjee et al., 2020). Four percent of the KMC population had no toilet facilities nearby and used gutters, open drains, canals, or vacant lands instead (KMC report, 2012a). There are 383 public (pay and use) toilets in the KMC area (KMC report, 2018) some of which are having poor quality without necessary sanitation facilities making them useless throughout the year (Mukherjee et al., 2020). Fifty percent of the population of KMC has access to sewerage services (Mukherjee and Ghosh, 2015). A total number of 358,750 households (75% of the total households) within KMC are directly connected to the underground sewer network. The collection efficiency of sewage is 71%. The collection efficiency is around 90% in the core city area whereas, the remaining peripheral areas have no formal sewer system yet and collection is zero (KMC report, 2018).

Water Accessibility

Water Accessibility points to the need for adequate and safe water, sanitation, and hygiene (WaSH) facilities to be located or constructed in such a way that they are always accessible to everybody. Safe access to clean water, sanitation and hygiene facilities is particularly important for people with constrained physical movement and marginalized groups who may face safety risks (Wallace and Coles, 2005; WHO, 2018; Mukherjee et al., 2020). Gender, ethnicity, religion, and caste matters when it comes to access and availability to toilets and required WaSH facilities, for example, females stay home and face the tremendous issues with access to WaSH. Provisions of WaSH are crucial factors of water security, maintaining basic health standard. *The provision of WASH in health care facilities serves to prevent infections and spread of disease, protect staff and patients, and uphold the dignity of vulnerable populations* (WHO, 2015, p. 4).

Our survey revealed that 22.5% households within KMC did not have any access to WaSH facilities. Our study revealed the importance of deprivation as a factor explaining water security. As, after almost 15 years, in 2018, 42.5% household in deprived areas had access to WaSH facilities and 32.2% respondents did not have any WaSH facilities within their accessibility, which can tend to open defecation. This percentage is much higher than the national average, where, according to Census 2011 data, open defecation among the slum dwellers in India was 18% (Satapathy, 2014; Sau, 2017). This finding also shows the need for better and more accurate data.

Fundamentally, water is a social good (Day, 1996; Rogers et al., 1998). Therefore, ensuring universal access to water is the most essential element for achieving urban water security (WWAP, 2019). Our results suggest that the most water-secure groups in Kolkata are either cis-gendered or general (upper) caste or more educated or people living in their own houses. Inequalities along the multiple intersecting dimensions of various social categories such as gender, caste, ethnicity and religion are strong in Indian societies, which are now deepened with the emerging prosperity of the country widening the gaps between majority and minorities (Anne et al., 2013). Power politics, livelihood gaps, inherent stigmatization are increasing the gaps in necessities, preferences, and capacities in every segment of city-life (Anne et al., 2013; Shahid and Pelling, 2020). As a result, the intersecting categories, and inter-categorical differences in access to water and sanitation provisions are complex and spatially heterogenous (Fletcher, 2018). These inequalities also include the extremes such as physical-sexual assaults and denial of access to water specially for marginalized groups such as transgender communities (Alston and Whittenbury, 2013; Boyce et al., 2018). Disregarding the essentiality of inclusive (and intersectional) analytical framework may ignore or generalize the existing inequalities in the urban water system (Yuval-Davis, 2006; Valentine, 2007; May, 2015; Fletcher, 2018). Gender issue has already been highlighted in the Dublin Principles (1992) on bridging the gender gap in water resource management and other literatures (Global Water Partnership, 2019). However, the notion of inclusive approach is still lacking its significance in the research and practices raising the concern of basic right to water (Mukherjee et al., 2020), and we have also seen very few studies on gender along a continuum where water security for those outside of the gender binary are considered.

Water Quality

Water quality must be safe for human consumption (i.e., drinking and other household purposes including cooking) as well as for personal and domestic hygiene. This means the water must be free from germs, chemical substances, and radiological hazards that constitute a threat to a person's health both short term and over a lifetime of consumption (Gleick, 2004; Mukherjee et al., 2020). According to our results, the Water Quality component of UWS of KMC area are significantly related to risks and hazards associated with urban water as well as type of households. The main sources of contamination in the supplied water services with KMC are leakage in the supply-pipes (Ghosh, 2002) and seepage from the landfills (Mandal et al., 2019), stormwater discharges containing industrial wastes and uncovered sewage in both surface water and groundwater (Singh et al., 2009). The analyses of the survey data reveal that in KMC, the supply of good quality drinking water is not sufficient and inadequate quality drove most of the total respondents of boroughs II, III, and III away from using the supplied water to find out other sources of water for drinking and other household purposes. These areas of KMC consist of the older parts of the Kolkata city, where the existence of leakage and outlived metal pipes are possible sources of contaminants in water (Chakravarty, 2007; Mukherjee and Ghosh, 2015; Basu, 2016).

Within the KMC, groundwater is susceptible to pollution due to the leakage from the open dumping of domestic and industrial wastes. Therefore, the direct usage of groundwater through both deeper and shallower tubewells and bore wells can have direct and indirect issues of water quality, including dysfunctional colors, odors, and other visible quality issues. Chakravarty (2007), traced the source of contaminants such as mercury (Hg), lead (Pb), cadmium (Cd) and chromium (Cr) in samples taken from tube wells, river Hugli, and piped water within KMC area. The presence of lead (Pb) in river water and drinking water were very much noticeable in almost all the samples in both summer and winter seasons while the presence of chromium has been noticed in river water during monsoon seasons. Presence of mercury during monsoon season has also been detected in samples within KMC (Chakravarty, 2007). Decrease in wetlands and increase in urbanized impervious surface within KMC area are another cause of discharge of wastes into the surface and groundwater systems and increase the pollution (both organic and inorganic contaminants) levels of receiving water (Mukherjee et al., 2021). McArthur et al. (2018) traced in few groundwater samples arsenic concentrations between 10 and 79 $\mu g\ L^{-1}$ to a factory site producing Paris Green, an arsenical pesticide manufactured between 1965 and 1985, sporadic lead $>10\ \mu g\ L^{-1}$ from well-fittings, many samples contaminated by Cl from wastewater (sewage and septage) and natural Mn > 0.3 mg L^{-1}.

Water Risks and Hazards

Water risks and hazards related issues include mainly floods, water scarcity, water-borne diseases due to the presence of organic and inorganic substances in the water and land subsidence. The changes in land use and land cover (LULC) within the KMC area since 1980 (Mukherjee et al., 2018) resulted in the drainage of wetlands and its replacement by either compact surfaces or barren land for urban development. The shrinkage of surface waterbodies, clearing of the trees in the city increased surface runoff (Kiran and Ramachandra, 1999) and consequently, groundwater level lowered (Hagler, 2007; Mendoza et al., 2011; Ali et al., 2018). According to our results, two boroughs, XIII and XIV, which are situated at the periphery of the KMC boundary and within the reach of Adi Ganga canal remained within "Around accepted threshold" status of UWS. This result establishes the links between deteriorated water quality of Adi Ganga canal and poor and inadequate living conditions, sanitation issues, and lack of municipal services in the canal side temporary/semi-permanent settlements where morbidity and mortality rates are high (Douglas, 1983). These problems are especially critical in socially excluded areas and for squatters in fringe areas (Kundu, 2003). Peri-urban fringe areas (e.g., newly added wards, such as 101, 141–46) are lacking access to piped water supply from the municipality. 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 numbers of people living in these areas have been a key focus for urban planning work in respect to accessibility of safe drinking water and availability of adequate sanitation facilities (Sau, 2017).

The importance of deprivation in the area of water security cannot be underestimated. During severe flooding, such as in September 1999, the deprived areas of the city suffered from a paucity of power supply, acute shortages of safe drinking water, outbreaks of water borne diseases such as gastro-enteritis, typhoid, entamoebiasis, hepatitis etc. and a long period of water logging (Mukherjee et al., 2018). Palit et al. (2012) conducted a study on the potential of different water sources, both for drinking and domestic purposes, for diarrheal disease transmission in Kolkata's urban slums (Palit et al., 2012). The results show a significantly higher prevalence of fecal coliforms (58%) in stored water for washing than the stored water for drinking (28%) and tap/tube well water (8%) collected (Palit et al., 2012). Samples containing stored water for washing also had the highest non-permissible range of physico-chemical parameters. Household water containers storing water for washing were rich in fecal coliforms and residual chlorine contents. Palit et al. (2012) found less than the satisfactory level of residual chlorine (57%), TDS (37%), and pH (20%) present in almost two thirds of the samples of water stored for washing (Palit et al., 2012).

Urban Water Security

The urban water security index (UWSI) reveals the intrinsic spatial disparity of water security within the city as a combined result of physical setup of the cityscape including subsurface structures, over-ground infrastructure as well as social inequality and exclusions (Sultana, 2020). 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 (KMC report, 2012a, 2018; Roy and Dhali, 2016; Times of India, 2019). The subsurface structure of the city having active clay layer, age of the existing sewage system, non-biodegradable solid waste generation, lack of adequate pumping stations to remove water from the water logged areas, land subsidence, sporadic development of high-rise buildings, increasing traffic on the roads (particularly in the central city areas) and increasing density of population in these areas are to be blamed for the water insecurity (Roy and Dhali, 2016; KMC report, 2018; Mukherjee et al., 2018). Borough XVI has another issue with water and its infrastructure as this borough includes the newly added areas which still lack required infrastructure like direct piped water services to the households (KMC report, 2012a; Mukherjee et al., 2018, 2020).

Multiple intersecting dimensions must be analyzed and considered to fully understand water security. Here we have shown intersecting points between water insecurity and societal disadvantages related to gender, deprivation, social class, caste, ethnicity, and religion (Simpson, 2009; Thompson, 2016). These intersectional disparities are *particularly critical for cis-women, other gendered people and for making progress toward* both SDG 5 (gender equality and empower all women and girls). To achieve SDG 6 (clean water and sanitation for all) we need to ensure we take into account these groups of people so we can ensure inclusive water security for everyone in a city (Truelove, 2011; Sultana, 2020; Dickin et al., 2021, p. 1). The participation of cis-female in the labor force is still considerably low across developing countries and emerging economics comparison to cis-male (Bhagat et al., 2008; Kundu and Mohanan, 2009; Agbodji et al., 2015; Biswas, 2018). Despite of the fact that the (cis)male-female gender gap has slowly decreased, cis-female workers have much lower participation rates than their cis-male counterparts and hence comprise a marginalized section (ILO, 2016; Biswas, 2018; Deshpande, 2020). As per census-2011 of India, the workforce participation rate for cis-females is 25.51% against 53.26% for cis-males in India as a whole and 18.08% against the 57.07% in West Bengal (Govt-WB, 2015; Biswas, 2018; Deshpande, 2020). Our survey results show that 31% cis-male respondents and 27.6% cis-female are employed. This is important in our analysis as we can better understand the particular water security issues related to where different groups experience what water security issues, i.e., cis-men in Kolkata are more vulnerable to water insecurity at their workplaces. In Kolkata (and India in general), the WaSH facilities both at workplaces and institutions, for all gendered, are either inadequate or are in poor condition (UN report, 2019; Paul et al., 2020). This type of focus can also bring us to look at conditions in schools, where (in India), 50% children do not have access to a toilet at school, within them 22% are cis-men (Deivam, 2016; Tiberghien, 2016). This scenario is same in other public places, including the marketplaces and railways stations where thousands of people commute through every day (Paul et al., 2020).

Water security issues experienced by trans, and other gendered people are even worse. They are not properly registered officially—often live-in high levels of deprivation and poverty and are not able to access work (Dhall and Boyce, 2015; Boyce et al., 2018). This means they on the one hand share characteristics and WaSH struggles of those living in poverty but have the double burden of the hostility toward their very way of living and identity (Dhall and Boyce, 2015; Boyce et al., 2018). Thus, they often face physical humiliation during fetching water or using the common public latrines (Boyce et al., 2018; Mukherjee et al., 2020). Therefore, the results from our survey showing the number of transgender inclusive public toilets (14; **Figure 2C**) are crucial, as they are among the first attempts at demonstrating the exclusion factor for achieving water security in Kolkata city.

The result of UWSI also depicts that the portion of the respondents who are regarded as working in "household" are the most water-secure and most of them are cis- women. However, as we have shown, this does not mean that cis- women overall are more water secure than men. What this does point to is a need to understand the complex set of factors differentiating and influencing people's water security when it comes to looking at water security by gender. The next section of this paragraph will speak about cis-women and as there is no national level statistics on trans-women's data as of now. Chances are high that a major portion of cis-women having higher education are not engaged in active workforce. This non-engagement of cis- women in active workforce does not only reduces their role as decision-maker about WaSH expenditures at home, but also for their workplaces lessening cis-women's empowerment and gender equality at work (Dickin et al., 2021, p. 1). This assumption is supported by a study which states that the Gross Enrolment Ratio in higher education for male population is 18.3% and for women it is 19.1% s for the year 2018–2019 (Mitra and Ghara, 2019). In contrast, Chatterjee et al. (2018) showed that the Indian cis-women's work force participation is low. Recent studies have observed that cis-women's education has largely *J*-shaped or *U*-shaped relationship with their work-force participation, particularly in India (Reddy, 1979; Sathar and Desai, 2000; Kingdon and Unni, 2001; Das and Desai, 2003; Das, 2006; Klasen and Pieters, 2015). Past studies asserted that both cultural factors (for example, norms restricting the mobility of women) and structural factors (for example, lack of appropriate job opportunities for educated women) play important roles in determining the *U*-shaped relationship between cis-women's education and work-force participation in India (Das and Desai, 2003; Chatterjee et al., 2018).

The 2011 census reports that 87.3% of office clerks and 93.1% of sales jobs are taken by cis-men (Chatterjee et al., 2018). Rather than demonstrating the lack of adequate jobs for moderately educated groups in the country, these statistics especially imply the exclusion of women from these jobs which explains the low rates of work-force participation for these women. Nevertheless, skilled work in education sector (and health sector) is not entirely gender segregated except in part, where some types of work, such as nursing, fit better with gender stereotypes of women's nurturing roles (Chatterjee et al., 2018). Then, much of these works necessitate education beyond secondary level. Therefore, the "weaker sex" segregation in these jobs ends in a greater demand for educated female workforce and the rise in work-force participation can then be observed among female having Bachelors' degree and above. According to the Census 2011, in India, more than three-quarters of teachers have education above secondary level, and over one-third of them, 36.8%, are women (Chatterjee et al., 2018). Therefore, WaSH provisions in educational institution (Paul et al., 2020) would also matter for the low water security of the respondents with Postgraduate degrees and above, considering the similar situation for the cis-male teachers.

Lack of and inadequacy of WaSH provision in the socially deprived areas in Kolkata is also influencing some boroughs' overall UWSI scores (Mukherjee et al., 2020), such as borough XIII. Moreover, the statistically significant correlations between water accessibility variable and monthly income, caste, religion, education, and employment status of the respondent show that water insecurity and social exclusion go hand in hand. We can see this in the socially deprived areas of borough XIII, where the majority are of Muslim religion having lower level of education and monthly household income, and we have a low UWS score. Within the city's deprived areas, 81% of the dwellers have direct piped water supply in their houses for drinking purpose; among them only 8% use the same supplied water for other household works such as toilet flushing, washing clothes etc (Mukherjee et al., 2020). However, 43% of the dwellers from these deprived areas depend on water from standposts outside their houses for household tasks other than drinking (Mukherjee et al., 2020). Gender inequalities play an important role here. Cultural aspects related to religion is found to shape water insecurity for different genders due to the influence they have on division of household tasks as well as on and restriction of certain social interactions. This links to Schenk's (2010) work, where they found that Muslim women are more water insecure in the deprived areas as they are not allowed to go outside to take bath) which made it difficult to maintain hygiene particularly in the summer days. This significant public exposure may not be a problem for Hindu women from the lower income groups living in those deprived areas in the city, which make them choose occupations like domestic servants or vegetable vendors (Roy et al., 1992; Schenk, 2010). These cultural factors are also behind the under-representation of Muslims women in higher education and employment which shape their water security in Kolkata (Roy et al., 1992; Schenk, 2010; Rahaman and Barman, 2015; Mollah, 2018; Mukherjee et al., 2020).

CONCLUSIONS

The inclusive framework for urban water security assessment presented in this article highlights the challenges of urban water security (UWS) in Kolkata which goes beyond traditional indicators such as quantity of supplied water, access to water and sanitation or water quality. It captures the issues of water (in)security holistically along the four major dimensions of UWS—availability, accessibility, quality water-related risk and hazards. It does so by drawing on bio-physical and social indicators to answer the key questions of UWS: *how, for whom and where a city is water insecure*. To answer this the empirical approach of the study used spatial analysis of all the components of UWS with a megacity perspective from a location within an emerging economy. The findings suggest that water insecurity of a city is not only due to the malfunction or inadequacy of city's water system but also stems from the intersecting disadvantages, inequalities, and exclusion found in a society. Along with conventional quantifiable components of bio-physico-chemical dimensions, social factors were included as a key dimension of UWS to capture and improve our understanding of UWS, and as a result provide better recommendations for effective policy measures.

Despite being water blessed by having River Hugli in the west, East Kolkata Wetlands in the east and vast groundwater reserve, Kolkata faces a range of UWS challenges. Declining inland surface waterbodies and their littoral zones due to the changes in urban land use, increasing water demand owing to population growth, poor sanitation and lack of enough water treatment facilities coupled with mismanagement, issues associated with unplanned, excessive, and 'unaccountable' groundwater extractions such as depletion of groundwater level, land subsidence and aquifer contamination aggravated the water insecurities in Kolkata. In emerging and developing countries like India, these challenges affect urban dwellers, who experience difficulties in meeting daily water needs. The gap between the availability, supply and demand for fresh water will widen even further in mega cities in emerging countries, where this unequal state of urban water security affects mostly the people residing in the societal margins. This means we need to direct our attention to the consequences for public health, livelihoods, and wellbeing of these populations, with a particular focus on gender disparities. Municipal governments, as a result, need to constantly reconcile available water supply with growing demand in an equitable manner.

The existing literature on UWS assessments is not holistic or inclusive and rarely considers both bio-physical and societal factors in consider quantitatively. Therefore, we cannot apply any already established weighting methods to all the indicators of UWS. Lack of representation of the ground reality and underestimating the micro level issues may produce a fragmented scene of the UWS. The limited number of respondents to the survey questionnaires, their individual background, beliefs, ideology, and personal judgment about water security produce uncertainty and subjectivity in the indicator scores. We do, however, have a large enough random sample to provide strong and robust findings. Moreover, scoring through qualitative interpretations of the existing literature could weaken the precision of the findings. To overcome this issue, we weighed the data according to the Census-2011 to accurately reflect the population studied (particularly for gender and religion categories). However, the data were aggregated spatially into borough level, which lost the heterogeneity at the ward level scale. This way, we may have lost valuable information about the inequality present in the water security spectrum across the city.

Overall, this study provides a unique quantitative index-based assessment framework to quantify UWS at the borough level and to define the presence of multiple intersecting dimensions between bio-physical environment and society. This study identifies water-insecure areas within an Indian megacity which are under deprivation in both spatially and socially beyond the possibilities of limited resources prudently. This novel quantitative approach would help policy makers and water stakeholders to fix their objectives to manage their available water and social resources judiciously toward achieving UWS managing the trade-offs and equity challenges. The variation within the city builds on and adds to our argument in the previous studies and underlines the need to look at within city variation in our future work where we would focus on more individual level from the data collection, validation approaches to index creation to prevail over this critical issue of urban water security.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

SM: conceptualization, methodology, validation, formal analysis, investigation, data curation, visualization, and writing—original draft preparation. SM and TS: software and resources. TS, PS, and BS: writing—review and editing. BS: supervision. SM and BS: project administration and funding acquisition. All authors contributed to the article and approved the submitted version.

FUNDING

We thank the German Academic Exchange Service (DAAD Research Grants - Doctoral Programmes in Germany funding no. 57299294) who provides a fellowship to conduct this study. We would like to thank the GeoX Network for additional supports for conducting surveys and organizing interviews. We also acknowledge financial support by the German Research Foundation and the Open Access Publication Fund of the Freie Universität Berlin. The publication of this article was funded by Freie Universität Berlin.

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to Prof. (Dr.) Kai Hartmann, Department of Earth Sciences, Freie Universität Berlin, Prof. (Dr.) Mahalaya Chatterjee, University of Calcutta, India and Dr. Dipankar Bhattacharya, KMDA, India who provided relevant data, insight, and expertise that greatly assisted the research. We are indebted to Dr. Dipanwita Chatterjee for her continuous assistance in Mapping. We would also like to show our gratitude to Mr. Sougata Saha, Comtel Consultants and Infraproject Pvt Ltd., India and Mr. Surajit Kar, Doctoral Researcher, University of Calcutta, India for assistance with Survey and Mapping during this research, and we thank the three reviewers for their insights.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.834239/full#supplementary-material

REFERENCES

Aboelnga, H. T., El-Naser, H., Ribbe, L., and Frechen, F. B. (2020). Assessing water security in water-scarce cities: applying the integrated urban water security index (IUWSI) in Madaba, Jordan. *Water* 12:1299. doi: 10.3390/w12051299

Aboelnga, H. T., Ribbe, L., Frechen, F. B., and Saghir, J. (2019). Urban Water security: definition and assessment framework. *Resources* 8:178. doi: 10.3390/resources8040178

Adams, E. A. (2017). Thirsty slums in African cities: household water insecurity in urban informal settlements of Lilongwe, Malawi. *Int. J. Water Resourc. Dev.* 34:869–887. doi: 10.1080/07900627.2017.1322941

ADB (2011). *Kolkata Environment Improvement Investment Program Feasibility Assessment*. Manila: Asian Development Bank.

Agbodji, A. E., Batana, Y. M., and Ouedraogo, D. (2015). Gender inequality in multidimensional welfare deprivation in West Africa: the case of Burkina Faso and Togo. *Int. J. Soc. Econ.*42, 980–1004. doi: 10.1108/IJSE-11-2013-0270

Aihara, Y., Shrestha, S., Kazama, F., and Nishida, K. (2015). Validation of household water insecurity scale in urban Nepal. *Water Policy* 17, 1019–1032. doi: 10.2166/wp.2015.116

Ali, M., Khan, S. J., Aslam, I., and Khan, Z. (2018). Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. *Landscape Urban Plan.* 102, 271–279. doi: 10.1016/j.landurbplan.2011.05.006

Allan, J. V., Kenway, S. J., and Head, B. W. (2018). Urban water security-what does it mean? *Urban Water J.* 15, 899–910. doi: 10.1080/1573062X.2019.1574843

Alston, M., and Whittenbury, K. (2013). Does climatic crisis in Australia's food bowl create a basis for change in agricultural gender relations? *Agric. Hum. Values* 30(1), 115–128. doi: 10.1007/s10460-012-9382-x

Anne, M., Callahan, J. L., and Kang, H. (2013). Gender and caste intersectionality in the Indian context. *Hum. Resourc. Manag.* 2013, 31–48. Available online at: https://www.infona.pl/resource/bwmeta1.element.desklight-be64aaaa-4cf7-441d-91ab-160bdd31ad1a (accessed January 29, 2022).

Basu, J. (2016). *Kolkata, a Water-Rich City Turning Water-Poor*. The Third Pole. Available online at: https://www.thethirdpole.net/2015/11/11/kolkata-a-water-rich-city-turning-water-poor (accessed February 24, 2021).

Bhagat, R. B., Das, K. C., Sebastian, D., and Mohanty, S. (2008). Levels, trends and structure of workforce in India: census based study 1981-2001. *Int. Inst. Popul. Sci.* 1–182. Available online at: https://scholar.google.co.in/citations?view_op=view_citation&hl=en&user=a436P_QAAAAJ&cstart=100&pagesize=100&sortby=title&citation_for_view=a436P_QAAAAJ:mVmsd5A6BfQC (accessed January 29, 2022).

Biswas, S. (2018). Work participation rate of women in West Bengal. *Int. J. Res. Hum. Arts Liter.* 6, 423–434.

Boyce, P., Brown, S., Cavill, S., Chaukekar, S., Chisenga, B., Dash, M., et al. (2018). Transgender-inclusive sanitation: insights from South Asia. *Waterlines* 37, 102–117. doi: 10.3362/1756-3488.18-00004

Castán Broto, V., and Neves Alves, S. (2018). Intersectionality challenges for the co-production of urban services: notes for a theoretical and methodological agenda. *Environ. Urban.* 30, 367–386. doi: 10.1177/0956247818790208

Census of India (2011). *Rural-Urban Distribution of Population (Provisional Population Totals). The Registrar General and Census Commissioner, India, New Delhi.* Census of India. Available online at: http://censusindia.gov.in/2011-prov-results/PPT_2.html (accessed April 4, 2020).

Chakravarty, I. (2007). *Water Problems for Kolkata Metropolitan Region, Ballardie Thompson and Matthews Pvt. Ltd.* Available online at: www.sulabhenvis.in/admin/.../Kolkata%20Sewerage%20systems.pdf (accessed February 02, 2020).

Chatterjee, A. (2014). *Water Supply System in Kolkata City and Adjoining Areas*. Available online at: https://medium.com/@anjan.chatterjee/water-supply-system-in-kolkata-city-and-adjoining-areas-b199099a4517 (accessed November 12, 2020).

Chatterjee, B., and Roy, A. (2021). *Creating Urban Water Resilience in India: A Water Balance Study of Chennai, Bengaluru, Coimbatore, and Delhi*. Observer Research Foundation, India. Available online at: https://www.orfonline.org/wp-content/uploads/2021/03/Monograph_Urban_Water.pdf (accessed August 6, 2021).

Chatterjee, E., Desai, S., and Vanneman, R. (2018). Indian paradox: rising education, declining women's employment. *Demogr. Res.* 38:855. doi: 10.4054/DemRes.2018.38.31

Chen, L., Zhang, G., Xu, Y. J., Chen, S., Wu, Y., Gao, Z., et al. (2020). Human activities and climate variability affecting inland water surface area in a high latitude river basin. *Water* 12:382. doi: 10.3390/w12020382

Clement, F. (2013). "From water productivity to water security: a paradigm shift," in *Water Security Principles, Perspectives and Practices,* ed B.A. Lankford (Abingdon, VA: Routledge), 148–165.

Cook, C., and Bakker, K. (2012). Water security: debating an emerging paradigm. *Glob. Environ. Change* 22, 94–102. doi: 10.1016/j.gloenvcha.2011.10.011

Das, M. B. (2006). *Do Traditional Axes of Exclusion Affect Labor Market Outcomes in India?* South Asia Series, Paper No. 97. Washington, DC: World Bank.

Das, M. B., and Desai, S. (2003). *Are Educated Women Less Likely to be Employed in India?* Social Protection Discussion Paper No. 313. Washington, DC: World Bank.

Day, D. (1996). Water as a social good. *Austral. J. Environ. Manage.* 3, 26–41. doi: 10.1080/14486563.1996.10648341

Deivam, M. (2016). Wash environment at school: a vision of clean India. *Int. J. Hum. Soc. Sci. Res.* 2, 40–44.

Demetriades, J., and Esplen, E. (2010). "The gender dimensions of poverty and climate change adaptation," in *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World,* eds R. Mearns, A. Norton (Washington, DC: The World Bank), 133–144.

Denton, F. (2002). Climate change vulnerability, impacts, and adaptation: why does gender matter? *Gend. Dev.* 10, 10–20. doi: 10.1080/13552070215903

Deshpande, A. (2020). Early effects of lockdown in India: gender gaps in job losses and domestic work. *Indian J. Lab. Econ.* 63, 87–90. doi: 10.1007/s41027-020-00261-2

Dhall, P., and Boyce, P. (2015). *Livelihood, Exclusion, and Opportunity: Socioeconomic Welfare Among Gender and Sexuality Non-Normative People in India*. Brighton: Institute of Development Studies.

Dickin, S., Bisung, E., Nansi, J., and Charles, K. (2021). Empowerment in water, sanitation and hygiene index. *World Dev.* 137:105158. doi: 10.1016/j.worlddev.2020.105158

Douglas, I. (1983). *The Urban Environment*. London: Edward Arnold (Publisher). Ltd.,.

Feng, X., Zhang, G., and Yin, X. (2010). Hydrological responses to climate change in Nenjiang river basin, Northeastern China. *Water Resour. Manag.* 25, 677–689. doi: 10.1007/s11269-010-9720-y

Filmer, D., and Pritchett, L. H. (2001). Estimating wealth effects without expenditure data -or tears: an application to educational enrolments in states of India. *Demography* 38, 115-132. doi: 10.1353/dem.2001.0003

Fletcher, A. J. (2018). "More than women and men: a framework for gender and intersectionality research on environmental crisis and conflict," in *Water Security Across the Gender Divide,* eds C. Fröhlich, G. Gioli, R. Cremades, and H. Myrttinen (Cham: Springer), 35–58. doi: 10.1007/978-3-319-64046-4_3

Forman, R. (ed.). (2014). "Urban water bodies," in *Urban Ecology: Science of Cities* (Cambridge: Cambridge University Press), 175–204. doi: 10.1017/CBO9781139030472.009

Garrick, D., and Hall, W. J. (2014). Water security and society: risks, metrics, and pathways. *Annu. Rev. Environ. Resour.* 39, 611–639. doi: 10.1146/annurev-environ-013012-093817

Ghosh, G. K. (2002). *Water of India: (Quality and Quantity)*. New Delhi: APH Publishing Corporation.

Giddings, B., Hopwood, B., and O'brien, G. (2002). Environment, economy and society: fitting them together into sustainable development. *Sust. Dev.* 10, 187–196. doi: 10.1002/sd.199

Giordano, M. (2017). "Water security," in *The International Encyclopedia of Geography: People, the Earth, Environment, and Technology, Vol. 1*, ed D. Richardson (Hoboken, NJ: JohnWiley and Sons). doi: 10.1002/9781118786352.wbieg0536

Gleick, P. H. (2004). *The World's Water 2004-2005: The Biennial Report on Freshwater Resources*. Washington, DC: Island Press.

Global Water Partnership (2019). *GWP Strategy 2020-2025: Mobilising for a Water Secure World.* Stockholm: GWP. Available online at: https://www.gwp.org/globalassets/global/about-gwp/strategic-documents/gwp-strategy-2020-2025.pdf%20accessed%20January%2016,%202021 (accessed January 16, 2021).

Gopalakrishnan, S. (2016). *No Public Toilets for Transgenders in the Country*. India Water Portal. Available online at: http://sanitation.indiawaterportal.org/english/node/4832 (accessed April 16, 2020).

Govt-WB (2015). *State Statistical Handbook West Bengal 2014*. Kolkata: Bureau of Applied Economics and Statistics, Department of Statistics and Programme Implementation, Government of West Bengal.

Grey, D., and Sadoff, C. W. (2007). Sink or Swim? Water security for growth and development. *Water Policy* 9, 545–571. doi: 10.2166/wp.2007.021

Hagler, B. (2007). *Environmental Baseline Study of Margala and Margala North Blocks*. Islamabad: MOL Pakistan Oil and Gas Company BV.

Harris, L., Kleiber, D., Goldin, J., Darkwah, A., and Morinville, C. (2017). Intersections of gender and water: comparative approaches to everyday gendered negotiations of water access in underserved areas of Accra, Ghana and Cape Town, South Africa. *J. Gend. Stud.* 26, 561–582. doi: 10.1080/09589236.2016.1150819

Hati, P., Roy, G., Bhattacharyya, I., Kundu, D., and Sengupta, D. (2020). Present scenario of water supply in Kolkata. *Int. Res. J. Eng. Technol.* 7, 4060–4066.

Hellberg, S. (2017). Water for survival, water for pleasure-A biopolitical perspective on the social sustainability of the basic water agenda. *Water Alternat.* 10:65. Available online at: http://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue1/342-a10-1-4/file (accessed January 29, 2022).

Hoekstra, A. Y. (2000). Appreciation of water: Four perspectives. *Water Pol.* 1, 605–622. Available online at: https://ayhoekstra.nl/pubs/Hoekstra-1998.pdf

ILO (2016). *Women at Work: Trends 2016.* Geneva: International Labour Office. Available online at: http://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_457317.pdf?utm_content=buffer92781&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer (Accessed February 22, 2021).

Kingdon, G. G., and Unni, J. (2001). Education and women's labour market outcomes in India. *Educ. Econ.* 9, 173–195. doi: 10.1080/09645290110056994

Kiran, R., and Ramachandra, T. V. (1999). Status of Wetlands in Bangalore and its Conservation aspects. *ENVIS J. Hum. Settle.* 16–24.

Klasen, S., and Pieters, J. (2015). What explains the stagnation of female labor force participation in urban India? *World Bank Econ. Rev.* 29, 449–478. doi: 10.1093/wber/lhv003

KMC report (2012a). *Kolkata Urban Sector Investment Plan.* Kolkata: Kolkata Municipal Corporation.

KMC report (2012b). *Kolkata Environmental Improvement Investment Program (Tranche 1)—Sewerage and Drainage Subproject. Kolkata Municipal Corporation*. Kolkata. Available online at: http://www.keiip.in/bl3/pdf/42266-023-ind-iee-02.pdf (accessed February 22, 2021).

KMC report (2018). *City Disaster Management Plan of Kolkata*. Available online at: http://wbdmd.gov.in/writereaddata/uploaded/DP/DPKolkata33359.pdf (accessed February 22, 2021).

Kundu, A., and Mohanan, P. C. (2009). "Employment and inequality outcomes in India," in *Joint Seminar on Employment and Inequality, organized by the Employment, Labour and Social Affairs Directorate and Development Centre* (Paris), 1–43.

Kundu, N. (2003). *The Case of Kolkata, India. Understanding Slums: Case Studies for the Global Report on Human Settlements*. London: UN-Habitat; Earthscan, 195–228 (Available online at: http://www.ucl.ac.uk/dpu-projects/Global_Report/cities/kolkata.htm (accessed October 20, 2016).

Lundqvist, J., Appasamy, P., and Nelliyat, P. (2003). Dimensions and approaches for Third World city water security. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 358, 1985–1996. doi: 10.1098/rstb.2003.1382

MacGregor, S. (2009). A stranger silence still: the need for feminist social research on climate change. *Sociol. Rev.* 57, 124–140. doi: 10.1111/j.1467-954X.2010.01889.x

Maiti, S., and Agrawal, P. K. (2005). Environmental degradation in the context of growing urbanization: a focus on the metropolitan cities of India. *J. Hum. Ecol.* 17, 277–287. doi: 10.1080/09709274.2005.11905793

Mandal, J., Ghosh, N., and Mukhopadhyay, A. (2019). Urban growth dynamics and changing land-use land-cover of megacity Kolkata and its environs. *J. Indian Soc. Remote Sens.* 47, 1707–1725. doi: 10.1007/s12524-019-01020-7

Manteghi, G., bin Limit, H., and Remaz, D. (2015). Water bodies an urban microclimate: a review. *Mod. Appl. Sci.* 9:1. doi: 10.5539/mas.v9n6p1

May, V. M. (2015). *Persuing Intersectionality, Unsettling Dominant Imaginaries*. New York, NY: Routledge. doi: 10.4324/9780203141991

McArthur, J. M., Sikdar, P. K., Leng, M. J., Ghosal, U., and Sen,. I. (2018). Groundwater quality beneath an Asian megacity on a delta: Kolkata's (Calcutta's) disappearing arsenic and present manganese. *Environ. Sci. Technol.* 52, 5161–5172. doi: 10.1021/acs.est.7b04996

Mendoza, M. E., Granados, E. L., Geneletti, D., Perez-Salicrup, D. R., and Salinas, V. (2011). Analysing land cover and land use change processes at watershed level: a multi temporal study in the Lake Cuitzeo Watershed, Mexico (1975–2003). *Appl. Geogr.* 31, 237–250. doi: 10.1016/j.apgeog.2010.05.010

Mitra, D., and Ghara, T. K. (2019). Gross enrolment ratio in higher education: a district level analysis of the state of West Bengal. *Asian Rev. Soc. Sci.* 8, 37–41. doi: 10.51983/arss-2019.8.3.1600

Mohan, M., Pathan, S., Narendrareddy, K., Kandya, A., and Pandey, S. (2011). Dynamics of urbanization and its impact on land-use/land-cover: a case study of megacity Delhi. *J. Environ. Prot.* 2, 1274–1283. doi: 10.4236/jep.2011.29147

Mollah, K. (2018). *Status of Muslim Women in West Bengal*. Available online at: http://ijrar.com/upload_issue/ijrar_issue_936.pdf (accessed February 22, 2021).

Moss, D. (2008). *EUNIS Habitat Classification–A Guide for Users*. European Topic Centre on Biological Diversity. Available online at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.231.4607&rep=rep1&type=pdf (accessed November 9, 2021).

Mukherjee, J., and Ghosh, A. (2015). "Water justice city profile: Kolkata, India," in *Translocal learning for water justice: Peri-urban pathways in India, Tanzania and Bolivia* (London: The Bartlett Development Planning Unit). Available online at: https://www.ucl.ac.uk/bartlett/development/sites/bartlett/files/kolkata_report.pdf (accessed March 5, 2021).

Mukherjee, S., Bebermeier, W., and Schütt, B. (2018). An overview of the impacts of land use land cover changes (1980–2014) on urban water security of Kolkata. *Land* 7:91. doi: 10.3390/land7030091

Mukherjee, S., Sundberg, T., and Schütt, B. (2020). Assessment of water security in socially excluded areas in Kolkata, India: an approach focusing on water, sanitation and hygiene. *Water* 12:746. doi: 10.3390/w12030746

Mukherjee, S., Sundberg, T., and Schütt, B. (2021). "Issues, dimensions and approaches of assessing urban water security in developing and emerging countries: an inclusive perspective," in Environmental Management: Issues and Concerns in Developing Countries, ed P. Sikdar (Springer), 151–184. doi: 10.1007/978-3-030-62529-0_9

Muller, M. (2016). Urban water security in Africa: the face of climate and development challenges. *Dev. South. Africa* 33, 67–80. doi: 10.1080/0376835X.2015.1113121

Neelakantan, T. R., and Ramakrishnan, K. (2017). Protection of urban water body infrastructure–policy requirements. *EandES* 80:012068. doi: 10.1088/1755-1315/80/1/012068

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., and Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: are we counting what counts? *Hab. Int.* 44, 358–366. doi: 10.1016/j.habitatint.2014.07.003

Obani, P., and Gupta, J. (2016). "Human security and access to water, sanitation, and hygiene: exploring the drivers and nexus," in *Handbook on Water Security*, eds C. Pahl-Wostl, A. Bhaduri, J. Gupta (Cheltenham and Northampton: Edward Elgar Publishing), 201–214.

OECD. (2016). *Water Governance in Cities, OECD Studies on Water*. Paris: OECD Publishing. doi: 10.1787/9789264251090-en

Palit, A., Batabyal, P., Kanungo, S., and Sur, D. (2012). In-house contamination of potable water in urban slum of Kolkata, India: a possible transmission route of diarrhea. *Water Sci. Technol.* 66 299–303. doi: 10.2166/wst.2012.177

Pangare, V. (2016). *Gender Equality, Water and Climate Change Adaptation in Megacities. Water, Megacities and Global Change: Portraits of 15 Emblematic Cities of the World*. Paris: UNESCO. Available online at: http://unesdoc.unesco.org/images/0024/002454/245419e.pdf (accessed March 7, 2018).

Paul, S. K., Kumar, R., Pal, R., and Ghosh, A. (2020). Safe drinking water and toilet facility in public places in India: what we need to do! *J. Fam. Med. Prim. Care* 9:2593. doi: 10.4103/jfmpc.jfmpc_318_20

Rahaman, H., and Barman, H. (2015). Muslims and education of West Bengal: theory to pragmatism. *Int. J. Hum. Soc. Sci. Invent.* 4, 32–38.

Raschka, S. (2015). *Principal Component Analysis in 3 Simple Steps.* Available online at: https://sebastianraschka.com/Articles/2015_pca_in_3_steps.html (accessed March 2, 2021).

Ray, I. (2007). Women, water, and development. *Ann. Rev. Environ. Resourc.* 32, 421–449. doi: 10.1146/annurev.energy.32.041806.143704

Reddy, D. N. (1979). Female work participation in India: facts, problems, and policies. *Ind. J. Indust. Relat.* 15, 197–212.

Rogers, P., Bhatia, R., and Huber, A. (1998). *Water as a Social and Economic Good: How to Put the Principle Into Practice*. Stockholm: Global Water Partnership. Available online at: http://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/4989/TAC2.PDF?sequence=1_1 (accessed November 9, 2021).

Romero-Lankao, P., and Gnatz, D. M. (2016). Conceptualizing urban water security in an urbanizing world. *Curr. Opin. Environ. Sust.* 21, 45–51. doi: 10.1016/j.cosust.2016.11.002

Rouse, M. J. (2013). *Institutional Governance and Regulation of Water Services*. London: IWA Publishing. doi: 10.2166/9781780404516

Roy, P., Ghosh, A., and Sinha, R. (1992). Measuring bustee environment in Calcutta. *Soc. Change* 22, 128–130.

Roy, R., and Dhali, M. (2016). Seasonal water logging problem in a mega city: a study of Kolkata, India. *J. Res.* 430, 1–9.

Sahu, P., Michael, H. A., Voss, C. I., and Sikdar, P. K. (2013). Impacts on groundwater recharge areas of megacity pumping: analysis of potential contamination of Kolkata, India, water supply. *Hydrol. Sci. J.* 58, 1340–1360. doi: 10.1080/02626667.2013.813946

Saravanan, S. (2010). *Violence Against Women in India: A Literature Review*. Available online at: http://182.71.188.10:8080/jspui/bitstream/123456789/98/1/Violence%20Against%20Women%20India%20-%2025.pdf (accessed April 14, 2020).

Satapathy, B. K. (2014). Safe drinking water in slums. *Econ. Polit. Wkly*. 49, 51.

Sathar, Z., and Desai, S. (2000). "Class and gender in rural Pakistan: Differentials in economic activity," in *Women, Poverty and Demographic Change*, ed B. Garcia (Oxford: Oxford University Press), 175–192.

Satterthwaite, D. (2016). Missing the millennium development goal targets for water and sanitation in urban areas. *Environ. Urban.* 28, 99–118. doi: 10.1177/0956247816628435

Sau, A. (2017). A study on water supply and sanitation at a slum in Kolkata. *Int. J. Med. Sci. Public Health* 6, 634–637. doi: 10.5455/ijmsph.2017.0739414112016

Schenk, C. (2010). Slum diversity in Kolkata. Columbia Undergrad. *J. South Asian Stud* 1, 91–108. Available online: http://www.columbia.edu/cu/cujsas/Volume%20I/Issue%20II/W%20Collin%20Schenk%20-%20Slum%20Diversity.pdf (accessed January 29, 2022

Shaban, A., Kourtit, K., and Nijkamp, P. (2020). India's urban system: sustainability and imbalanced growth of cities. *Sustainability* 12:2941. doi: 10.3390/su12072941

Shaban, A., and Sattar, S. (2011). Water security and sustainability in urban India. *Int. J. Glob. Environ. Issues* 11, 231–254. doi: 10.1504/IJGENVI.2011.044552

Shahid, S., and Pelling, M. (2020). *Leaving no One Behind in Tomorrow's Cities: Strengthening Gender, Intersectionality and Social Inclusion in the COVID-19 Crisis and Beyond, Tomorrow's Cities Comment #6, May 2020*. Available online at: https://tomorrowscities.org/leaving-no-one-behind-tomorrows-cities-strengthening-gender-intersectionality-and-social-inclusion (accessed November 9, 2021).

Shrestha, S., Aihara, Y., Bhattarai, A. P., Bista, N., Kondo, N., Futaba, K., et al. (2018). Development of an objective water security index and assessment of its association with quality of life in urban areas of developing countries. *SSM Popul. Health* 6, 276–285. doi: 10.1016/j.ssmph.2018.10.007

Simpson, J. (2009). *Everyone Belongs: A Toolkit for Applying Intersectionality*. Canadian Research Institute for the Advancement of Women (CRIAW), Ottawa, Canada. Available online at:http://also-chicago.org/also_site/wp-content/uploads/2017/03/Everyone_Belongs-A-toolkit-for-applying-intersectionality.pdf (accessed January 30, 2022).

Singh, R., Maheshwari, B., and Malano, H. M. (2009). "Developing a conceptual model for water accounting in peri-urban catchments," in *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation*, eds R. S. Anderssen, R. D. Braddock, L. T. H. Newham (Cairns: 18th World IMACS / MODSIM Congress) 2377–2383.

Srinivasan, V., Konar, M., and Sivapalan, M. (2017). A dynamic framework for water security. *Water Sec.* 1, 12–20. doi: 10.1016/j.wasec.2017.03.001

Sullivan, C. A. (2011). Quantifying water vulnerability: a multi-dimensional approach. *Stochast. Environ. Res. Risk Assess.* 25, 627–640. doi: 10.1007/s00477-010-0426-8

Sultana, F. (2020). Embodied intersectionalities of urban citizenship:water, infrastructure, and gender in the global South. *Ann. Am. Assoc. Geogr.* 110, 1407–1424. doi: 10.1080/24694452.2020.1715193

Thompson, J. A. (2016). Intersectionality and water: how social relations intersect with ecological difference. *Gend. Place Cult.* 23, 1286–1301. doi: 10.1080/0966369X.2016.1160038

Tiberghien, J. (2016). *WaterAid School WASH Research: India Country Report*. Available online at: https://washmatters.wateraid.org/sites/g/files/jkxoof256/files/WaterAid%20school%20WASH%20research%20report%20India.pdf (accessed March 5, 2021).

Times of India (2019). *Majerhat Bridge Work may Have Caused Behala-Kidderpore Flood*. Available online at: http://timesofindia.indiatimes.com/articleshow/70777574.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst (accessed February 22, 2021).

Truelove, Y. (2011). (Re-) Conceptualizing water inequality in Delhi, India through a feminist political ecology framework. *Geoforum* 42, 143–152. doi: 10.1016/j.geoforum.2011.01.004

UN (2010). *The Human Right to Water and Sanitation. Resolution Adopted by the General Assembly on 28 July 2010: 64/292*. Paris: United Nations. Available online at: https://undocs.org/A/RES/64/292 (accessed April 14, 2020).

UN report (2019). *Water, Sanitation and Hygiene*. Paris: United Nations. Available online at: https://www.unwater.org/water-facts/water-sanitation-and-hygiene/ (accessed February 22, 2021).

UNs (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. Paris: United Nations. Available online at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf (accessed November 9, 2021).

Valentine, G. (2007). Theorizing and researching intersectionality: a challenge for feminist geography. *Prof. Geogr.* 59, 10–21. doi: 10.1111/j.1467-9272.2007.00587.x

van Ginkel, K. C., Hoekstra, A. Y., Buurman, J., and Hogeboom, R. J. (2018). Urban water security dashboard: Systems approach to characterizing the water security of cities. *J. Water Resourc. Plan. Manag.* 144:04018075. doi: 10.1061/(ASCE)WR.1943-5452.0000997

Veldkamp, T., Wada, Y., Aerts, J., Doll, P., Gosling, S. N., Liu, J., et al. (2017). Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nat. Commun*. 8:15697. doi: 10.1038/ncomms15697

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science* 289, 284–288. doi: 10.1126/science.289.5477.284

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., and Prusevich, A. (2010). Global threats to human water security and river biodiversity. *Nature* 467, 555–561. doi: 10.1038/nature09440

Vyas, S., and Kumaranayake, L. (2006). Constructing socio-economic status indices: how touse principal components analysis. *Health Policy Plan* 21, 459-468. doi: 10.1093/heapol/czl029

Wallace, T., and Coles, A. (2005). "Water, gender and development: an introduction," in *Gender, Water and Development*, eds A. Coles, and T. Wallace (New York, NY: Berg Publishers), 1–20. doi: 10.4324/9781003085461-1

Wheater, H. S. (2015). "Water security – science and management challenges. hydrological sciences and water security: past, present and future," in *Proceedings of the 11th Kovacs Colloquium* (Paris).

Wheater, H. S., and Gober, P. (2014). "Meeting the science challenges of water security in the Saskatchewan River Basin: a regional hydroclimate project from Western Canada," in *Dooge Nash International Symposium*, eds J. J. O'Sullivan, and M. Bruen (Dublin: University College Dublin), 431–446.

WHO (2015). *Water, Sanitation and Hygiene in Health Care Facilities: Status in Low- and Middle-Income Countries and Way Forward*. Geneva: World Health Organization. Available online at: https://apps.who.int/iris/bitstream/handle/10665/154588/9789241508476_eng.pdf (accessed November 25, 2020).

WHO (2018). *Guidelines on Sanitation and Health*. Geneva: World Health Organization. Available online at: https://apps.who.int/iris/bitstream/handle/10665/274939/9789241514705-eng.pdf?ua=1 (accessed November 25, 2020).

WHO (2020). *Unsafe Drinking-Water, Sanitation and Waste Management*. Geneva: World Health Organization. Available online at: https://www.who.int/sustainable-development/cities/health-risks/water-sanitation/en/ (accessed April 15, 2020).

WWAP (2019). *Leaving no One Behind: The United Nations World Water Development Report-2019*. Paris: World Water Assessment Programme; United Nations.

Young, K. (2015). *Human Dimensions of Urban Water Bodies and Associated Green Spaces*. (Master of Science Dissertation), Texas Tech University, USA. Available online at: https://ttu-ir.tdl.org/bitstream/handle/2346/63580/YOUNG-THESIS-2015.pdf?sequence=1 (accessed November 19, 2020).

Yuval-Davis, N. (2006). Intersectionality and feminist politics. *Euro. J. Womens Stud.* 13, 193–209. doi: 10.1177/1350506806065752

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

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 26 August 2022
DOI 10.3389/frwa.2022.906407

Capacity development for water reuse in in-formal partnerships in northern Namibia

Fanny Frick-Trzebitzky[1]*, Thomas Kluge[1], Stefan Stegemann[2] and Martin Zimmermann[1]

[1]ISOE—Institute for Social-Ecological Research, Frankfurt am Main, Germany, [2]Emschergenossenschaft, Essen, Germany

In central northern Namibia, challenges in water governance related to scarcity meet needs in capacity development on municipal levels. Reuse of treated water in agriculture forms a technical innovation in urbanizing arid regions, because it potentially contributes to both improving water availability and reducing pollution from waste water in arid regions. Governing this transformative approach entails a complexity of processes and actors at different levels and in a range of sectors. The aim of this research is to assess the potential of an informal municipal partnership to (a) support capacity development in implementation of innovation in urban water systems (here: water reuse), and (b) compensate for lack of coordination in governance. Establishing a municipal partnership for wastewater treatment was part of a living lab approach analyzing the potential for water reuse, in collaboration of an interdisciplinary team of researchers, municipal decision-makers, engineers and farmers. Findings show the potential and limitations in capacity development in municipal water governance by means of an informal partnership. The lessons learnt on establishing an informal municipal partnership for learning and capacity development in water governance provide valuable insights for water governance in both research and practice, in particular but not limited to the field of water reuse as means of transforming socio-hydrological relations toward sustainability. The research thus contributes to research on water reuse governance, and to transformative research on water in social-ecological systems.

KEYWORDS

municipal partnerships, water governance, transdisciplinary research and methods, social-ecological transformations, adaptive governance

OPEN ACCESS

EDITED BY
Jenia Mukherjee,
Indian Institute of Technology Kharagpur, India

REVIEWED BY
Amrita Sen,
Indian Institute of Technology Kharagpur, India
Subham Mukherjee,
Hebrew University of Jerusalem, Israel

*CORRESPONDENCE
Fanny Frick-Trzebitzky
frick@isoe.de

SPECIALTY SECTION
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

RECEIVED 28 March 2022
ACCEPTED 27 June 2022
PUBLISHED 26 August 2022

CITATION
Frick-Trzebitzky F, Kluge T, Stegemann S and Zimmermann M (2022) Capacity development for water reuse in in-formal partnerships in northern Namibia. *Front. Water* 4:906407. doi: 10.3389/frwa.2022.906407

Introduction

In the face of growing water challenges, in urbanizing arid regions and under the impacts of climate change in particular, capacity needs in water management are high. The 2020 status report on the progress toward meeting the SDGs highlights the urgent need for accelerated action on implementing sanitation services and integrated water resource management, or else the SDG 6: to ensure availability and sustainable management of water and sanitation for all will not be met by 2030 (United Nations, 2020). In the same year, the UN[1] have singled out capacity development as one out of five accelerators to achieve the SDG 6 by 2030 (UN Water, 2020). At municipal level in regions experiencing population growth in particular, management capacities are lacking and governance challenges are stark.

Water reuse is both a transformative approach in integrated water resource management, and an illustrative case of the complexities entailed in developing capacities in water governance across modes, levels and sectors. The urgency of enhancing reuse and wastewater treatment capacity is recognized in the Global Target 6.a under the SDG on water, explicitly highlighting the importance of North-South collaboration in technology development (United Nations General Assembly, 2017 7/10/2017)[2]. Water reuse can be considered transformative in arid regions with drainless areas in particular. Such conditions prevail in Northern Central Namibia. Here evaporation and transpiration are the only mechanisms by which water unsuitable for infiltration can be disposed of, as discharge into rivers after treatment (preflooder) is no option. Waste waters are collected and left to evaporate in waste stabilization ponds (WSP)—an approach to waste water management where hydrological conditions prevent discharging or infiltrating waste water into existing water bodies. Overflowing of WSP during the rainy season leads to flooding of inhabited areas with untreated water and associated health risks. In (semi-)arid regions, and especially in sub-Saharan African countries, water supply is also an issue. Rapid population growth increases the need for alternative water resources due to drivers such as increasing domestic, agricultural and industrial consumption, as well as climate change and climate variability. In combination, the particularities of water use in drainless areas in semi-arid and arid regions imply costs and benefits in water management that differ considerably from those in most parts of the world. Against this background, water reuse is the only option to reduce the pressure on wastewater ponds while also reducing freshwater supply needs (Zimmermann et al., 2019).

At the same time, reusing water at municipal level involves a range of capacities to be developed. Firstly, reusing water (in agriculture) requires new forms of knowledge and collaboration at different levels and across sectors. Key to sustainable water reuse systems is that technological solutions are based on a holistic scientific, economic and social understanding of the entire (urban) water system (Bahri, 2009). Technical expertise to fully understand hydrological information is needed, which many decision-makers lack (Hofste et al., 2019). Cross-scale and cross-sectoral collaboration is a prerequisite for successful water reuse in agriculture (Bahri, 2009). Secondly, implementation of water reuse systems in drainless areas requires an alternative calculation of costs and benefits. Generating resources from wastewater is often not profitable in economic terms when the alternative environmental costs of not treating water and overexploitation of freshwater resources are not factored in (Di Mario et al., 2018). Collaborative approaches may enable economies of scale. Thirdly, open questions remain as to how to change deeply embedded reservations toward reusing water. Moreover, the politics and power asymmetries involved in water reuse governance have barely been explored (Beveridge et al., 2017). This results in both a research gap and a capacity need to create political alliances for reuse (Kjellén, 2018).

Research on water reuse governance has largely focused on economic and awareness aspects, leaving the complexity of institutional arrangements for reuse under-researched (Beveridge et al., 2017). Meanwhile, practical examples of municipal cooperation in the water sector suggest the potential of partnerships in supporting capacity development. This potential is substantiated by literature on water and adaptive governance that teases out the role of informal and bottom up arrangements (Kemerink-Seyoum et al., 2019; Pahl-Wostl, 2019). However, while case studies exist, little is known about the effectiveness of such partnerships (Boag and McDonald, 2010), and their contribution to developing capacity, particularly in the global South (Moodley, 2019).

The present research seeks to explore the potential of municipal partnerships in developing capacity for water reuse. Given the role of semi-formal networks in both compensating a weak governance coordination and in developing capacities, we conceptualize informal municipal networks as cooperative arrangements between local governments where learning takes place and capacities are developed and leveraged. This may include technical, regulatory, adaptive as well as integrative capacities. In bringing together the capacities of multiple municipal actors, such partnerships have the potential for enhancing capacities by combining resources, for instance in the acquisition of technical equipment (economies of scale). A flexible set-up allows for capacity development in

1 Through the coordinating body on water and sanitation, UN-Water.

2 "6.A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies".

various, changing constellations according to needs in an adaptive manner. This conceptualization situates informal municipal networks at the interface of (1) bottom-up processes of collaboration in the socio-technical tinkering in water management (Kemerink-Seyoum et al., 2019) and (2) formalized collaborative arrangements with the specific objective of enhancing capacities in water governance (Boag and McDonald, 2010). Thus defined informal public partnerships potentially strengthen water governance capacities in local governments, regulatory water governance capacities in networks, and create capacities strengthening meta-governance. Here we study this potential in the context of an innovation in the water sector (water reuse) that is designed to support the social-ecological transformation (Hummel et al., 2017) of municipal water supply in central northern Namibia.

We understand 'wastewater treatment plant partnerships' as semi-formal networks of knowledge exchange and for sharing special technical equipment. The research question addressed here is therefore: What is the potential for municipal partnerships in water reuse, and how can they be designed and implemented to improve capacity development for water reuse in the Namibian context? The research seeks to contribute to research on water (reuse) governance by (1) specifying types of capacity needs for reuse governance in Northern Namibia, and (2) deriving lessons learnt for implementation of wastewater treatment plant partnerships (wwtpps) in support of capacity development and governance.

Conceptual framework

The conceptual framework of our research draws on three main concepts, namely (a) meta-governance, (b) informal networks and municipal cooperation, and (c) learning in adaptive water governance. We consider these concepts cornerstones in a governance framework supporting the social-ecological transformation of water systems toward sustainability (Hummel et al., 2017). Here the innovation of a water reuse concept is taken as an example of a social-ecological transformation in the water sector.

Water governance can be understood as a societal function regulating the management, flow and distribution of water in social-ecological systems (Pahl-Wostl, 2019), given the dynamics and uncertainties of social-ecological interactions around water, the concept of adaptive governance has gained grounds to describe the ability of governance approaches to adjust to change (Koontz et al., 2015). Water governance research has increasingly emphasized the complexity and plurality of what can be described as "modes" of governance (Pahl-Wostl, 2019). For instance, different norms from international conventions, statutory law and traditional law may intersect in "legal pluralism" (see for instance Boelens, 2009). Accordingly, water governance is often shaped by different entities that are not related in a hierarchical order but rather stem from different organizational systems (polycentrism), and that operate at different scales (multi-level governance) (Koontz et al., 2015; Pahl-Wostl, 2019). While polycentrism and multi-level governance conceptualize the complexity and plurality of water governance, research on understanding the interlinkages between modes of governance remains limited. Drawing on the distinction of hierarchy, network and market systems as modes of governance, Pahl-Wostl (2019) has compared water governance arrangements in multiple cases across the globe. She has identified both a need for, and a general lack of a mediating governance mode steering the interaction of these three modes of governance; she calls this "meta-governance".

Especially where governmental capacities are low, bottom up strategies may compensate lack of coordination among different modes of governance (meta-governance). Different institutional and socio-technical arrangements in water governance shape everyday water governance. Local stakeholders may for instance take a leading role in contesting prevailing governance modes and establishing cooperative modes in a rather informal way (Cleaver and Whaley, 2018; Kemerink-Seyoum et al., 2019). Formalized contractual collaborations among public or between public and non-profit entities in the water sector may be designed to improve infrastructure, water delivery services or develop capacities in local governments (Boag and McDonald, 2010; Sanz, 2013). However, a supportive environment is needed in order to (a) avoid the undermining of network governance and partnerships by higher level powers, and (b) ensure that priorities set in informal networks do not run counter to legal provisions in pursuit of meeting the SDG 6 targets (Pahl-Wostl, 2019).

Learning and governmental capacities are key factors for enabling a supportive meta-governance. Learning in institutions can take multiple forms from technical learning to social learning and transformative co-production of knowledge. For adaptive water governance in particular, these different forms of learning are key. While formal learning in fixed institutions tends to replicate routines and focus on technical capacity development, flexible networks where diverse actors can move in and out of processes of knowledge co-production facilitate adaptive governance (Pelling et al., 2008; Bos and Brown, 2012; Pahl-Wostl et al., 2013; Koontz et al., 2015). At the same time, technical learning is an important element of adaptive water governance (Bos and Brown, 2012) that is particularly relevant in the context of infrastructure innovations such as water reuse. Learning in water governance furthermore requires a supportive, experimental and reflexive governance context that enables bringing together multiple forms of knowledge (Bos and Brown, 2012; van der Molen, 2018).

Research design and method

In order to address the research question, we conducted a generic analysis of the emergence and performance of a wastewater treatment plant partnership (wwtpp) in Northern Namibia. The case is one where capacity development in wastewater management is urgently needed, given the challenging social-ecological conditions that are particular to Central Northern Namibia. Here a wwtpp has been set up within a transdisciplinary research project on water reuse. The formation and establishment of the wwtpp unfolded concomitant to the construction of a pilot site for the technical treatment of municipal wastewaters at a WSP for water reuse in Outapi. The pilot site consists of water treatment facilities, the pre-existing wastewater ponds, as well as a plot for plant and irrigation experiments. On-site research involved technical experiments and continued measurements by engineers and scientists in close collaboration with Outapi town council. The transdisciplinary research partnership is a continuation of longstanding collaboration on water reuse (Zimmermann et al., 2015, 2019).

The establishment of a partnership for wastewater treatment among neighboring municipalities and regional authorities in Northern Namibia was part of a transdisciplinary research project using an approach inspired by so-called real-world laboratories. Real-world interventions are the core of real-world laboratories and are framed by co-design, co-production and co-evaluation. The three steps are in a flexible order and usually repeated several times (Wanner et al., 2018). Real world laboratories bear similarities with 'living lab' initiatives which—particularly in the African context—place an emphasis on facilitating learning (Hooli et al., 2016). The real world laboratory approach was operationalized in the EPoNa project by developing and piloting both the improved WSP system in Outapi and the wwtpp in close cooperation with the town council. The continuous exchange of scientific and practical knowledge among the authors as well as with decision-makers and technicians overlooking WSP in the case study area complemented this methodological approach. Figure 1 shows the improved WSP system and set up of different treatment steps for research purposes in form of a flow chart. Construction of the system began in 2017. However, the technical component of the wastewater treatment plant and resource recovery technology is not scope of this research paper and has been presented in detail by one of the authors and further members of the EpoNa project consortium elsewhere (Lackner et al., 2017; Zimmermann et al., 2021).

In a genealogical analysis of the wwtpp's formation, inner and outer perspectives are combined by looking at the partnership formed in Namibia based on project documents (protocols of meetings and site visits to WSP), field notes from the transdisciplinary research process, and semi-structured interviews with key stakeholders and experts ($N = 24$). In the initial phase, one of the authors visited several municipalities in order get an overview on their situations and challenges. His reports served as a basis for identification of potential benefits of the wwtpp.

Three principles for measuring collaborative governance success (see Silva et al., 2018) guided the analysis of the wwtpp's emergence, namely drivers for collaboration, scope of cooperation (motives, for instance economies of scale) and nature of institutional structures (namely degree of formality/integration). The question "What are the capacity needs?" was addressed in the first two meetings of the wwtpp as well as in interviews and site visits by the transdisciplinary research team. Topics and formats of knowledge exchange were identified and addressed in continued exchange between the authors of the paper, the wwtpp members, further participants at the workshops, and other members of the research consortium. Reflections on the learning process were collected in interviews. The potential of a wwtpp for strengthening capacities for water reuse through collaborative governance was assessed through a combined analysis of meeting minutes, field notes and interview material on the effectiveness of the wwtpp. Key lessons learned were derived from the combined analysis of the wwtpp's emergence, capacity development and collaborative governance potential.

Background to the case

Treatment of wastewater is gaining municipal attention in Northern Namibia as the environmental costs of discharging water untreated are rising and new regulations enforced. The southern African Water Act 54 from 1956 (Republic of South Africa, 1956) was the first policy to mandate purification of wastewater and other effluents from industrial water use. Based on the "need to reform" Namibia's water policy, the National Water Policy White Paper (Ministry of Agriculture, Water and Rural Development, 2000) advises the country to "adopt a systematic approach to water resources management, using an integrated, multisector framework that considers issues of decentralization, social equity, ecological protection, and economic growth". As a reaction, a new Water Act was published in 2004. It declares that disposal of effluent requires permission from state authorities, as a measure to protect existing water resources (Government Gazette of the Republic of Namibia, 2004). Due to trending changes in water resources management, the newest reform of the Water Resources Management Act fosters integrated water resource management approaches by including conservation measures as water infrastructure, promoting participation and devolution of decision-making on water to the lowest levels of government. Operating systems for wastewater discharge are to be provided by local authorities and water services providers (Government Gazette of the Republic of Namibia, 2013).

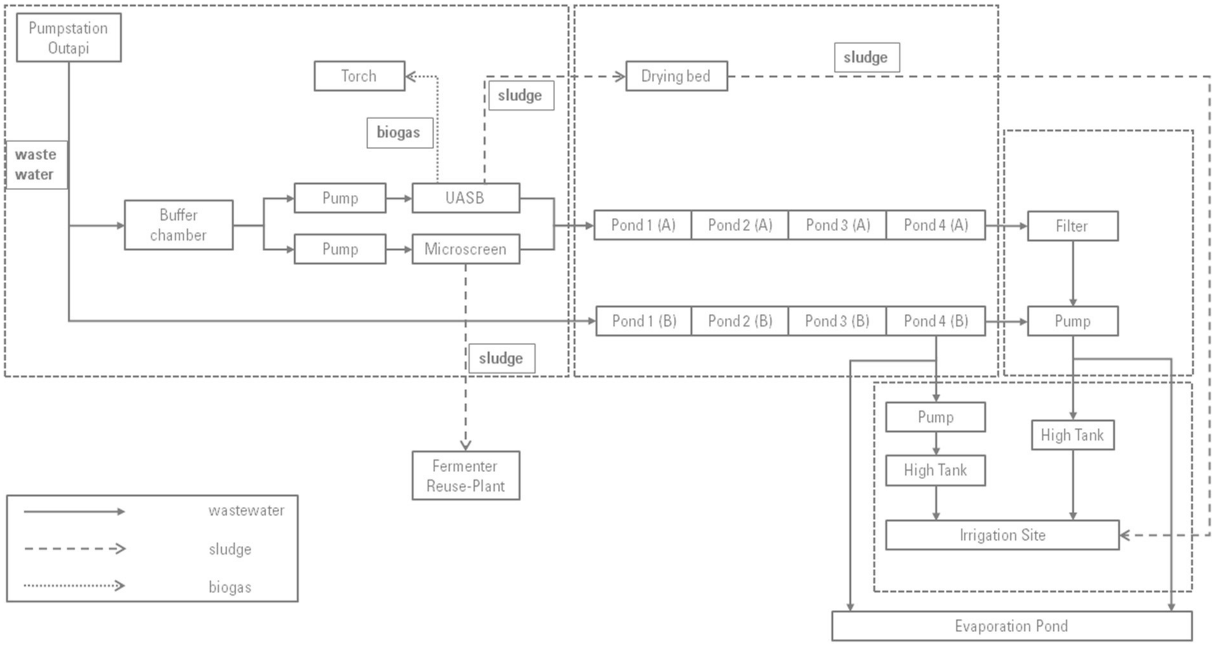


FIGURE 1
Flow chart of the improved waste stabilization pond system. Own design based on Sinn et al. (2019).

Results

In the following sections we present the characteristics of the wwtpp established in Central Northern Namibia, needs and processes of capacity development in the partnership, and its role in relation to meta-governance in the water sector in the region. We discuss the relation of informal and formal moments in the partnership, the role of knowledge co-production in capacity development and the potential of the partnership in enhancing meta-governance in the water sector.

Establishing an informal partnership for municipal water governance in Central Northern Namibia

The establishment of the wwtpp is best understood against the background of the drivers that led to its formation, its scope, and its organizational structure.

Drivers for and scope of setting up a partnership

The special challenges in wastewater management in northern Namibia are exacerbated by limited capacities at municipal authority levels. The rapid growth of the population—as in many other African small and medium-sized towns—quickly leads to overloading of the wastewater treatment facilities, which are often implemented as WSP. Perennial overflowing of the ponds is a consequence of their overloading, with serious impacts on environmental health as untreated waters enter ecosystems and livestock drinks from it (Figure 2). In many cases, the municipalities are unable to cope with the combination of urbanization effects and climate-related events such as heavy rainfall. What comes on top is the low availability of water in the arid region, combined with the absence of rivers or tributaries. Here wastewater could be an important resource for producing water for irrigation agriculture, e.g., for animal fodder production, while at the same time using nutrients.

The WSP in the Cuvelai-Etosha Basin are exemplary for numerous WSP of many African municipalities. Problems such as overloading and inadequate management lead to the fact that their discharge quality is only marginally better than the inflow quality. One goal of the research project[3] was to support the development of solutions such as water reuse in fodder production through capacity development and strengthening governance structures in inter-municipal cooperation. This is because the limited capacity in local authorities for dealing with these challenges is linked to insufficient availability of resources and skills. Through cooperation, resources could be used more efficiently and competencies built up. Against this background, a wwtpp was established in northern Namibia as part of the research project EPoNa.

The overall objective of the wwtpp is to address challenges in wastewater management through capacity development. The network intends to facilitate the exchange of information and

3 EPoNa stands for Enhancement of Ponds in North-Central Namibia.

FIGURE 2
Overflowing of untreated wastewater from a Waste Stabilization Pond (WSP) in Eenhana municipality in 2018. Photo: Fanny Frick-Trzebitzky.

experience with regard to questions of strategic decisions in water management, operation and maintenance as well as the procurement of materials and spare parts. In addition, it provides a platform for possible mergers of operators for the joint operation of plants in the region, in special-purpose associations or other forms of municipal cooperation.

Organizational structure and type of partnership

The wwtpp was increasingly formalized over time, as summarized in Figure 3. The first committee of the wwtpp was appointed at the 4th workshop in October 2018. As of 2019, the wwtpp consists of a core of five municipalities and one village that form the steering committee (Outapi, Okahao, Oshikuku, Eenhana, Ruacana, Tsandi). These organize regular meetings for intercommunal exchange on the management of wastewater and WSP and send out invitations. In addition, other municipalities, villages and regional councils participate in the network's meetings.

Due to the efforts of the large cities in northern Namibia to construct conventional wastewater treatment plants in the medium term, the focus of the wwtpp continues to be on medium-sized towns as well as villages and settlements, represented by the Regional Councils. According to the typology of public-public partnerships proposed by Boag and McDonald (2010), the wwtpp is an intra-state public authority-public authority partnership in a weakly formalized form.

Table 1 summarizes key characteristics of the wwtpp regarding drivers, scope and institutional structures.

Informal or semi-formal?

The initiation of the partnership is a response to the dynamic changes in land and water use in Central northern Namibia that are putting municipal water management systems under great pressure, exacerbated by climate and demographic change. Established in the context of a living lab on water reuse, it forms part of an experimental approach to adaptive water governance. Initiated by municipal actors and researchers as an informal network, the wwtpp does not fall clearly under either of the categories "bottom up, informal" (Pahl-Wostl, 2019), "everyday tinkering" (Kemerink-Seyoum et al., 2019) or "contractual collaboration" (Boag and McDonald, 2010). Our conceptualization of semi-formal networks proves helpful in understanding the wwtpp as an evolving network that is partly formalized and may take on different forms in the future.

Capacity development

Capacity development in the wwtpp was addressed by identifying capacity needs, developing respective contents and formats of learning and assessing processes of knowledge co-production in the course of these formats.

Capacity needs

The participating municipalities in the Namibian wwtpp face similar challenges and needs for capacity development, which were identified at the first meeting initiated by the research project in 2017. In particular the lack of cost controlling in the budgets of the municipalities, the overloading and poor operation of the existing WSP and treatment plants, vandalism at the plants, the lack of budget for reinvestments, as well as the improper emptying of private septic tanks by service providers are common challenges. They contribute to the fact that WSP are insufficiently maintained and cleaned, and consequently regularly overflow. In the wwtpp, municipalities address these challenges by holding meetings (in workshop format) on specific issues.

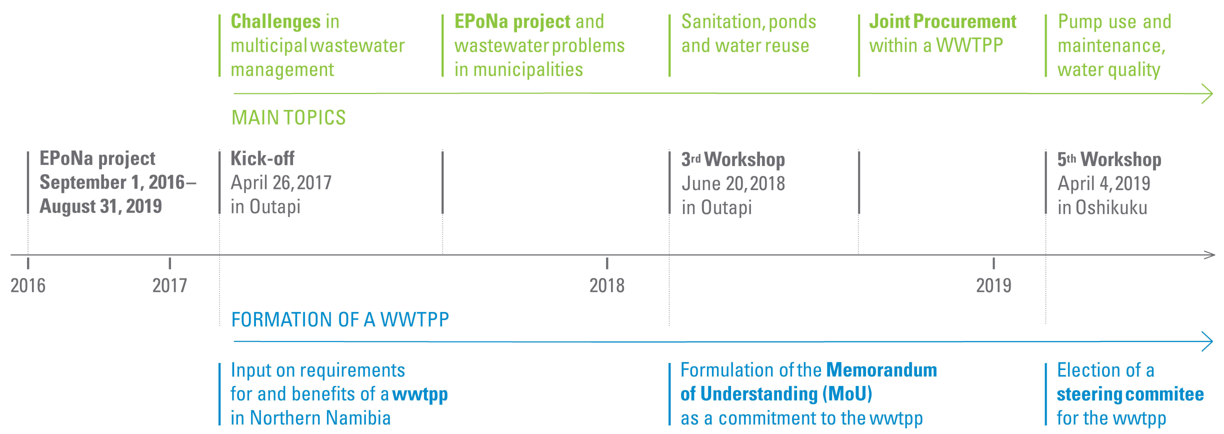


FIGURE 3
Main topics addressed and formalization of the wastewater treatment plant partnership (wwtpp) in Central Northern Namibia.

We have identified the following challenges in the site visits to WSP in the study region in 2017[4] and subsequent discussions in the partnership[5]:

Firstly, general financing problems and insufficient maintenance lead to mismanagement and eventually overflowing of WSP. On average, less than half of the population is connected to municipal wastewater systems. Household costs for wastewater infrastructure and services are a barrier to wider coverage. However, municipalities struggle with lowering the fees as there is no governmental budget to support maintenance of the treatment plants, which would enhance their longevity and capacity.

Secondly, a lack of capacity development and specialized training furthermore lead to mismanagement of the WSP and puts a further constraint on budgeting. In some municipalities, for instance, covering costs for staff trainings burdens the same financial pool as maintenance of the treatment system. Mismanagement of WSP in form of omissions to desilt ponds contributes to blocking of pumps and overflowing, especially in the rainy season.

Thirdly, many citizens are reportedly not aware about what not to dispose through the wastewater systems, nor about reuse potential of treated wastewater. Plastic waste and hygiene articles accumulate in pipes and WSP. Other inflows that affect the water quality are detergents from car wash and fat from restaurants. Reuse of the treated wastewater is difficult to realize in the municipalities, mainly because decision-makers and technicians consider cultural views, societal disapproval and insufficient water quality as hindering factors.

4 The field notes were documented in the form of unpublished operational reports Stegemann (2017).

5 See minutes of the wwtpp's meetings ISOE—Institut für sozial-ökologische Forschung (2017a,b, 2018a,b, 2019).

Learning

By combining input from experts and topic-related exchange at eye level, the wwtpp enables learning and creates opportunities for collaboration. At the second meeting, for example, the dimensioning of WSP, a lack of technical know-how in the municipal administrations, problems with pumps and spare parts as well as reuse potentials were discussed. At the third workshop, water reuse and the technical handling of WSP were key topics discussed and illustrated at a visit to the EPoNa pilot plant for wastewater treatment and reuse in feed production. The central theme of the fourth meeting was public and municipal procurement and tendering. The Head of the Procurement Unit of the Namibian Ministry of Finance gave a presentation and was available for questions and discussion. In particular, the options, potentials and prerequisites for joint tenders and contract awards in the wwtpp were identified.

At the fifth meeting, participants discussed questions about spare parts and tools for pumps (e.g., can these be used jointly by neighboring municipalities?), pumping stations (e.g., where are the weak points and how can the regional municipalities support each other?), purchasing and tenders (e.g., what are the advantages of joint tendering for maintenance services?) as well as education and training (e.g., how can corresponding requirements be covered jointly?). Another topic was water quality with regard to wastewater treatment and quality standards for irrigation and drinking water. The input and subsequent discussion addressed the differentiation between different water qualities and associated uses as well as technical, financial and institutional aspects of water use. In subsequent discussion groups, the hurdles and potentials of water reuse were the main topic.

Interviewees state effects of mutual learning and knowledge exchange: "because [the wwtpp] creates a networking platform. We can always assist each other, and we can learn from best

TABLE 1 Drivers, scopes and institutional structures of wwtpp.

	Characteristics of the wwtpp in central northern Namibia
Incentives/drivers for partnering	Enhanced environmental and public health risk from insufficiently managed wastewater in context of limited capacity at municipal level and dynamic population growth
Scope	Capacity: Enhancing technical, operational and strategic management capacities in municipalities Financial: Joint procurement envisioned; potential for reducing municipal costs by appointing consultants and contractors jointly identified but not yet implemented Socio-political: enhancing bargaining power Infrastructure: improved maintenance and efficiency of WSP and pumps through sharing of technical resources
Nature of institutional structures (Partnership type)	Network of local and regional authorities initially coordinated by research partners; external expert inputs

practices from others and probably emulate the best practices in our own town." (wwtpp member Mr. R.,[6]). They furthermore stress the relevance of capacity development based on expert input: "I think what we need is, as I indicated, a partnership. Once we got a partnership in place, the whole concept will come in from the technical point of view. (…) currently, what I belief we need, is experts or expertise from some areas. The structure which I think is going to work, is that the stakeholders who have to get involved with us, they need to learn from EPoNa and also from other stakeholders, just to have expertise, who are able to inform us (…)" (wwtpp member Mr. S.).

Table 2 summarizes key characteristics of the wwtpp regarding formats and topics of knowledge exchange.

Involving stakeholders for capacity development

Bringing together diverse actors involved in water governance in the case study area at the partnership's workshop enabled social learning in constellations unlikely to be addressed in formal formats (e.g., technicians and CEOs). While partners of the network appreciated this dimension, needs for technical expertise were also high on the agenda (see quote above and list of identified capacity needs). Treating specific technical questions, however, raises questions on whose knowledge to

6 All initials have been changed to maintain anonymity.

TABLE 2 Topics and formats of knowledge exchange.

	Characteristics of the wwtpp in central northern Namibia
Formats of knowledge exchange	Semi-formal meetings (workshops) with expert input and more informal peer-to-peer learning in group discussions
Topics	operational and strategic management topics, e.g., water reuse, joint procurement, pump maintenance and water quality

integrate. Here only those topics were addressed at workshops that a variety of actors could relate to. In particularly at the fourth workshop under the theme of joint procurement several key actors (namely: councilors and financial managers of the collaborating municipalities) were absent and technicians present who could not relate well to the topic discussed. This indicates a potential difficulty in managing a flexible network without losing commitment. It may also hint to a need for strengthening integrative governance capacities (van der Molen, 2018) in municipalities, and for further knowledge-exchange on the multitude of knowledge and competencies needed in adaptive water governance.

Governance capacities

The partnership created in form of the wwtpp established a semi-formal arrangement for governing municipal waters parallel to more hierarchical state authorities and structures. It potentially compensates lacks in meta-governance. At the same time, political interests may also hinder stability and effectiveness of the partnership.

Enhancing negotiation power

Interviewees stress the potential benefit of economies of scale and of enhancing negotiation power of the wwtpp: "when you go as an individual town it won't be heard, but if you come with more towns who have the same conditions and the same problems, the government might listen and fund us. (…) I think when all the towns go to the government with one voice, with one proposal and request of funds to overcome this problem, I think it would work." (wwtpp member Mr. H.). However, during the process, structural limitations to capacity development at municipal level become visible in the course of network establishment. Most importantly, the institutional context of devolution of responsibility for municipal wastewater management in North Central Namibia, where most municipalities and their governments have only existed for <2 decades, has led to outsourcing of all major planning steps from initial design to technical maintenance. In this context of dependency on consultants, options and opportunities for sharing costs by exchanging tools and machines are barely visible to municipal decision-makers. Further stock-taking and situational analyses are needed to start collaborating on specific technical items and associated tendering. Moreover, council members increasingly raised the issue of political backing needed for a meaningful commitment to the wwtpp. This will involve broad awareness raising in the wider public, as well as among local politicians.

Potential of partnerships under weak meta-governance

The dependency of collaboration in the wwtpp on political support reveals a weakness in government capacities in the hierarchical mode: Here the devolution of competencies under the umbrella of decentralization without respective budget authority appears to create a lock-in. Local authorities are hardly able to establish and maintain water management systems based on the capacities they have. Pertaining to the network governance mode, the wwtpp may serve to compensate deficiencies in the hierarchical mode, for instance by joining resources and enhancing negotiation power, as outlined above. Given its flexible structure and openness to involve higher level authority stakeholders, it potentially also supports a stronger meta-governance of water. In its current mode, this potential is however highly dependent on political backing currently not in place.

Discussion

Key lessons learnt

The potential of wwtpp for capacity development in water reuse lies in the immediacy and flexibility of knowledge exchange and sharing of capacities. Topics addressed at wwtpp meetings ranged from basic technical know-how on the maintenance of pumps, procurement options in financing infrastructure and related services to strategic decisions on water management, namely introducing water reuse as a response to pressing challenges in both water supply and environmental health. An MoU served to formalize and institutionalize participation of various stakeholders and their engagement in dialogues, facilitating knowledge and capacity development as well as creating awareness for the topic beyond the networks. A great potential of wwtpps lies in creating synergies by sharing costs for instance for investment in technical items (e.g., spare parts, machinery) and services, such as consultation of engineers. This flexibility in addressing knowledge gaps as they show to be relevant (needs-based) characterizes the case. It appears particularly appropriate for creating capacity in water reuse, given the limited knowledge on reuse and its governance at the hands of decision makers, operators and technicians.

Differences in knowledge and perceptions became evident between technicians, managers, environmental health officers, amongst others; hence, establishing shared knowledge on water reuse is both a potential and a challenge in the current wwtpp. A positive perception of reuse amongst politicians and wider public was identified as crucial, because they are key stakeholders in budget relevant decisions on how current capacity needs in the water sector are addressed. All of these actors' perceptions are needed for system transformation toward water reuse. The wwtpp has the potential for change in attitudes toward reuse and putting it on the political agenda. However, its existence is at the same time dependent on wider political interests.

The experiences from Namibia have moreover revealed core issues in the design and implementation of wwtpps. There was, first, the consolidation of the network, which required a certain formalization. The clear designation of roles and tasks within the network in the Memorandum of Understanding proved to be an important factor in obtaining an explicit declaration of membership by local administrations (especially the steering committee). The latter is important to ensure the organization of events and related expenses. Thus, the informal exchange is still an important element at the meetings, but the basic structure—contrary to the original conception—has a comparatively formal character. Secondly, a remaining challenge is the networking and organization of the steering committee beyond the meetings. Here it is necessary to develop new routines and lived practices.

Thirdly, it became increasingly apparent that the high dependency of the administrations on external consultants in the planning, procurement and maintenance of WSP impeded the exchange of experience at the technical level: at times, the participants lacked detailed knowledge, for example to specify possibilities for the exchange of technical resources. This shows two things: firstly, that it is reasonable to limit the group of participants to certain functions in order to further deepen the knowledge on individual topics in the wwtpp, and secondly, that there is still a great need to build up competences within the municipalities, which cannot be covered from within the network. With the development of the wwtpp, a format has been created here to enable, for example, training across municipalities.

In sum, the following factors for setting up wwtpps for capacity development can be derived.

Adjusting institutional structures to context specific requirements: The case shows that the degree of formalization and the interaction of more and less formal structures need to be in line with requirements for uncomplicated exchange of information and participation of relevant stakeholders. Here formalization was a prerequisite to ensure for instance coverage of travel costs.

Maintaining flexibility in formats and topics: As topics emerge in discussions, the need for specific formats of collaboration and knowledge exchange ought to be adjusted. In Namibia, a continued need for expert input on technological know-how was identified by participants.

Matching topics and participants: While initial workshops addressed multiple stakeholders from operational to managing/CEO levels, it soon became clear that peer-to-peer exchange on specific topics (such as maintenance of pumps; joint procurement; introduction of water reuse) requires a selection of participants according to functional group and everyday working environment. Being aware of financial implications of any measure discussed and involving respective stakeholders, however, is a cross-cutting issue.

Principle of proximity: Ensuring manageable travel distances for meetings enhances chances of continued commitment and interaction.

Regular meetings: Because the knowledge exchange is based on personal interaction, meetings need to be held regularly; the rotation of host enhances commitment, ownership of the partnership and spreads the burden of organizational duties.

Political backing: The support by political decision-makers (town and regional councilors) is key to enable changes in management, and to maintain activities in the wwtpp especially given the costs and personnel involved.

Municipal partnerships as a contribution to capacity development in water governance

Establishing a pilot treatment and reuse system at the WSP in Outapi was a core component of the Epona project that demonstrated the effectiveness of reducing environmental health risks (i.e., the level of pathogens in water discharge from WSP and reducing freshwater demand by reusing water in agriculture.). Based on the assessment of E.coli, pathogen reduction was considerable (Mohr et al., 2020). The project results on this technical innovation and its impacts on society and nature have been published elsewhere (Zimmermann and Neu, 2022) and did not form part of the present analysis. However, they underline the potential of developing capacity in water reuse at municipal levels for sustainable water governance. The anticipation of these results were furthermore a core motivation of municipalities' stakeholders to join the partnership. In the remainder of this section, we discuss the core findings on establishing a municipal partnership as a contribution to capacity development in water governance, focusing on municipal water reuse.

Our research has shown that great potential lies in the sharing of costs and equipment through the partnerships. Challenges in implementing capacity development through wwtpp, however, emerged in relation to the calculation of costs and benefits of reusing water. In an alternative calculation of sanitation costs investment in water reuse systems is to be assessed against the avoided environmental health costs for discharging untreated wastewater in an arid area (Di Mario et al., 2018). This involves novel forms of collaborations within and across municipal authorities. However, municipalities rely on the expertise and technological skills of consultants in managing wastewater, and any investment in wastewater management (including in capacity development) is dependent on political interest, given the tight budgets municipalities have.

Outsourcing of public responsibilities in provision of services (here: wastewater treatment and sanitation) has led to outsourcing of both technology and know-how, reinforcing low levels of institutional capacity within the municipalities, and creating dependency on external consultants. Consultants tend to continue the tradition of sectoral knowledge development. Here the case findings substantiate the claim by (Muller, 2018) whereby (international) large consultancies and specialized firms tend to act as knowledge gatekeepers, diminishing local government capacities, a process he terms "recolonization" in the South African water sector. The wwtpp has the potential to counter these structures and promote local level leadership through joint procurement for consultancy services and training, as was identified on the fourth meeting of the wwtpp in Namibia.

The process of implementing a wwtpp in Northern Namibia has revealed specific requirements for the design of a municipal partnership for capacity development, above all the need for formalization of the partnership at an early stage. This mirrors literature on adaptive governance whereby a federal governance frame enables greater flexibility at lower levels of decision-making, whereas a more centralized, hierarchical governance frame (as here in Namibia) calls for more rigid structures at lower levels (Koontz et al., 2015). Intersections with authoritative modes of governance (Pahl-Wostl, 2019) appear to be crucial to the performance of wwtpps, especially as municipalities' and individuals' commitment to participate is dependent on higher level budget decisions. The case suggests that an MoU can embed a municipal partnership as part of a hybrid water governance style (Pahl-Wostl, 2019) and contribute to government backing of capacity development for water reuse (Di Mario et al., 2018). In the present case, this was particularly relevant as municipalities' and individuals' commitment to participate is dependent on higher level budget decisions.

In sum, the experiences from the EPoNa project show an urgent need for creating synergies in capacity development among municipalities that a wwtpp may serve to address. The partnership established created a space for both formal and informal mutual learning. We have identified a great potential for developing and strengthening capacities and reducing municipal costs for wastewater treatment, in particular when combined with technical innovations, such as here a treatment system for water reuse in agriculture. How this potential of the wwtpp can be used will depend on the long-term commitment of town councils to work in partnership for which political backing is key (see also: Beveridge et al., 2017; Muller, 2018).

Conclusion

Our analysis of a newly established informal public partnership on wastewater treatment and reuse (wwtpp) has revealed the potential of municipal partnerships to facilitate capacity development in managing municipal water and sanitation, here by reusing water in agriculture. In transdisciplinary workshop settings we exposed core topics for capacity development, namely: general financing problems and insufficient maintenance that lead to mismanagement and eventually overflowing of WSP, specialized training on management of WSP, and public awareness about what not to dispose through the wastewater systems, as well as about reuse potential of treated wastewater. The capacity needs identified show the culmination of deficiencies in wastewater infrastructure (here: WSP) and its management, rising water demands and sanitation needs in environmental health concerns. In particular the need for more holistic comprehension of wastewater management as part of a vulnerable (urban) water and sanitation system (Bahri, 2009) became apparent in the collection of core challenges in wastewater management in the partnering municipalities. The wwtpp provided a platform for deepening respective knowledge, predominantly through expert inputs from the EPoNa project. It moreover spurred discussion over strategic decisions in water management to overcome current environmental risks resulting from exploitation of freshwater resources and overflowing of WSP. Overall, we identified six key factors to bear in mind when designing a wwtpp for capacity development. These are (1) context-specific institutional set-up, (2) flexibility in formats and topics, (3) matching topics and participants, (4) principle of proximity, (5) regular meetings, and (6) political backing.

To conclude, the research presented expands existing research on water reuse governance on three levels.

(1) On a practice-oriented level, the analysis of the wwtpp has shown that municipal collaboration not only serves to share and disseminate new knowledge effectively. More importantly, the format of wwtpps allows new knowledge to emerge, and for knowledge needs to be identified and addressed immediately. This appears to support social-ecological transformation of municipal water management toward sustainable solutions. A flexible structure of the partnerships is helpful; at the same time, conditions for participation must be clear. Wwtpps moreover have the potential for disrupting disempowering structures (here: dependency on consultants) by generating enhanced capacity for negotiation and alternative financing through partnerships, and by reducing the reliance on external expert knowledge. Political interests and power structures deserve continued attention in future research and implementation of similar arrangements. Future evaluations of the pilot's effectiveness in improving sanitation and contributing to water use efficiency will potentially foster political support for reusing water.

(2) The research presented contributes to a more differentiated understanding of 'implementation barriers' in the water reuse governance debate, primarily by distinguishing between the perceptions and knowledge of researchers, technicians, engineers, consultants, and politicians, in a more differentiated perspective on "awareness". Closing the "implementation gap" involves opening up processes of knowledge production, and re-conceptualizing the process of "implementation" in water reuse debates—moving beyond need for awareness raising and knowledge transfer toward knowledge integration and learning across sectors and levels.

(3) Our findings on capacity development in water reuse governance furthermore add to the field of sustainable water governance more widely. We have demonstrated the potential of such partnerships to compensate for gaps in integration across levels and sectors (meta-governance; Pahl-Wostl, 2019), especially where coordination at regional and national levels is weak. In the case analyzed, the legacy of poor capacity development and limited resources in municipal water management involves a strong reliance on external consultants and political will for implementing transformational change in managing municipal waters. Here or findings raise important questions on dealing with power relations in knowledge production for adaptive governance.

As van der Molen (2018) argues, "building well-informed environmental governance arrangements is not just a matter of managing the interfaces between knowledge and governance; it is also a matter of capacity-building in order to enable the reflexivity of governance arrangements." (p. 24). While the partnership performed as a forum for flexible knowledge exchange and learning in peer to peer, science experts to practitioners, and policy-makers to policy-implementers constellations, the decisive role of consultants and political decision makers may counteract learning toward transformational change. Demonstrating the potential of technical innovations in the field in a pilot project was a core element in the wwtpp analyzed here. It was central to exposing technical capacity needs and path-dependencies in the distribution of technical know-how (and respective gaps) among key actors. Against this background, incorporating and integrating technical innovations in capacity development not only in local partnerships but across levels and modes of governance is central to actuate capacities along the meta-governance framework. Future research should engage further with the roles of consultancy and political decision-making in order to identify further pathways toward sustainability transformations in municipal water governance.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Institute of Social-Ecological Research (ISOE)'s Ethical Board, ISOE. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Research conception: MZ, TK, and FF–T. Writing: FF–T. Supervision, project administration, and funding acquisition: MZ. Data collection and analysis: All authors.

Funding

This work was accomplished as part of the project EPoNa—Enhancement of Ponds in Northern Namibia (Grant Number 02WAV1401A), funded by the German Federal Ministry of Education and Research (BMBF). This work was further supported by the German Federal Ministry of Education and Research (BMBF) as part of the project regulate—regulation of groundwater in telecoupled social-ecological systems under funding no 01UU2003A, within the framework of the Strategy Research for Sustainability (FONA) www.fona.de/en (accessed on 13 October 2021) as part of its Social-Ecological Research funding priority.

Acknowledgments

The authors thank all members of the wastewater treatment plant partnership in Northern Namibia and participants at the workshops for their close cooperation and open discussion. We particularly acknowledge the commitment of the Outapi Town Council to this research endeavor. We furthermore thank Sophia Keller, Felix Neu and Corinna Saß for their support of our research activities. We thank Markus Rauchecker, the editor and three reviewers for their valuable comments on earlier versions of the manuscript.

Conflict of interest

SS was employed by Emschergenossenschaft.

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

Publisher's note

References

Bahri, A. (2009). *Managing the Other Side of the Water Cycle: Making Wastewater an Asset. Edited by Global Water Partnership Technical Committee. Mölnycke, Sweden* (TEC Background Papers, 13).

Beveridge, R., Moss, T., and Naumann, M. (2017). Sociospatial understanding of water politics: tracing the multidimensionality of water reuse. *Water Altern.* 10, 22–40.

Boag, G., and McDonald, D. A. (2010). A critical review of public-public partnerships in water services. *Water Altern.* 3.

Boelens, R. (2009). The politics of disciplining water rights. *Dev. Change* 4:307–31. doi: 10.1111/j.1467-7660.2009.01516.x

Bos, J. J., and Brown, R. R. (2012). Governance experimentation and factors of success in socio-technical transitions in the urban water sector. *Technol. Forecast. Soc. Change.* 79, 1340–1353. doi: 10.1016/j.techfore.2012.04.006

Cleaver, F., and Whaley, L. (2018). Understanding process, power, and meaning in adaptive governance: a critical institutional reading. *Ecol. Soc.* 23, 49. doi: 10.5751/ES-10212-230249

Di Mario, L., Rao, K., and Drechsel, P. (2018). The enabling environment and finance for resource recovery and reuse. 19. *In Miriam Otoo, Pay Drechsel (Eds.). Resource recovery from waste. Business models for energy, nutrient and water reuse in low- and middle-income countries. London, New York: Earthscan from Routledge Taylor and Francis Group, pp*. 777–800.

Government Gazette of the Republic of Namibia (2004). *Water Resources Management Act 2004. Act No. 24, 2004*. Windhoek, Namibia.

Government Gazette of the Republic of Namibia (2013). *Water Resources Management Act 2013. Act No. 11, 2013*. Windhoek, Namibia.

Hofste, R. W., Kuzma, S., Walker, S., Sutanudjaja, E. H., Bierkens, M. F. P., Kuijper, M. J. M., et al. (2019). *Aqueduct 3, 0. Updated Decision-Relevant Global Water Risk Indicators*. Washington, D.C., USA: World Resources Institute. Available online at https://www.wri.org/publication/aqueduct-30 (accessed November 11, 2022).

Hooli, L., Jauhiainen, J. S., and Lähde, K. (2016). Living labs and knowledge creation in developing countries: Living labs as a tool for socio-economic resilience in Tanzania. *Afr. J. Sci. Technol. Innov. Dev.* 8, 61–70. doi: 10.1080/20421338.2015.1132534

Hummel, D., Jahn, T., Keil, F., Liehr, S., and Stieß, I. (2017). Social ecology as critical, transdisciplinary science—conceptualizing, analyzing and shaping societal relations to nature. *Sustainability*. 9, 1050. doi: 10.3390/su9071050

ISOE—Institut für sozial-ökologische Forschung (2017a). *Minutes of the 1st Wastewater Treatment Plant Partnership Workshop. Outapi Town Hotel, April 26th, 2017, 11am—12.30pm*. Tokyo: EPoNa (unpublished).

ISOE—Institut für sozial-ökologische Forschung (2017b). *Minutes of the 2nd Meeting of the Wastewater Treatment Plant Partnership. October 18th, 2017*. Outapi: Outapi Town Hotel.

ISOE—Institut für sozial-ökologische Forschung (2018a). *Minutes of the 3rd Meeting of the Wastewater Treatment Plant Partnership. June 20th, 2018*. Outapi: Outapi Town Hotel.

ISOE—Institut für sozial-ökologische Forschung (2018b). *Minutes of the 4th Meeting of the Wastewater Treatment Plant Partnership*. *Okahao* (accessed on October 25, 2018).

ISOE—Institut für sozial-ökologische Forschung (2019). *Mintutes of the 5th Wastewater Treatment Plant Partnership*. *Oshikuku* (accessed on April 4, 2019).

Kemerink-Seyoum, J. S., Chitata, T., Domínguez Guzmán, C., Novoa-Sanchez, L. M., and Zwarteveen, M. Z. (2019). Attention to sociotechnical tinkering with irrigation infrastructure as a way to rethink water governance. *Water* 11, 1670. doi: 10.3390/w11081670

Kjellén, M. (2018). Wastewater Governance and the Local, Regional and Global Environments. *Water Altern*. 11, 219–237.

Koontz, T. M., Gupta, D., Mudliar, P., and Ranjan, P. (2015). Adaptive institutions in social-ecological systems governance: a synthesis framework. *Environ. Sci. Pol.* 53, 139–151. doi: 10.1016/j.envsci.2015.01.003

Lackner, S., Sinn, J., Zimmermann, M., Max, J., Rudolph, K-. U., Gerlach, M., et al. (2017). Upgrading waste water treatment ponds to produce irrigation water in Namibia. *Watersolutions* 158:82–85.

Ministry of Agriculture, Water and Rural Development (2000). *National Water Policy White Paper*. Policy Framework for Equitable, Efficient and Sustainable Water Resources Management and Water Services. Edited by Republic of Namibia. Namibia.

Mohr, M., Dockhorn, T., Drewes, J. E., Karwat, S., Lackner, S., Lotz, B., et al. (2020). Assuring water quality along multi-barrier treatment systems for agricultural water reuse. *J. Water Reuse. Desalin*. 10, 332–346. doi: 10.2166/wrd.2020.039

Moodley, S. (2019). Defining city-to-city learning in southern Africa: Exploring practitioner sensitivities in the knowledge transfer process. *In Habitat International* 85, 34–40. doi: 10.1016/j.habitatint.2019.02.004

Muller, M. (2018). Decolonising engineering in South Africa—Experience to date and some emerging challenges. In S. Afr. J. *Sci* 114 (5/6). doi: 10.17159/sajs.2018/a0270

Pahl-Wostl, C. (2019). The role of governance modes and meta-governance in the transformation toward sustainable water governance. *In Environmental Science and Policy* 91, 6–16. doi: 10.1016/j.envsci.2018.10.008

Pahl-Wostl, C., Becker, G., Knieper, C., and Sendzimir, J. (2013). How Multilevel Societal Learning Processes Facilitate Transformative Change: A Comparative Case Study Analysis on Flood Management. *In Ecology and Society* 18 (4). doi: 10.5751/ES-05779-180458

Pelling, M., High, C., Dearing, J., and Smith, D. (2008). Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organisations. *In Environment and Planning A* 40, 867–884. doi: 10.1068/a39148

Republic of South Africa (1956). Water Act 54 of 1956 (SA). Windhoek, Namibia. Available online at http://extwprlegs1.fao.org/docs/pdf/saf1272.pdf.

Sanz, M. P., Veenstra, S., de Montalvo, U. W., van Tulder, R., and Alaerts, G. (2013). What counts as 'results' in capacity development partnerships between water operators? A multi-path approach toward accountability, adaptation and learning. *Water Pol*. 15, 242–266. doi: 10.2166/wp.2013.022

Silva, P., Teles, F., and Ferreira, J. (2018). Intermunicipal cooperation: The quest for governance capacity? *In International Review of Administrative Sciences* 84, 619–638. doi: 10.1177/0020852317740411

Sinn, J., Cornel, P., and Lackner, S. (2019). Waste stabilization ponds with pre-treatment provide irrigation water—a case study in Namibia. 12th IWA International Conference on Water Reclamation and Reuse.

Stegemann, S. (2017). *Tätigkeitsbericht Outapi* (Internal project report) Unpublished.

UN Water (2020). *The Sustainable Development Goal 6 Global Acceleration Framework*. Geneva: UN-Water

United Nations (2020). *The Sustainable Development Goals Report 2020*. New York: United Nations (UN).

United Nations General Assembly (2017). *Resolution adopted by the General Assembly on 6 July 2017. A/RES/71/313.*

van der Molen, F. (2018). How knowledge enables governance: The coproduction of environmental governance capacity. *Environ. Sci. Pol.* 87, 18–25. doi: 10.1016/j.envsci.2018.05.016

Wanner, M., Hilger, A., Westerkowski, J., Rose, M., Stelzer, F., Schäpke, N., et al. (2018). Toward a cyclical concept of real-world laboratories. a transdisciplinary research practice for sustainability transitions. *disP Plann. Rev.* 54, 94–114. doi: 10.1080/02513625.2018.1487651

Zimmermann, M., Boysen, B., Ebrahimi, E., Fischer, M., Henzen, E., Hilsdorf, J., et al. (2021). Replication Guideline for Water Reuse in Agricultural Irrigation. Upgrading wastewater pond systems to generate irrigation water for animal fodder production using the example of Outapi, Namibia (ISOE—Materialien Soziale Ökologie, 63). Available online at https://webopac.isoe.de/read/pdfs/msoe-63-isoe-2021.pdf (accessed on June 2, 2022).

Zimmermann, M., Deffner, J., Müller, K., Kramm, J., Papangelou, A., Cornel, P., et al. (Eds.) (2015). *Sanitation and Water Reuse—Implementation Concept. Frankfurt am Main*. Germany: ISOE—Institut für sozial-ökologische Forschung (CuveWaters Papers, 11).

Zimmermann, M., Liehr, S., Kluge, T., and Cornel, P. (2019). Integrating Sanitation, Water Reuse and the Production of Food Crops-—6 Years of Experiences in Central Northern Namibia. *Presentation at the 12th IWA International Conference on Water Reclamation and Reuse. IWA International Conference*. Berlin, 6/16/2019.

Zimmermann, M., and Neu, F. (2022). Social-ecological impact assessment and success factors of a water reuse system for irrigation purposes in Central Northern Namibia. *Water*. 14, 2381. doi: 10.3390/w14152381

frontiers | Frontiers in Water

TYPE Policy and Practice Reviews
PUBLISHED 10 November 2022
DOI 10.3389/frwa.2022.1022730

Water policy, politics, and practice: The case of Kitui County, Kenya

Johanna Koehler[1,2]*, Cliff Nyaga[2], Rob Hope[2], Pauline Kiamba[3], Nancy Gladstone[2], Mike Thomas[3], Albert Mumma[4] and Andrew Trevett[5]

[1]Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, Netherlands, [2]Smith School of Enterprise and the Environment, University of Oxford, Oxford, United Kingdom, [3]Rural Focus Ltd., Nairobi, Kenya, [4]Faculty of Law, University of Nairobi, Nairobi, Kenya, [5]United Nations Children's Fund (UNICEF), Luanda, Angola

Check for updates

OPEN ACCESS

EDITED BY
Sara Marks,
Swiss Federal Institute of Aquatic Science and Technology, Switzerland

REVIEWED BY
Jaap Evers,
IHE Delft Institute for Water Education, Netherlands
Özge Can Dogmus,
Mehmet Akif Ersoy University, Turkey

*CORRESPONDENCE
Johanna Koehler
johanna.koehler@vu.nl

SPECIALTY SECTION
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

RECEIVED 18 August 2022
ACCEPTED 10 October 2022
PUBLISHED 10 November 2022

CITATION
Koehler J, Nyaga C, Hope R, Kiamba P, Gladstone N, Thomas M, Mumma A and Trevett A (2022) Water policy, politics, and practice: The case of Kitui County, Kenya.
Front. Water 4:1022730.
doi: 10.3389/frwa.2022.1022730

The devolution of governance to county level in Kenya provides a window for innovation in water policy and practice, critical to improving water security in rural areas where almost half of households lack basic water services. In rural Kitui County, Kenya, a number of projects supported by different funders have served as policy experiments over the past 10 years. We apply an action-oriented knowledge framework to explore the kinds of knowledge that have been produced in the course of these interventions and reflect on what kinds of knowledge are contributing to institutional change and how they are contributing to sustainability in the rural water sector. Actionable recommendations for the further development of county-level water policy include: First, ensure local ownership of the policy-making process whilst enabling appropriate technical and legal support; second, take long timeframes of institutional change into account in donor programming; third, establish water, sanitation and hygiene forums bringing diverse actors within the sector together to build cohesion, facilitate knowledge exchange, enable collaborative learning, and deliver collective action.

KEYWORDS

water policy, water services, decentralization, policy experiments, pluralism, knowledge, sustainability, Kenya

Introduction

Policy practices

Since the late 1980s, over 80 percent of developing countries have adopted some form of decentralization due to widespread international support for decentralized governance (Crawford and Hartmann, 2008) with the goal being to address pressing social, economic and environmental challenges. Specifically, the goal comprises poverty reduction, conflict resolution, and the improvement of basic service provision, *inter alia*. The water sector in Kenya is undergoing significant institutional change following the country's governance reform (Cheeseman et al., 2016; Koehler, 2018; Koehler et al., 2021), which provides policy windows to test and implement wide-ranging sector change required for progress toward universal basic water services by 2030. The challenge is particularly acute in rural areas, where just under half the population live without access to basic or safely managed water services (WHO/UNICEF, 2021).

Decentralization reforms are commonly introduced to improve accountability and responsiveness of government by altering the distribution and structure of resources, responsibilities, and accountability (Smoke, 2003; Conyers, 2007; Faguet, 2014; Gaynor, 2014; Mwihaki, 2018). While decentralization is often presented as a common tool in water policy to improve service delivery, it often fails to deliver on its promises (Robinson, 2007). Further, Prasad (2006) argues that the profit-seeking motive of the private sector seems difficult to reconcile with providing services to the poor due to its tendency to "cherry-pick" better-off customers in less risky environments. Whilst public, private, and civil society actors are active in experimenting and driving the future direction of water policy, experience with such reforms and outcomes for the water services sector are mixed.

We reflect on policy practices over the past 10 years in one of Kenya's larger counties, Kitui County, where the majority of the 1.13 million people reside in rural areas. Three kinds of knowledge are examined that can be used to support actions for sustainability of the rural water sector: knowledge that informs intentional design, knowledge that enhances shared agency, and knowledge that enables contextual realization (Caniglia et al., 2021). We use this framework to reflect on how research in Kitui has helped actors engage with different kinds of knowledge and how that has created change.

Policy change in Kenya's water sector

The Constitution of Kenya 2010 made some significant changes to governance structures, including introducing counties as a devolved level of government with specified mandates, which included, among others, water and sanitation services, stormwater drainage, soil and water conservation and the responsibility to ensure public participation in public affairs (Government of Kenya, 2010). The new county governments came into effect after the 2013 general election with the requirement to establish county policies and legislation consistent with the constitution and national policies and legislation.

Devolving water services to the 47 counties has posed a major challenge for the new county-level institutions creating the potential for growing regional discrepancies. To streamline the process and level the field, new laws, policies, and regulations are needed. However, political processes are unfolding in parallel with the technocratic building of institutions. We identify four institutional interests that may interfere in and perturb systematic, linear sector change and are outlined in the following paragraph: (a) national-county power dynamics; (b) within-county power dynamics; (c) community alignment, and (d) externally driven policy experiments.

The national Water Act 2016 clarifies some aspects of service provision and the structure of the new subnational institutions; however, county budget allocations, especially for the rural water sector and institutions such as schools and clinics remain ambiguous (Hope et al., 2021). Within county water directorates there are varying political processes that are not clear from the outside. This includes varying agendas of the Members of County Assembly (MCA) and the County Executive Committee (CEC), who are partly motivated by election cycles and community support (Koehler, 2018), and the interests of the bureaucratic elite, which may diverge. In terms of community alignment, voting blocs may emerge in alignment with politically associated investments in local economic infrastructure, which can influence adoption or rejection of new approaches. Finally, development projects—viewed here as externally driven policy experiments—create implicit pressure for change and impact that may not always align with the strategic priorities set by the governor or other county-level government actors. This complex array of policy influences demonstrates the need for a legal framework at the county level to guide decision-making, operations, and financing in the water sector. The development of such a framework and its implementation will in turn be subject to these overlapping processes. However, we describe below how new knowledge contributions to intentional design, shared agency, and contextual realization have increased the likelihood of Kitui County achieving sustainable rural water services.

Policy window for research and policy engagement in the Kitui County water sector

Kitui County is Kenya's sixth-largest county by area (30,430 km^2), with 95 percent of the 1.1 million residents living in rural areas (KNBS, 2019). It has an arid and semi-arid climate featuring a bi-modal annual rainfall pattern. The longer dry season commences in May or June and lasts until rains arrive in October or November, but the seasons vary unpredictably and in some years there is very little rainfall for almost 6 months (Hope et al., 2021). For the 400,000 people in Kitui relying on surface water as their main drinking water source (KNBS, 2019) and those who practice rainwater harvesting via roofs and gutters, rock catchments and sand dams, the extended dry period creates water supply challenges. Groundwater resources, lifted by hand pumps or pumped to piped systems and kiosks using solar, electric or diesel power, offer a buffer against drought for many Kitui county residents, but there are issues with quality (natural salinity), infrastructure maintenance and functionality. In 2017, an audit of water infrastructure in the county identified 460 piped water schemes, of which only 56 percent were fully functioning, and 687 hand pumps, of which only 45 percent were fully functioning (Nyaga, 2019; Figure 1). With large-scale institutional change ongoing in the country, a policy window opened for rural water sector research and policy engagement. Permission for the research described in this study was agreed with the Kitui County Government, the national Ministry of Education and UNICEF (Kenya). The National Council for Science and Technology Institute awarded a research license to the University of Oxford and the University of Nairobi supported by ethical approval from the University of Oxford.

Projects as policy experiments

Rondinelli (1983) argues the more complex development problems, and the more uncertain the relationship between policy prescription and development outcome, the more necessary are simplifying models of change and detailed planning and management procedures. Mosse (2005) states that the relationship between policy and practice is understood in terms of an unintended "gap" between theory and practice, reduced by better policy more effectively implemented. He then asks the provocative question: "*What if, instead of policy producing practice, practices produce policy…*?" (p.3). He argues that changes to governance brought by development schemes cannot be imposed but require collaboration and compromise. Reputation and legitimacy—upon which governance depends—are scarce resources for governments, donors, state development agencies, or even NGOs operating in competitive environments (Li, 1999). The question is not *whether* but *how* a development project works, through its contribution to knowledge production during and beyond implementation; not whether a project succeeds, but how "success" is produced and claimed.

In this knowledge production process, key elements include control over the interpretation of events as power lies in the narratives that maintain an organization's own definition of the problem, the constant work of translation (of policy goals into practical interests and practical interests back into policy goals), and also creating order and unity through political acts of composition *of the social domain* despite ongoing fragmentation and dissent (Latour, 2000). In the context of Kitui County the "system" challenges require that government makes a tangible commitment via policy interpreting the challenges of rural water services in a future-oriented way, requiring an adequate composition of actors included in the system, translating their activities within a sanctioned composition.

Experiments as knowledge producers at the science–policy interface are expected to provide decision-makers with evidence of the effects of a policy (McFadgen and Huitema, 2018). We use Caniglia et al.'s (2021) pluralistic and integrated approach to action-oriented knowledge for sustainability to reflect on the processes of interpretation, translation, and composition across three dimensions of actions for sustainability: first, knowledge informing intentional design, second, knowledge enhancing shared agency by addressing differences in interests, views, values, and power, and third, knowledge enabling the realization of action in specific contexts.

Individual and social learning require that societal and academic actors develop a capacity for knowledge pluralism, which, according to Caniglia et al. (2021), can enhance sustainability science in two main ways: investigating the role of knowledge in action processes as well as navigating action processes through knowledge, which can help researchers and practitioners in the design, formative evaluation, and further development of interventions. In line with the authors' claim we recognize that if we want to contribute to shaping change toward sustainability through research, we need to shift away from the assumption that researchers should be separate from the processes of change that they investigate. That said, experimenting in real-world settings raises methodological questions around the participation of stakeholders as well as ethical questions around responsibility for and legitimacy of interventions (Bergmann et al., 2021).

In Kitui County, Kenya, a number of projects supported by different funders have served as policy experiments (see Figure 2). Activities led by the University of Oxford started in 2012 with the authors' involvement, leading to the establishment of the FundiFix company in 2014 and to supporting the registration of the Kitui Water Services Maintenance Trust Fund in 2016. This work was supported by research grants from DFID/FCDO (2011–14; 2015–2021), UNICEF (2014–16) and USAID (2016–2021). Moreover, FundiFix developments in Kitui County were informed by parallel work in Kwale County and with national policy-makers. Knowledge production was tied to different financing streams.

The UK Foreign, Commonwealth and Development Office (FCDO, formerly DFID) provided the original funding for the deployment of smart handpumps in Mwingi North from 2012 (see Section Outcomes), and through the REACH programme it provided policy direction with the wider objective of making over 10 million people water secure, thus guiding policy into the direction of water-related poverty alleviation.

The United Nations Children's Fund (UNICEF) has operated in Kenya for decades, supporting water and sanitation projects, coordinating the various actors in the rural water sector through regular Water, Sanitation and Hygiene (WASH) forums, and also funding the development of a professional maintenance service provision model.

The United States Agency for International Development (USAID) has also had several large-scale WASH-focused programs in the county, including the Kenya Integrated Water and Sanitation Program (KIWASH), Afya Halisi, and the

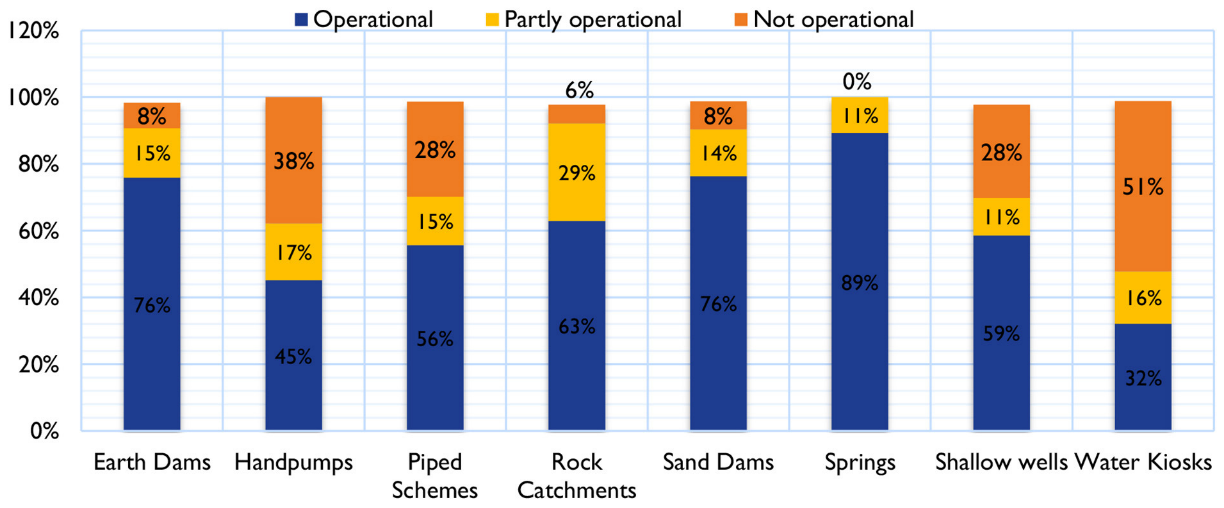


FIGURE 1
Functionality of Kitui County water sources on day of audit by source type (Source: Nyaga, 2019).

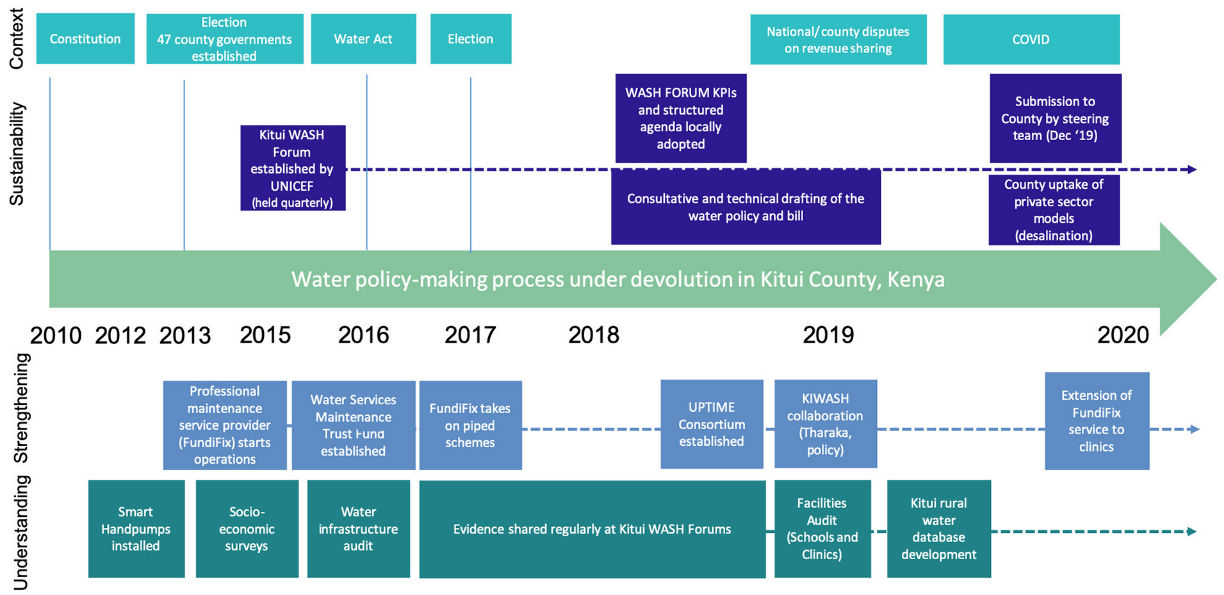


FIGURE 2
Timeline of policy experimentation and water policy-making in Kitui County, Kenya.

Sustainable WASH Systems (SWS) Learning Partnership. With broad actor recognition of the need for a legal framework at the county level to guide decision-making, operations, and financing in the water sector, a first county water bill is in development and due to be presented to the county assembly in 2022.

In Table 1 we use Caniligia et al.'s framework of kinds of knowledge supporting actions for sustainability to explore how various data collection activities and policy experiments in Kitui County provide knowledge and address the following questions: First, what understanding of the system and of information dissemination motivates policy development (intentional design)? Second, what collaborative approaches support the development of a policy that is both accepted and understood (shared agency)? Third, what implications do policy and legislation have on the long-term sustainability of service delivery (contextual realization)?

The following three sections explore the relationship between policy experiments, different kinds of knowledge

TABLE 1 Kinds of knowledge supporting actions for sustainability of the rural water sector in Kitui County, Kenya [adapted from Caniglia et al. (2021)].

	Kinds of knowledge	Description *Knowledge that…*	Examples of knowledge production and exchange in Kenya
Knowledge informing **intentional design**	Generative	Draws upon and engages with multiple perspectives for the creation of new and alternative social–ecological, institutional and cultural relationships and arrangements	Design and testing of professional service provider FundiFix
	Prescriptive	Informs recommendations about more desirable options to realize intentions and that guides and inspires actors in creating change	Water infrastructure audits (communities, schools, clinics) and household survey
	Strategic	Defines priorities of actions for the realization of intentions and that relies on an understanding of fits and misfits between intentions and context, the anticipation of possible consequences of actions and the capacity to change circumstances	Working papers, briefs, articles: evidence base for policy experimentation
Knowledge enhancing **shared agency**	Empowering	Enables agency (individual and collective), builds capacities and supports actors to realize intentions	Kitui WASH Forum Database development
	Co-produced	Emerges from collective processes, includes different actors and incorporates their diverse and divergent perspectives, views and interests	FundiFix negotiation with users and government (incl. contracting, tariff-setting, and revenue collection); integration of water quality monitoring
	Critical	Questions existing institutions, interrogates prevailing power asymmetries, and contests conventional assumptions and values	Paradigm disruption of community management; development of new legislation
Knowledge enabling **contextual realization**	Situated	Emerges from and is often tailored to specific contexts	FundiFix expansion to clinics and schools
	Tactical	Supports actors in advancing toward the realization of change by creating alliances and capitalizing on existing resources and opportunities	Water Services Maintenance Trust Fund
	Emergent	Knowledge generated in open-ended and exploratory cycles of intervention, reflection and evaluation	Kitui Water Policy and Bill

production and exchange activities and their influence on the policy process in Kitui County. It should be noted that most activities have primary and secondary contributions toward knowledge for rural water sustainability. Moreover, while the framework provides a useful classification, we recognize its general nature which has the consequence that there is no unique allocation of activities to the kinds of knowledge produced. Furthermore, the composition of authors with affiliations across research and private sector institutions, their interpretation of the framework, and translation with regard to specific activities in Kitui need to be highlighted in this context.

Knowledge production and exchange informing intentional design toward rural water sustainability

By establishing an intention to act, actors commit to creating change in situations characterized by normative uncertainties, contradictions, and political conflicts (Turnhout et al., 2020; Caniglia et al., 2021). The intention to act is usually supported by improved information through different knowledge production and exchange activities outlined below. These do not necessarily resolve conflicts but can reduce uncertainties.

The rural water challenge of how to achieve reliable water services for those parts of the population outside formal service provision areas has been extensively reported in the literature (Harvey and Reed, 2006; Whittington et al., 2008; Foster, 2013; Whaley and Cleaver, 2017) and provided the motivation for the intentional design and testing of a professional repair and maintenance service model in Kitui County, Kenya, called FundiFix (REACH, 2016). The type of knowledge obtained is generative – bringing different inputs together to create new and alternative institutional arrangements. In this case novel information gathered by smart handpumps enabled a reduction of days that handpumps remained broken from around a month to <3 days (Thomson et al., 2012; SSEE, 2014; Thomson, 2020) and a willingness-to-pay study with the rural communities gauged community interest and supported the design of the professionalized maintenance service model

(Koehler et al., 2015). Drawing on multiple perspectives the model constitutes a policy experiment built on the principles of professional services, smart monitoring, financial sustainability, and institutional coordination. Further knowledge production and exchange activities as well as funding requirements have contributed to the evolution of FundiFix to an established service, including its expansion from handpumps only to serving piped schemes in 2017. With growing user demand, though not always regular user payments, FundiFix is now providing around 55,000 people in Kitui County with reliable water.

In order to better understand the rural water situation in Kitui County several data collection activities were conducted: two water audits and the development of a WASH database. These generated prescriptive knowledge for WASH actors in the county and provided a basis for scaling the service from Mwingi North to other sub-counties.

The first water infrastructure audit included 3,100 rural waterpoints in 2017 in liaison with relevant county offices, including Office of the Governor, Ministry, and sub-County Water Officers. Better understanding the types and functionality of waterpoints across the county constituted knowledge that informs recommendations about options of possible improvements in the system (Nyaga, 2019). The audit data complement a household survey conducted in Mwingi North in 2018 and informed the development of a Kitui County Energy Plan in 2020, supported by IIED and CAFOD, with a pilot planned for the water sector due to the availability of extensive information. The audit data were also used by Kitui County Government to negotiate a planned World Bank investment in solar water infrastructure in the county. In addition, at the institutional level, an audit of water, sanitation and hygiene facilities in schools and healthcare facilities was developed in consultation with UNICEF Kenya, the Ministry of Education, and the County Ministries of Health and Water, and completed in October 2019, followed by dissemination through national and county platforms in 2020/21.

The facilities audit included 1,887 primary and secondary schools in Kitui County and 121 healthcare facilities, including hospitals, health centers and dispensaries (Hope et al., 2021; Katuva et al., 2022). The need for institutional coordination across the health, education, and WASH sectors is demonstrated by the evidence: half of the schools have no hand-washing facility, a third of healthcare dispensaries lack basic hygiene services and one in five lack basic water services, fewer than one in two schools report toilets as clean, few teachers have water quality concerns (4 percent) though monthly monitoring at schools reveals multiple hazards, including *E. coli*, fluoride, salinity, and nitrate. While both levels of government acknowledge the need for strategic action to expand the professional service to schools and health care facilities, at the time of writing specific commitment has yet to materialize.

Information generated in these activities has been synthesized in various knowledge products as part of a strategic approach to building an evidence base on Kitui's water sector, such as working papers, policy briefs and journal articles (Thomson et al., 2012; SSEE, 2014, 2015; Hope, 2015; Koehler et al., 2015, 2020; REACH, 2016; Nyaga, 2018, 2019; McNicholl et al., 2019, 2020; Hope et al., 2020, 2021; Foster et al., 2022; Katuva et al., 2022). These provide the evidence base for knowledge exchange with county and national government stakeholders, also to navigate the challenge of allocating responsibility in Kenya's devolved system, and with wider WASH actors in the public, private and civil society sectors. Academic output based on such policy experiments is also geared to contribute to sector change by providing new empirical and theoretical perspectives on the ancient challenge of rural water sustainability and by strategically influencing funding agencies in the design of their future WASH programming.

Knowledge production and exchange enhancing shared agency in rural water sustainability

Shared agency is a critical element in policy experiments to ensure credibility and legitimacy (McFadgen and Huitema, 2018). Improving sustainability usually requires that several individuals and organizations exercise their will by taking action in concerted ways. Shared agency for change is developed through social interactions, for instance in the case of cooperative efforts involving multiple societal actors in an organization (Caniglia et al., 2021).

First, institutional coordination in the form of the Kitui WASH forums provides an opportunity for actors to advance shared agency by creating alliances while capitalizing on existing resources and opportunities. Initiated by UNICEF, these forums are convened quarterly, with at least ten coalition meetings held to date and with the participation of 47–63 actors drawn from national and county governments, NGOs, bilateral programs, donors, the private sector, community groups, and academic/research institutions (Nyaga, 2018). The primary goal of the forums is to systematically plan for WASH investments and to document all available data on operational, financial and institutional aspects of WASH systems. WASH forum surveys conducted from 2017 to 2021 provide insights about the coalition, including behaviors, priorities for rural water sustainability in Kitui County, and feedback on the design of the coalition's dialogue. In 2019, Kitui County Government adopted ten Key Performance Indicators (KPIs) for monitoring water sector change with respect to the Governor's manifesto and the Ministry of Water objective. These forums also provided the opportunity for the previous data collection campaigns (e.g., audits) to be shared and discussed and for tactical interventions in the water policy and bill development process. Kitui County has committed to taking over the financing of the forums in the future. The knowledge produced through this institutional experiment may have supported the empowerment of local actors for better coordination of the Kitui WASH sector; however, many practices occurring in parallel need to be considered concurrently.

It was clear from the first WASH forums that there were insufficient data to guide planning and investment. Therefore, a WASH database has been proposed by the research teams as the uncertainty in decision-making is partly around the lack of data available or shared between stakeholders. The database thus provided a common framework which supported but did not impose a means to increase transparency and accountability in decision-making, leaving it open on who engages when and in what way. The process of database development was anchored within the Kitui WASH forums to ensure collective development and to understand stakeholder motivators for adoption, strengthening interventions required for the successful adoption of databases, and the role or impact of databases in supporting alignment of sector priorities and actors for sustainability. In interviews conducted for an organizational network analysis (ONA) priorities around monitoring water schemes were also identified by some actors (Kiamba and Chintalapati, 2019). The database provides an inventory of water infrastructure, using the data and knowledge generated through the audits, and to be kept updated *via* the flow of operational and financial performance reports. Pending on-going use, it may progressively influence sector planning, resource allocations, and wider accountability including by donor programming.

Second, emerging from collective processes with local stakeholders and communities is the business development of the maintenance service provider FundiFix. This co-production of knowledge with communities involves the contracting arrangements, financial procedures, and service scope with regard to water quality. Contracts with communities are on a 1-year rolling basis established through regular engagement between the service provider, local county water office, and local communities. Tariffs are set based in line with a willingness-to-pay study (Koehler et al., 2015), however, revenue collection is variable and not as predicted by the willingness-to-pay study. On-going community engagement by the service provider is needed to adapt to local challenges and ensure that the service caters to local needs. Bukachi et al. (2020) also found that there are gendered implications of revenue collection and community reservations about the professional maintenance approach. Since 2019 FundiFix operations expanded to include water quality monitoring, hosting a field water quality lab in their premises in Kyuso Town (Charles et al., 2020; Nowicki et al., 2020). Shared agency of the service provider and local communities thus indicates need for and supports continued improvements in service performance and delivery.

Third, in order to achieve system transformation toward sustainability, a critical engagement with existing institutions is necessary. The policy experiments in Kitui County have questioned the long-standing community management paradigm by examining community preferences and capacity around service provision (Hope, 2015; Hope et al., 2021). The FundiFix model recognizes the role of communities and attempts to reallocate operational risks to lead to better outcomes with a professionalized service which guarantees repairs within 3 days for handpumps and service visits for piped systems within 5 days. This maintains the role of community organization around asset ownership, collecting fees, and managing their own waterpoints but allows maintenance risks to be pooled at a supra-communal level (REACH, 2016).

By formally recognizing the role of both public and private actors in the water sector, the national Water Act of 2016 had already provided a pathway for the critical evaluation of the community-based management paradigm, creating a legislated "space" in which professional maintenance service providers have been able to develop (Article 94) (Republic of Kenya, 2016). The county water bill and policy now provide a local pathway to institutionalize such approaches in Kitui County, building on previous policy experiments. After incorporating inputs from the County Assembly Committee members, the updated version of the draft policy and bill were presented to public actor validation workshops held in November 2019 at the eight sub-counties and at the county level. A total of 755 people (528 men and 227 women) participated in the sub-county workshops. These actors included (i) chairpersons of major water schemes, (ii) representatives of NGOs, (iii) representatives of CBOs, (iv) rural administration (county and national government), (v) religious leaders, (vi) representatives of key institutions, (vii) political leaders (MCAs and MPs) and (viii) advocacy groups. The public participation aimed at creating awareness of the policy and the bill, and at obtaining critical views of the public and other WASH actors at the sub-county level.

Knowledge production and exchange enabling the realization of rural water sustainability in specific contexts

Actions to improve sustainability take place in co-evolving social, cultural, ecological, economic, institutional and technological systems (Caniglia et al., 2021). Three elements are critical in the contextual realization of rural water sector change in Kitui County: the COVID-19 context and the increasing challenge of WASH service delivery due to climate variability, the evolution of a funding mechanism to allow the longer-term sustainability of WASH services, and the political process of passing the Kitui water policy and bill through the county assembly and the executive committee.

First, the specific context of the COVID-19 pandemic highlighted the opportunity to pilot the delivery model with healthcare facilities in Kitui. With FCDO/REACH funding, FundiFix extended its services to 11 healthcare facilities as an immediate COVID-19 response but also with the longer-term goal of bridging the institutional gap between the water, health and education sectors (Katuva et al., 2022) and promoting equal conditions for the rural population. Partners thus became agents of change, which was mediated by trust and "shared agency". The wider context demonstrates that government and other actors were unable to respond to the unsatisfactory water and hygiene conditions in rural healthcare facilities before and during the initial stages of the pandemic. This experiment tailored to the context of the global pandemic provides further situated knowledge of the scope of professional service models to operate in a crisis situation and serve essential facilities such as rural healthcare facilities and thus also achieve further scale to ensure long-term sustainability; however, resources and a clear allocation of responsibilities remain major gaps in a rapid response to a global crisis.

Second, while many rural water users subscribe to the professional maintenance service, they only cover between 15 to 25 percent of the direct service costs and their payment behaviors remain irregular in many cases. This led to a further tactical step in the policy experiment to establish a funding mechanism, the Kitui County Water Service Maintenance Trust Fund (WSMTF), in 2016. This Trust Fund provides a mechanism to pool funding from government, donors, and private investors, based on performance-based evidence of waterpoint functionality and user payments, which allows advancement toward the realization of change by creating alliances and capitalizing on existing resources and opportunities in the rural water sector (Hope et al., 2019, 168). In 2017, donor funds paid for 81 percent of WSMTF contracts; by 2020, the donor proportion had fallen to 24 percent (REACH, 2021). In the same period, the annual WSMTF resources increased from just under USD 50,000 to over USD 190,000 as the number of water users expanded from 15,000 people to over 75,000 people. This work has supported the concurrent development of the Uptime consortium of rural water service providers which, as of 2021, had attracted USD 1 million for results-based contracts guaranteeing reliable water services for around 1.5 million people in four countries (McNicholl et al., 2021).

Finally, the aforementioned policy experiments and knowledge production activities contributed to building an emergent evidence base for the drafting of Kitui's first water bill and policy, both of which were funded by USAID programs. The policy and bill incorporate new findings of the institutional experiments in the county, and have been and continue to be open to exploratory cycles of intervention, reflection and evaluation in the county's process of establishing its water institutions. This is reflected in the iterative process involved in the drafting of the water bill, which was achieved via a number of technocratic procedures under interference of political interests. Formation of a technical working group was followed by a desk review and a situation analysis. Then followed the stage of the consultative and technical drafting of the county water policy and the water bill as well as a meeting with Kenya legal experts on water issues. In a county assembly committee workshop the political aspects were taken into account and mediated. Importantly, for content communication and translation, public consultations were also held; however, these were also at times used for political purposes. Finally, various views were taken into account for the preparation of the final drafts of the policy and water bill. If enacted, the county water bill will be key for sustainable change in the areas of coordination, finance, monitoring framework, and professional service delivery models. The core components are explored in more depth in Section Outcomes.

Outcome and implications: Key institutional changes in Kitui's water sector

Outcomes

The Kitui water bill and policy offers a basis to advance more sustainable WASH systems with clarity and political support on revised arrangements for roles and responsibilities of county government to plan, build, maintain, monitor, and finance sustainable WASH services. It provides for sustainable funding and finance arrangements, including guidelines linking capital and operational expenditure, affordable tariffs, and alternative funding models, also highlighting sector coordination through WASH forum and monitoring systems. It further discusses service delivery contracts, including rural water utilities and maintenance service providers, with their role in ensuring non-discrimination in service provision by wealth, location, gender, and facilities (e.g. schools, healthcare facilities, and hospitals). Finally, it makes provisions for water resource management and protection, both of surface water and groundwater (Koehler et al., 2021). The work was informed by national policy developments and existing constitutional commitments with reference to the Sustainable Development Goals (SDG 6). We provide a more detailed overview on the six key contributions of the new policy and bill below.

i. *Institutionalization of the County WASHCOORD Forum:* The County WASHCOORD Forum, which was externally launched by UNICEF, will be internalized into county operations through being legally enshrined and financially supported by the county government. It provides a structure within which various civil society, research institutions and NGO actors can engage with the county government on policy, planning and performance. The structure is also cascaded to the sub-county level. If the bill is enacted, the Forum shall be funded from the Kitui County Water Services Fund (see *Establishment of a Kitui County Water Services Fund*).

ii. *Leadership of the County Water Directorate:* The County Water Directorate has the primary responsibility to ensure water and sanitation services are monitored and reach the public. The bill clarifies various responsibilities and structures within the directorate in relation to planning, approving designs, certifying works, monitoring, reporting, and inspections. Some unique roles for the Directorate include registration of WRUAs and community water providers, establishing an information management system for water services, monitoring services, and reporting and issuing service quality compliance certificates.

iii. *Establishment of a Kitui County Water Services Fund*: After the incubation of the Water Services Maintenance Trust Fund as part of the research project, a County Water Services Fund is formally integrated into county operations and established under Article 65 to pool and manage public, private and donor funds to finance specific activities that support the county's long-term goals to deliver sustainable universal access to safe and affordable water and sanitation services. Kitui County Water Services Fund is expected to receive funds from the County Budget (ten percent), levies from the County Water Service Providers, and support from external partners. The Fund shall be invested in specific strategic activities which are typically under-funded, including county WASH sector coordination, operation and maintenance, water security, human resource capacity building, and water resources protection. At least 50 percent of the annual budget of the fund shall be ringfenced for operation, repair and/or maintenance of drinking water supply and sanitation infrastructure, equipment and facilities in areas considered not to be commercially viable. To strengthen accountability, the fund shall be administered by a Fund Administrator guided by a Fund Advisory Panel as per Fund Utilization Policy.

iv. *Recognition of the role of County Water Service Providers and Maintenance Service Providers*: Recognizing factors that affect the performance of water service providers (WSP) and other rural social enterprises, including clustering of schemes, scale, exclusivity, and formal contracting, the county shall have one or more WSPs to provide water services within a specified service area. Other entities providing water services shall operate under license from the respective county WSP. This implies that the County WSPs shall have delegated responsibility to regulate these water providers (such as community water projects) within their areas. The bill proposes strict performance and fiscal accountability on all WSPs to enhance water and sanitation service delivery. The county will recognize the role of Maintenance Service Providers on professional preventive and/or responsive repair and maintenance to keep water supply infrastructure functioning on a daily basis. The Water and Maintenance Service Providers shall be eligible for financial and technical support from the County Government.

v. *Water Action Groups (WAG) for accountability in regulation:* WAG is a nascent structure incubated by the national regulator WASREB to give consumers a voice on the quality of water services. This provides an accountability loop on the WSPs. The WAGs may receive funding support from the County Water Services Fund.

vi. *Linking the resource and supply—Water Resources User Associations (WRUAs)*: A WRUA is a structure provided for in national water legislation to facilitate community-based water resource management. The WRUAs provide a vehicle through which source protection measures can be implemented. The bill enables a relationship between WRUAs and the County Government as well as with the national government. The WRUAs shall be registered by the county government and may receive funds from the County Water Services Fund to support county level conservation activities, subject to meeting accountability criteria.

Several questions concerning ownership and accountability arose in the policy process that required exchange of knowledge and further discussion between different parties.

Clause 62 of the Kitui bill tackles the long-standing challenge in rural water management of ownership of community water assets, including land ownership and control of access to community water assets. It stipulates that all water works developed by WASH actors in future when the bill becomes law shall be held in trust by the county government. There remains a challenge with respect to ownership of existing water assets, mostly due to informal processes previously applied by sector actors, where free land and labor contribution by the community was the norm. Lack of official land acquisition paperwork has allowed individual owners or their families to claim ownership or compensation a few years later and at times interrupted service access. For the latter issue, the bill provides for processes for ascertaining the origin of water assets for community water works. Further, Clause 77(6) provides for the formalization of all agreements entailing any land granted or leased by a community or an individual for the purpose of developing county water and sanitation assets.

Another important issue is the accountability for work done by contractors and the capacity gap in terms of executing the contracted works. According to Clause 60, a project implementation committee shall be established, with links to the WASHCOORD Forum, to monitor project implementation. The committee will approve the Certificate of Completion to confirm that the works have been completed in accordance with the approved design and any design changes approved by the Directorate.

Wider sector implications

By formally recognizing the role of public, private and community actors in the rural water sector, Kenya's national Water Act of 2016 provided a pathway for extending beyond the community-based management paradigm in rural water services, creating a legislated "space" in which intentionally designed professional maintenance service providers have been able to develop (Article 94) (Republic of Kenya, 2016) relying on shared agency. Building on previous work, Kitui County's Water Bill and Policy are poised to institutionalize such approaches at the county level. Some challenging issues remain:

Limited gender and minority representation in the policy process

There was low representation of women during the public participation forums (31 percent women against 69 percent men). Women being key actors in WASH issues, they ought to be encouraged to attend these decision-making forums to share their knowledge and perspectives, also by facilitating female focus group discussions. This requires structural adjustments also in terms of gender representation in the Water Directorate. The bill now requires that a third of either gender is represented in all county water sector appointments. It also recognizes vulnerable groups by instituting special measures that ensure their access to water and sanitation services. These measures include setting investment priorities and tariff policies that are responsive to the needs of vulnerable groups.

Varied knowledge of policy process and sector-specific issues

Given the recent decentralization reform, many participants in the development of the policy document had limited knowledge of pertinent policy issues including the formulation process. For example, most participants struggled to differentiate policy measures from development plan activities. Moreover, members of the Technical Working Group had diverse opinions on which issues needed to be included in the policy and bill. Here the role of policy experiments and the evidence they provide became critical again, for example in improving knowledge about the role of trust funds as a longer-term financial mechanism.

Impact of political interests

Political interests affect policy development, sometimes push relevant knowledge into the background, and potentially hamper longer-term initiatives. Competition between different Members of County Assembly led to conflicts of interest in terms of influence. The majority of the MCAs were incentivized by monetary allowances to align public support, mostly from their wards, which limits and sometimes hinders their broader contribution toward the subject matter of improving wider rural water sustainability, especially with regard to long-term initiatives.

Recommendations

The core recommendation emerging from this exploration of how knowledge production has informed policy development in Kitui County is that local ownership of the policy-making process is central to its success. Indeed, there is a fine balancing act for local and external actors to effectively reach an acceptable outcome while recognizing the need for technical support. The policy development process must be owned by the institution that will be responsible for implementation as well as enforcement. In the case of Kitui County Water Policy, the Water Department in the Ministry of Agriculture, Water and Livestock Development took full responsibility in coordinating the entire process. The involvement of experienced representatives of the public and non-state actors in the policy formulation process is critical. These should be of senior level who have the capacity to feed knowledge gains into the process and can confidently commit their departments. In the case of Kitui County, the Technical Working Group comprised senior officers in various departments of the Kitui County Government. These officers were able to deliberate on matters with professionalism and they fully owned the policy document.

That said, there are three important caveats that should be considered in relation to devolved water policy development. First, most members of Kitui's Technical Working Group are County Government officials with many other responsibilities. As such they may not have time to develop technical documents and therefore seek policy support from government institutions responsible for policy development, such as the Kenya Institute of Public Policy Research and Analysis (KIPPRA). Second, ensuring a balanced and representative policy development team with broad expertise for the comprehensive representation of issues requires further effort. Third, development partners funded activities for the policy and bill development process. Government funding to support the process would likely change the policy-making dynamics and the question of ownership over certain aspects.

To advance along the path to sustainable WASH services in Kitui County and beyond, further recommendations from this research include:

(1) Account for the long timeframes of institutional change. Harnessing the opening of a policy window for institutional change in the rural water sector (i.e., decentralization in Kenya) is critical; yet in most cases the following legal and policy changes will require a decadal timeframe. Moreover, most large donors operate within 3–5-year timeframes and therefore limit financial sustainability in their design. This requires new thinking on how to catalyze more flexible funding approaches to reflect on the relative risks and benefits of the size and duration of donor projects on system sustainability.
(2) Draw on legal expertise and build trust for policy experiments in the rural water sector. Incubating a professional service model and sharing performance data has been critical in demonstrating an alternative approach to rural water services in Kitui County and in exploring its opportunities and challenges. FundiFix acted as a policy experiment, sharing otherwise commercially sensitive data to promote sector understanding and inform policy design. Moreover, local legal expertise for institutional innovation, including the Trust Fund, as well as the development of the water bill and policy has been critical for anchoring institutional change in existing frameworks and building trust with national and county governments. This is important to ensure the institutional and financial backing for policy experiments to become embedded in long-term practice of delivering rural water services.
(3) Establish collaborative learning approaches through WASH forums. Bringing the diverse actors of Kitui's WASH sector together for multilateral communication has been and continues to be critical for building cohesion, knowledge exchange, and collective action. As a place where the dynamics of national-county policy, intra-county politics, community and donor practice play out, such forums provide an important platform for coordinating sector activities and long-term planning as well as defining boundaries of the WASH system, including clarifying responsibilities.

Discussion

What if, instead of policy producing practice, practices produce policy? The discussion of policy, politics, and practice in Kitui's water sector highlights that Mosse's (2005) question is highly relevant, including the question of control over interpretation, translation, and composition of who sits at the table in the design, agency, and contextual realization of policy changes toward a more sustainable water sector along the pillars of equality, institutions, accountability, and finance.

Policy experiments that produce new insights appear to be critical for breaking out of the reproduction of existing policy models in national-county, within-county and external policy dynamics; yet the broader instrumentalities and contingencies of aid and the scales within which they operate remain. While we apply a pluralistic and integrated approach to action-oriented knowledge for sustainability, as Caniglia et al. (2021) suggest, we recognize that the seats at the table still remain limited across public, private, and community actors. For instance, limited gender and minority representation as well as various power games with internal and external actors cloud the plurality of voices, even if initially heard, that are integrated into the final drafts of the bill and policy. Using this knowledge framework, however, allows us to question and discuss the types of "knowledge", or evidence, produced alongside rural water sector development in Kitui County. It proves a useful framework in the context of sustainability research; however, we recognize that the application to the knowledge production and exchange activities in Kitui could be conducted in multiple ways depending on the composition of decision-making bodies and the intent and perspectives of the designers, implementers, and researchers represented there as well as on the interpretation and narratives they provide, and the translation of policy goals into practice and vice versa (Latour, 2000).

A further step would be to critically review new path dependencies that the different types of knowledge create. Whether actors engage with knowledge that informs institutional design, or with knowledge that nurtures shared agency, or with knowledge that becomes relevant in specific contexts, or with a combination thereof, may provide early insights into how sustainable certain policy experiments might be in the long run. However, it will only be evidenced by on-going county investment in the various tools and approaches. Whether the water policy in Kitui County, Kenya, will become a major driver in producing sustainable practices will have far-reaching consequences not only for the county itself but for the rural water sector more broadly. What is critical to note is the decadal timeframes for progress and that work on sustainability requires patience and multiple partnerships among public, private, and civil society actors to increase chances of progress.

Author contributions

JK: conceptualization, methodology, investigation, writing—original draft, and review and editing. CN and PK: investigation and review and editing. RH: conceptualization and writing—review and editing. NG: review and editing. MT, AM, and AT: conceptualization and review and editing. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work draws upon research including Smart Water Systems (DFID, R5737), a Rural Water Sustainability Project funded by UNICEF ESARO (240R/A0/09/001/003/006), the Sustainable WASH Systems Learning Partnership funded by USAID under the terms of Cooperative Agreement AID OAA-A-16-00075, including a report for the funder, and the REACH Programme funded by the Foreign, Commonwealth & Development Office (Project Code 201880).

Acknowledgments

We recognize the contribution of colleagues, including Patrick Thomson, Jacob Katuva, Susie Goodall, Peter Harvey, Saskia Nowicki, and Government of Kenya partners.

Conflict of interest

Author CN is a Director of FundiFix Ltd. since inception in 2015 and is also contracted by the University of Oxford to support research on the delivery of its operations in Kenya. Author JK is part of a University of Oxford research team that designed and incubated the FundiFix model. Authors RH, MT, and AM are Trustees of the Water Services Maintenance Trust Fund (registered under Kenyan law) which provides results-based funding to address the subsidy required for FundiFix to maintain rural waterpoints. Author MT is a Director of Rural Focus Ltd. and has worked with RH on University of Oxford research contracts in Kenya since 2008. All of them have worked to support Kitui County Government in developing a first county Water Bill reflecting Kenyan and global experiences and best practice.

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

Publisher's note

Author disclaimer

The views expressed and information contained in this article are not necessarily those of or endorsed by FCDO or other funders that can accept no responsibility for such views or information or for any reliance placed on them.

References

Bergmann, M., Schäpke, N., Marg, O., Stelzer, F., Lang, D. J., Bossert, M., et al. (2021). Transdisciplinary sustainability research in real-world labs: success factors and methods for change. *Sustain. Sci.* 16, 541–564. doi: 10.1007/s11625-020-00886-8

Bukachi, S., Omia, D., Musyoka, M., Wambua, F., Ngutu, M., and Korzenevica, M. (2020). *Can social capital quench thirst? Evidence from rural Kenya*. Available online at: https://reachwater.org.uk/can-social-capital-quench-thirst-evidence-from-rural-kenya/ (accessed July 5, 2022).

Caniglia, G., Luederitz, C., von Wirth, T., Fazey, I., Martín-López, B., Hondrila, K., et al. (2021). A pluralistic and integrated approach to action-oriented knowledge for sustainability. *Nat. Sustain.* 4, 93–100. doi: 10.1038/s41893-020-00616-z

Charles, K. J., Nowicki, S., and Bartram, J. K. (2020). A framework for monitoring the safety of water services: from measurements to security. *Npj Clean Water* 3, 36. doi: 10.1038/s41545-020-00083-1

Cheeseman, N., Lynch, G., and Willis, J. (2016). Decentralisation in Kenya: the governance of governors. *J. Mod. Afr. Stud.* 54, 1–35. doi: 10.1017/S0022278X1500097X

Conyers, D. (2007). Decentralisation and service delivery: lessons from Sub-Saharan Africa. *IDS Bulletin* 38, 18–32. doi: 10.1111/j.1759-5436.2007.tb00334.x

Crawford, G., and Hartmann, C. (2008). *Decentralisation in Africa: A Pathway out of Poverty and Conflict*. Amsterdam: Amsterdam University Press.

Faguet, J.-P. (2014). Decentralization and Governance. *World Dev.* 53, 2–13. doi: 10.1016/j.worlddev.2013.01.002

Foster, T. (2013). Predictors of sustainability for community-managed handpumps in Sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda. *Environ. Sci. Technol.* 47, 12037–12046. doi: 10.1021/es402086n

Foster, T., Hope, R., Nyaga, C., Koehler, J., Katuva, J., Thomson, P., et al. (2022). *Investing in Professionalized Maintenance to Increase Social and Economic Returns From Drinking Water Infrastructure in Rural Kenya*. Policy Brief, Sustainable WASH Systems Learning Partnership and REACH Programme. Oxford: Smith School of Enterprise and the Environment, University of Oxford.

Gaynor, N. (2014). Bringing the citizen back in: supporting decentralisation in Fragile States - a view from Burundi. *Dev. Policy Rev.* 32, 203–218. doi: 10.1111/dpr.12051

Government of Kenya (2010). *The Constitution of Kenya*. Nairobi: National Council for Law Reporting.

Harvey, P. A., and Reed, R. A. (2006). Community-managed water supplies in Africa: sustainable or dispensable? *Community Dev. J.* 42, 365–378. doi: 10.1093/cdj/bsl001

Hope, R. (2015). Is community water management the community's choice? Implications for water and development policy in Africa. *Water Policy* 17, 664 LP—678. doi: 10.2166/wp.2014.170

Hope, R., Foster, T., Koehler, J., and Thomson, P. (2019). Rural water policy in Africa and Asia. In: Dadson, J., Garrick, S.J., Penning-Rowsell, D.E., Hall, E.C., Hope, J.W., and Hughes R. editors. *Water Science, Policy and Management: A Global Challenge*. New York, NY: John Wiley and Sons, Ltd.

Hope, R., Katuva, J., Nyaga, C., Koehler, J., Charles, K., Nowicki, S., et al. (2021). *Delivering Safely-Managed Water to Schools in Kenya*. REACH Working Paper.

Hope, R., Thomson, P., Koehler, J., and Foster, T. (2020). Rethinking the economics of rural water in Africa. *Oxford Rev. Econ. Pol.* 36, 171–190. doi: 10.1093/oxrep/grz036

Katuva, J., Hope, R., McBurney, E., Gladstone, N., Koehler, J., Nyaga, C., et al. (2022). *Improving water and handwashing services in rural health care facilities in Kitui County, Kenya*. Policy Brief, Sustainable WASH Systems Learning

Partnership and REACH Programme. Oxford: Smith School of Enterprise and the Environment, University of Oxford.

Kiamba, P., and Chintalapati, P. (2019). *Understanding Coordination in Kitui County's Water Sector: An Analysis of Stakeholder Interactions and Perspectives.* Sustainable WASH Systems Learning Partnership: United States Agency for International Development.

KNBS (2019). *2019 Kenya Population and Housing Census, Volume II. Distribution of Population by Administrative Units.* Nairobi: KNBS.

Koehler, J. (2018). Exploring policy perceptions and responsibility of devolved decision-making for water service delivery in Kenya's 47 county governments. *Geoforum* 92, 68–80. doi: 10.1016/j.geoforum.2018.02.018

Koehler, J., Nyaga, C., Hope, R., Kiamba, P., Gladstone, N., Thomas, M., et al. (2021). *Legal and policy change to promote the sustainability of WASH services in Kitui County, Kenya*. Sustainable WASH Systems Learning Partnership: United States Agency for International Development.

Koehler, J., Thomson, P., Goodall, S., Katuva, J., and Hope, R. (2020). Institutional pluralism and water user behavior in rural Africa. *World Dev.* 140, 105231. doi: 10.1016/j.worlddev.2020.105231

Koehler, J., Thomson, P., and Hope, R. (2015). Pump-priming payments for sustainable water services in rural Africa. *World Dev. 74*, 397–411. doi: 10.1016/j.worlddev.2015.05.020

Latour, B. (2000). When things strike back: a possible contribution of science studies. *Br. J. Sociol.* 5, 105–123. doi: 10.1080/000713100358453

Li, T. M. (1999). Compromising power: development, culture and rule in Indonesia. *Cult. Anthropol.* 14, 295–322. doi: 10.1525/can.1999.14.3.295

McFadgen, B., and Huitema, D. (2018). Experimentation at the interface of science and policy: a multi-case analysis of how policy experiments influence political decision-makers. *Pol. Sci.* 51, 161–187. doi: 10.1007/s11077-017-9276-2

McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., Dupuis, M., et al. (2020). *Results-based Contracts for Rural Water Services.* (Working Paper 2). Uptime Consortium.

McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., Dupuis, M., et al. (2021). *Delivering Global Rural Water Services Through Results-Based Contracts.* (Working Paper 3). Uptime Consortium.

McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., van der Wilk, N., et al. (2019). *Performance-Based Funding for Reliable Rural Water Services in Africa.* (Working Paper 1). Uptime Consortium.

Mosse, D. (2005). *Cultivating Development: An Ethnography of Aid Policy and Practice*. London: Pluto Press.

Mwihaki, N. J. (2018). Decentralisation as a tool in improving water governance in Kenya. *Water Pol.* 20, 252–65. doi: 10.2166/wp.2018.102

Nowicki, S., Koehler, J., and Charles, K. J. (2020). Including water quality monitoring in rural water services: why safe water requires challenging the quantity versus quality dichotomy. *Npj Clean Water* 3, 14. doi: 10.1038/s41545-020-0062-x

Nyaga, C. (2018). *Understanding Factors and Actors to Achieve Sustainable Drinking Water Systems in Kitui County, Kenya*. Sustainable WASH Systems Learning Partnership: United States Agency for International Development.

Nyaga, C. (2019). *A Water Infrastructure Audit of Kitui County.* Sustainable WASH Systems Learning Partnership: United States Agency for International Development.

Prasad, N. (2006), Privatisation results: private sector participation in water services after 15 years. *Dev. Pol. Rev.* 24, 669–692. doi: 10.1111/j.1467-7679.2006.00353.x

REACH (2016). *The FundiFix Model: Maintaining Rural Water Services*. Oxford: University of Oxford.

REACH. (2021). *Scaling-up Results-Based Funding for Rural Water Services.* (REACH Working Paper). Oxford: University of Oxford.

Republic of Kenya (2016). *The Water Act*. Nairobi: National Council for Law Reporting.

Robinson, M. (2007). Does decentralisation improve equity and efficiency in public service delivery provision? *IDS Bull.* 38, 7–17. doi: 10.1111/j.1759-5436.2007.tb00333.x

Rondinelli, D. (1983). *Development Projects as Policy Experiments*. Methuen: Methuen Publishing.

Smoke, P. (2003). Decentralisation in Africa: goals, dimensions, myths and challenges. *Public Adm. Dev.* 23, 7–16. doi: 10.1002/pad.255

SSEE (2014). *From Rights to Results in Rural Water Services - Evidence from Kyuso, Kenya*. (Water Programme Working Paper 1). Oxford: Smith School of Enterprise and the Environment, University of Oxford.

SSEE (2015). *Insuring Against Rural Water Risks. Evidence From Kwale, Kenya.* (Water Programme Working Paper 3). Oxford: Smith School of Enterprise and the Environment, University of Oxford.

Thomson, P. (2020). Remote monitoring of rural water systems: a pathway to improved performance and sustainability? *WiresWATER* 8, e1502. doi: 10.1002/wat2.1502

Thomson, P., Hope, R., and Foster, T. (2012). GSM-enabled remote monitoring of rural handpumps: a proof-of-concept study. *J. Hydroinform.* 14, 29–39. doi: 10.2166/hydro.2012.183

Turnhout, E., Metze, T., Wyborn, C., Klenk, N., and Louder, E. (2020). The politics of co-production: participation, power, and transformation. *Curr. Opin. Environ. Sustain.* 42, 15–21. doi: 10.1016/j.cosust.2019.11.009

Whaley, L., and Cleaver, F. (2017). Can 'functionality' save the community management model of rural water supply? *Water Res. Rural Dev.* 9, 56–66. doi: 10.1016/j.wrr.2017.04.001

Whittington, D., Davis, J., Prokopy, L., Komives, K., Thorsten, R., Lukacs, H., et al. (2008). How well is the demand-driven, community management model for rural water supply systems doing? Evidence from Bolivia, Peru and Ghana. *BWIP Working Paper* 22. doi: 10.2139/ssrn.1265532

WHO/UNICEF (2021). *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020: Five Years Into the SDGs*. Geneva: World Health Organization and the United Nations Children's Fund. Licence: CC BY-NC-SA 3.0 IGO.

frontiers | Frontiers in Water

TYPE Hypothesis and Theory
PUBLISHED 25 November 2022
DOI 10.3389/frwa.2022.1002721

OPEN ACCESS

EDITED BY
Jenia Mukherjee,
Indian Institute of Technology Kharagpur, India

REVIEWED BY
Sara Nowreen,
Bangladesh University of Engineering and Technology, Bangladesh
Augustin F. C. Holl,
Xiamen University, China
Mayra Gutiérrez-González,
Universidad Autónoma de Baja California Sur, Mexico

*CORRESPONDENCE
Britt Basel
brittbasel@ecothropic.com

SPECIALTY SECTION
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

RECEIVED 25 July 2022
ACCEPTED 27 September 2022
PUBLISHED 25 November 2022

CITATION
Basel B, Hoogesteger J and Hellegers P (2022) Promise and paradox: A critical sociohydrological perspective on small-scale managed aquifer recharge.
Front. Water 4:1002721.
doi: 10.3389/frwa.2022.1002721

Promise and paradox: A critical sociohydrological perspective on small-scale managed aquifer recharge

Britt Basel[1,2,3]*, Jaime Hoogesteger[3] and Petra Hellegers[3]

[1]Ecothropic, Cimarron, CO, United States, [2]Ecothropic México A.C., San Cristóbal de las Casas, Mexico, [3]Water Resources Management Group, Department of Environmental Sciences, Wageningen University, Wageningen, Netherlands

Small-scale managed aquifer recharge (MAR) has significant potential as a bottom-up, community-based adaptation solution for increasing local groundwater availability and reducing the experience of drought for small-holder agriculturalists and rural populations. Using a suite of low-tech and low-cost techniques, small-scale MAR increases the infiltration of surface water runoff to replenish groundwater and deliver a suite of societal and ecosystem benefits. While the technique is hydrologically promising, populations may not act, implementation may not be permitted, interventions may not be effective for the population in question, or unexpected consequences (paradoxes) may result. For small-scale MAR to effectively reduce the experience of drought, it is imperative to unravel how such interventions play out within the complexity of the sociohydrological system in which they are implemented. Building on previous conceptualizations of the sociohydrological system, we apply the lens of political ecology to conceptualize the interplay between biophysical, climate, and social systems. Additionally, we explore considerations, feedbacks, and potential paradoxes in the uptake, implementation, and effectiveness of small-scale MAR interventions. We show that within the parameters of climate trends, small-scale MAR may serve to increase the functionality of ecosystems and reduce the impact of climate extremes, while protecting livelihoods and supporting society. In a positive feedback loop, small-scale MAR may both reduce the likelihood of experiencing drought while simultaneously increasing the ability and likelihood of the population to cope with or further avoid drought. Paradoxes and negative feedback processes, however, must be avoided. Specific factors, and how such factors interplay, will be different in each context where small-scale MAR is implemented. Conceptualizing the sociohydrological system in which small-scale MAR is implemented, including explicitly accounting for climate trends and using a power-sensitive approach, allows us to avoid overestimating or oversimplifying small-scale MAR as a solution, while supporting practical and effective implementation.

KEYWORDS

managed aquifer recharge (MAR), water sowing and harvesting, groundwater recharge, sociohydrology, community-based adaptation, Nature-based Solution, climate adaptation, drought risk reduction

Introduction

Groundwater from replenishable unconfined shallow aquifers and non-replenishable confined aquifers is often a key resource for reliable and good quality water, especially for populations living in arid regions (Hoogesteger, 2022). Small-holder farmers often depend on water from shallow wells for livelihoods and household use. Water levels in shallow and unconfined aquifers is recharged by rainfall and surface water percolating through soil and substrates, streambeds, and terrestrial wetlands (Dillon et al., 2019). The unconfined aquifer can be considered a renewable resource when recharge rates are balanced with the rate of water withdrawals. Shallow groundwater is increasingly important for livelihoods as changing precipitation patterns challenge water availability in a context of increased competition for water and an increasing number of rural-urban water transfers (Molle and Berkoff, 2009; Molle et al., 2010; Hommes and Boelens, 2017; Hommes et al., 2019).

Human interventions in the landscape that increase the infiltration of surface water runoff have been shown to have significant impact on water tables, increasing groundwater availability (Patel and Prabhakar, 2012; Renganayaki and Elango, 2013; Malik et al., 2014; Rockström et al., 2014; Sadoff et al., 2015). With managed aquifer recharge (MAR) interventions, increasing the amount of water in the targeted aquifer is an explicit aim, while in other interventions (e.g., irrigation expansion, watershed restoration, soil conservation, and water harvesting) recharge may be an unintended effect and invisible benefit.

This paper explores MAR as a suite of socio-technical interventions that are intended to increase the infiltration of surface water runoff into groundwater systems through small (in infrastructural scale), low-tech, and low-cost techniques that can be easily implemented by local land managers. For example, small check dams built from stones, earth, cement or other materials may slow water flowing down small ravines, increasing rates of water infiltration into substrates. Contour bunds, linear mounds built horizontally along slopes (often in degraded or cultivated areas), use similar materials and function comparably, detaining water flowing down slopes. Rainwater runoff from roads can be channeled into porous roadside ditches or small-infiltration wells. Wetlands, which naturally mitigate flooding and maintain local water tables, can be protected. Such techniques have been used by human populations across diverse geographies for millennia for capturing seasonal rainfall and increasing long-term drought resilience (Kennedy, 1995; Pandey et al., 2003; Malik et al., 2014; Dillon et al., 2019; Ochoa-Tocachi et al., 2019).

The hydrological impact of MAR on increased groundwater levels has been widely discussed and documented (Patel and Prabhakar, 2012; Renganayaki and Elango, 2013; Malik et al., 2014; Rockström et al., 2014; Sadoff et al., 2015; Basel et al., 2020b). Interventions may also reduce soil erosion caused by runoff, and spread water availability more evenly throughout the year, reducing peak flows while increasing base flows (by slowing the movement of water through a watershed by passing it slowly through sediments instead of quickly overland (Dillon et al., 2019). Small-scale MAR techniques may reduce hydro-meteorological risks of drought and flooding, support soil humidity (mitigating the vulnerability of agriculture to climate trends), and regulate water tables that maintain vegetation and biodiversity (reducing local temperature extremes and regulating microclimates through evapotranspiration (Otieno and Anyah, 2012; Ribeiro, 2020; Seddon et al., 2020).

Small-scale MAR is increasingly relevant given current and projected climate trends and related hydro-meteorological extremes, and is recognized as a promising adaptation strategy for reducing vulnerability to climate impacts (Shah, 2009; Guyennon et al., 2017; International Groundwater Assessment Centre, 2020; IPCC, 2021). Rural and indigenous populations often have place-based and generational experience in managing local resources, and through daily interactions with resources are *de facto* resource managers (Berkes and Armitage, 2010; Boillat and Berkes, 2013; Reid, 2016; Basel et al., 2020a). Small-scale MAR interventions may then be particularly useful for people with land-based and groundwater-dependent livelihoods. As a small-scale, locally-driven, bottom-up measure, MAR is a promising strategy for community-based adaptation to climate change (Basel et al., 2020b).

As interventions can serve "...to protect, sustainably manage, and restore natural or modified ecosystems," therefore "…providing human wellbeing and biodiversity benefits," MAR can be also be considered a Nature-based Solution (Cohen-Shacham et al., 2016, p. 5). Given the potential benefits small-scale MAR offers for people and ecosystems, interventions may seem to be a nostrum for development interventionists working to address Sustainable Development Goal 6 which aims to "ensure availability and sustainable management of water and sanitation for all." The potential hydrological impact of an intervention does not however ensure the intervention delivers increased water availability. Hydrological interventions are implemented within a complex socio-ecological system (SES) (Ostrom, 2009), and furthermore within a hydrological system in which:

> "…humans influence water resources through behavior and infrastructural interventions. In turn, the availability of hydrological resources and hydro-climatic events influence human behavior and interventions, creating interplay and feedbacks between the two systems." (Rusca and Di Baldassarre, 2019).

Furthermore, water management and water distribution are also political. The flow of water is not only guided by gravity but also the interplay of power relations. While small-scale

MAR is hydrologically promising, populations may not act, implementation may not be permitted, interventions may not benefit the intended population, or unexpected consequences (paradoxes) may result.

Existing literature has largely focused on the hydrological and technical aspects of small-scale MAR; limited exceptions include Kennedy (1995), Pandey et al. (2003), Lasage and Verburg (2015), Lasage et al. (2015), and Ochoa-Tocachi et al. (2019). The complexity of the human-water interactions results in feedbacks and emergent dynamics that call for a more holistic approach (Blöschl et al., 2013). The implementation of small-scale MAR as a community-based adaptation strategy requires contextualizing these interventions within the complex sociohydrological system in which they are implemented. As a preliminary step to address this gap, this paper explores the following question: How can we conceptualize the sociohydrological system in which small-scale MAR interventions are implemented to increase groundwater availability in small or upper catchments?

To do this, we turn to and then further develop existing conceptualizations of the sociohydrological system. We propose climate trends as an additional and linked system that interacts with both human and hydrological systems. A critical lens is then applied to better understand the matrix of factors that may influence intervention outcomes, including possible paradoxes. Based on these understandings, the Methodology used is presented below. The Results section begins by applying a critical lens to solutions-oriented research and then presents the sociohydrological conceptualization of small-scale managed aquifer recharge from a critical sociohydrological perspective. The following three subsections on the biophysical, climate, and social systems are dedicated to exploring the interplay between these systems within the sociohydrological system in which small-scale MAR is implemented. The paper concludes with an overview of the conceptualization of the system and key findings.

Methodology

To situate small-scale MAR within existing sociohydrological understandings of linked human-water systems and explore system dynamics, we turned to and then further developed previous conceptualizations and models of the sociohydrological system. To identify relevant conceptualizations and models for analysis, we used a snowball approach. The search was started using Google Scholar, chosen for the diversity of resources represented in the platform. Appropriate literature to review was then selected using the following criterion: (1) relatively recent research (since the founding of the discipline in 2014);[1] (2) applicable research topics; and (3) the presentation of a conceptualization/analysis of the sociohydrological system. Using this approach, nine papers, dating 2014–2021, were chosen for in-depth comparison and analysis[2]. The review was not intended to be exhaustive but rather representative, aimed at drawing on existing conceptualizations and understandings of the sociohydrological system to consider how small-scale MAR is situated within these understandings.

Each paper was reviewed to identify key themes, system variables, drivers, feedbacks, paradoxes, and possible research gaps. Resulting data were then compared across the papers to cluster similar and related concepts, and then identify agreements, patterns, and contradictions. Where the focus of the research was on agriculture, we extrapolated research findings as they would apply to water availability for combined agricultural and household use.

We then anchored these considerations in the framework presented in Di Baldassarre et al. (2018) and the conceptualization of the sociohydrological process of community-based adaptation presented in Basel et al. (2020b). These two frameworks were used as a "base map" for visualizing the relationships between the key biophysical, climate, and social considerations identified in the analysis of the selected papers, as related to small-scale MAR.

Results

Applying a critical lens to solutions oriented-research

Research on the interplay between human and water systems has largely been divided into two approaches. Hydrosocial literature applies a political ecology lens to examine social processes including power and scalar politics (for example Boelens, 2014; Linton and Budds, 2014; Boelens et al., 2016; Vos et al., 2020). Sociohydrology, rooted in the earth sciences, applies a (post) positivist approach to address specific issues (Wesselinck et al., 2017; Ross and Chang, 2020). According to Ross and Chang (2020, p. 1) "Without comprehending those interactive relationships, appropriate human responses

1 While extensive previous research on human and water systems exists (see Results section for further detail), the sociohydrological discipline for exploring system interactions was proposed in 2014 by Sivapalan et al. (2014).

2 The nine papers, dating 2014–2021, which were chosen for in-depth comparison and analysis, are as follows: (1) Elshafei et al. (2014); (2) Hale et al. (2015); (3) Kuil et al. (2016); (4) Kumar et al. (2020); (5) Penny and Goddard (2018); (6) Roobavannan et al. (2017); (7) Savelli et al. (2021); (8) Sivapalan et al. (2014); (9) Vanelli and Kobiyama (2021).

to challenges and hazards involved in hydrologic systems become effectively impossible." The sociohydrological literature therefore addresses the interactions between hydrology, hydro-climatic events, society, and interventions, seeking to understand how humans can alter or influence hydrological regimes and, circularly, how water availability and water related-hazards influence human behavior, which in turn, influences hydrological regimes (Pande and Sivapalan, 2016; Di Baldassarre et al., 2019; Rusca and Di Baldassarre, 2019; Basel et al., 2020b).

Applying the sociohydrological approach to small-scale MAR then supports "appropriate human responses" to the experience of drought. However, questions including who benefits, who loses, who has decision-making power, and the discourses that drive those decisions, also come into play. The answers to these questions influence how, when, by whom, and with what results small-scale MAR is implemented. These questions are inherently related to politics and power, across macro, micro, and basin scales. Therefore we assert that sociohydrological research has to increasingly account for social institutions, practices and norms by making research power-sensitive (see Melsen et al., 2018; Rusca and Di Baldassarre, 2019; Madani and Shafiee-Jood, 2020).

The following conceptualization draws on, consolidates, and further develops existing knowledge while recognizing that models simplify inherently complex systems, resulting in potential power issues and bias. Conceptualizing the system however allows us to recognize the complexity of the system, and identify important considerations, positive and negative feedback processes, and possible paradoxes. As we are reminded by Ostrom et al. (2007), there are no panaceas. Every context where small-scale MAR is implemented will represent a unique confluence of factors that must be considered accordingly. As political ecology further reminds us:

> "Cross-regional and cross-cultural comparison may reveal important opportunities for mutual learning or even grassroots' cross-border engagement and solidarity, without falling in the trap of mainstream policies and neoliberal discourses promoting 'good governance' and 'best practices'..." (Vos et al., 2020, p. 9).

A sociohydrological conceptualization of small-scale managed aquifer recharge

A proposed conceptualization of the system in which small-scale MAR is implemented is depicted in Figure 1. The diagram shows a sociohydrological system made up of (i) biophysical, (ii) climate, and (iii) social subsystems. The structure and state of each subsystem respond to drivers within this sociohydrological system. Responses also act as drivers that circularly act on all three subsystems. The climate system drives local weather which drives the state, structure, and response of the social and biophysical subsystems. The state and structure of the biophysical subsystem respond with ecosystem/hydrological function and hazards which become drivers affecting local climate and the social subsystem, which may respond with socio-political and/or technological interventions.

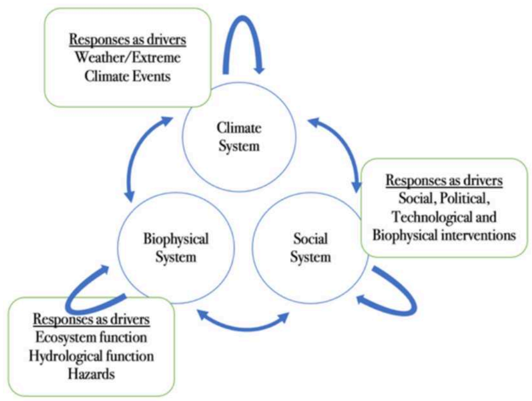


FIGURE 1
The proposed conceptualization of the sociohydrological system in which small-scale managed aquifer recharge interventions are implemented. Adapted from: Di Baldassarre et al. (2013), Di Baldassarre et al. (2018), Rusca and Di Baldassarre (2019), and Basel et al. (2020b).

Small-scale MAR is one response of the social system to climate, social, and biophysical drivers. Small-scale MAR interventions consequently drive the state, structure, and response of all subsystems; namely the biophysical, climate (particularly regarding microclimates), and social. The interaction between systems may result in feedbacks (between systems or a system acting upon itself) and/or paradoxes (unintended consequences). For example, an intervention could inadvertently increase the vulnerability of the population the intervention was intended to help. Paradoxes may result because human behavior is highly unpredictable (Wesselinck et al., 2017). Societies are vastly diverse with social dynamics, identities, and decision making-behavior developing across vastly divergent historical, cultural, and political pathways. Sociohydrology has identified multiple such phenomena that may apply to the sociohydrological system in which small-scale MAR is implemented (see Di Baldassarre et al., 2019). These include *safe-development paradox* (Kates et al., 2006); *supply-demand cycle* (Kallis, 2010); *adaptation effect* (Di Baldassarre et al., 2015); *pendulum swing* (see Gleick and Palaniappan, 2010); *rebound effect* (Kandasamy et al., 2014); and *aggregation* *effect* (see Olson, 1965; Ostrom, 1990; Zwarteveen et al., 2017).[3] Recognizing and planning for the potential eventuality of phenomena and possible paradoxes is fundamental to designing effective solutions (i.e., small-scale MAR resulting in decreased experience of drought).

System dynamics (and the possible occurrence of paradoxes) are complicated by spatial and temporal scales. Small-scale MAR interventions are implemented at a basin or catchment level, but are influenced by, and connected to, both macro- and micro-spatial scales spanning hydrological, climatic, social, and political processes. Dynamic interactions between slow and fast variables across all elements of the system are also simultaneously at play (Elshafei et al., 2014). As Biggs et al. (2012; as quoted by Penny and Goddard, 2018, p. 40) explains, "Slow variables determine the underlying structure of the socio-ecological system (SES), whereas the dynamics of the system typically arise from interactions and feedback processes between fast variables that respond to conditions created by slow variables." The structure (the condition of a system over an extended time frame—e.g., ~30 years) of each subsystem may be considered a slow changing variable, whereas the current state (rapidly changing conditions) of each subsystem might be considered a fast-changing variable, which overtime can affect the (slow-changing) structure of each subsystem. To exemplify the possible interactions (and paradoxes) between slow and fast variables, we consider the following: the construction of small-scale MAR infrastructure may be a relatively fast process, while watching wells fill may be a slow process, as infiltrated groundwater slowly moves through substrates. When people do not see results from their efforts, they may be less likely to continue to act. Alternatively, MAR interventions may be implemented after hydrological drought has increased the hydrophobia of soils and rainfall is inadequate to recharge water tables. As a result, intervention was too late to prevent the experience of impending drought, minimizing the impetus to create and maintain small-scale MAR infrastructure. Conversely, the experience of drought may be suddenly felt, while generating social will to build small-scale MAR infrastructure may take years.

In summary, the conceptualization of the sociohydrological system in which small-scale MAR is implemented is representative of the interplay between natural, social (defined by a diversity of local characteristics and unpredictability), and climatological processes (as further discussed below). The dynamic stage of small-scale MAR, including the complexities and range or potential drivers and responses, and value-driven decisions, suggests the system can be understood as a complex adaptive system (CAS), defined by "interconnectedness, innovation, [and] non-linear change"—in which uncertainly plays a central role (Bohensky et al., 2015, p. 142; Penny and Goddard, 2018; Clark and Harley, 2020).

The biophysical subsystem: Key variables and drivers

Water moves through the biophysical system guided by geomorphology, hydrological processes, ecological processes, and the climate regime. Slow-changing characteristics of the system including catchment size, type of aquifer, and a myriad of other factors explained in technical manuals, determine if, how, and where recharged water will naturally flow (Elshafei et al., 2014; Hale et al., 2015), including which human populations will benefit from increased water tables; how upstream recharge affects downstream populations, ecosystems, and flood/drought risk; or whether recharged water flows into inaccessible deep aquifers. The state of the biophysical system can be understood as the shorter-term responses of the biophysical system to interactions between social-climate-biophysical systems.[4]

The state of the system includes hydrologic function (including precipitation, evaporation, land use, basin modification, water balance, and water extraction rates), environmental degradation/alteration of landscape, and ecosystem health (including diversity, redundancy, and connectivity; Penny and Goddard, 2018). A sociohydrological approach suggests the structure, state, and functionality of the biophysical system, including environmental change factors, determine ecosystem services[5,6] (Elshafei et al., 2014; Mao et al., 2017). The state of the system is a "...product of conflicting factors from both sides (social and hydrological), such as human demand and ecosystem supply, human disturbances and ecosystem regulation and regeneration, and human management and water resources" (Mao et al., 2017, p. 3,661). Increased hydrological extremes of flood and drought can result. As expressed by Anne von Loon,[7] "drought and floods are caused by extremes of the same hydrological cycle and

3 Please see Di Baldassarre et al. (2019, p.6331) for the characteristics and implications of these sociohydrological phenomena and related sub-phenomena.

4 Referred to as Environmental Change by Di Baldassarre et al. (2018).

5 i.e., the function of ecosystems in determining water availability and hydrologic extremes.

6 The term ecosystem services shows a linguistic bias toward being human-centric (humans benefited by ecosystems). While, Mao et al. (2017) present a critique of standard approaches to ecosystem services by aiming to address human-water coupled systems, the focus arguably maintains this bias without recognizing other worldviews which may be oriented toward a less extractivist and more reciprocity-based and integrated perspective of human/ecosystem relationships which may be at play when small-scale recharge is implemented (see Basel et al., 2020b).

7 From: https://vu.nl/en/about-vu/more-about/perfectstorm-story lines-of-future-extremes-ivm. Accessed July 9, 2022.

hence are correlated by dynamic feedback, strongly interlinked with human processes. Treating droughts and floods as independent phenomena, while ignoring their interaction with societal forces, leads to incomplete/distorted understanding of the processes that lead to the impacts experienced, and hence to possible underestimations of future risks." The interplay between all of these factors is further responsive to changes in the climate system including extreme weather events, high temperatures, and precipitation trends.

The biophysical system is therefore not simply a clearly delineated product of the earth sciences, but plastic, being molded by the dynamic and constant interactions within and between systems. As a social system intervention in the biophysical system, small-scale MAR is simply one lever within this complex system. The illustrative examples of possible interactions are innumerous. Changes in vegetative landcover and soil permeability including deforestation, reforestation, afforestation, and urbanization may affect local microclimates (i.e., average local temperatures, high and low temperature extremes, ambient humidity, and local precipitation events), which in turn affect the water balance in a localized area. Changes in local climate regimes can further reduce precipitation, runoff, and soil permeability, shifting baseline hydrological conditions and trajectories. Land and agricultural management that results in decreased soil humidity can compound the impact of extended periods of high temperatures and correlating high evaporation rates. The result is hydrophobic soil conditions which further reduce soil humidity and recharge rates. Water resource use and transfer, including through virtual water exports[8] can lower water tables, affecting vegetative cover, biodiversity, and local and regional climates (Otieno and Anyah, 2012; Keune et al., 2016). The functionality of the biophysical system then reflects not only the natural sciences but the normative goals and political choices of the people managing and interacting with the biophysical system (Mao et al., 2017), which could include reducing the risk of drought and increasing ecosystem function to facilitate positive system feedback processes (i.e., increasing local groundwater levels).

The social system is also molded by the biophysical environment through the relationship between people and functional ecosystems. This relationship provides for livelihoods, food, and water, while also supporting and influencing culture, knowledge, and social cohesion (see Hale et al., 2015; Basel et al., 2020a,b). The reciprocal relationship between people and the natural environmental is especially important for traditional and subsistence-based populations which may be the most likely to implement small-scale MAR interventions (Basel et al., 2020b). While decreased ecosystem functionality increases the biophysical possibility of drought, decreased ecosystem services may simultaneously increase community sensitivity and overall vulnerability to drought through inhibiting the ability for the population to adapt (cope, avoid, or reduce the impact of the hazard) (Elshafei et al., 2014; Kuil et al., 2016; Roobavannan et al., 2017; Basel et al., 2020b). For example, drought may reduce agricultural production and livelihoods, limiting food availability and/or financial resources populations have to acquire food from alternative sources. Decreased livelihoods may encourage migration, deteriorating local social coherence (reducing the likelihood of collective action to implement small-scale MAR) and the presence of physically capable individuals to build MAR infrastructure (further discussed below).

8 See Dell'Angelo et al. (2018) and Vos and Boelens (2018).

The climate subsystem: Key variables and drivers

> *"Although climate is inarguably changing society, social practices are also impacting on the climate. Nature and culture are deeply entangled, and researchers must examine how each is shaping the other. But they are largely failing to do so."* Hulme (2011, p. 177).

Climate drives the water cycle. Current climate trends, largely driven by human actions, are changing precipitation patterns, rates of evapotranspiration, intensity of rainfall, extreme weather events, and feedbacks within the climate system. As a result, climate change is increasing the frequency and intensity of drought (and floods), while driving reverberating consequences throughout the biophysical and social systems (Hulme, 2011; Jiménez Cisneros et al., 2014; IPCC, 2021). The intensity of climate change related impacts is then further exacerbated by social system drivers (e.g., changes in land use; water exports; over extraction of water resources).

While sociohydrological research is frequently framed within, and justified by, the context of changing climate trends and resulting hydro-meteorological extremes, existing literature largely fails to explicitly account for climate variables because of the complexity this would add to analysis [see Kumar et al. (2020)[9] and Elshafei et al. (2014)].[10] In the case of small-scale MAR, the complexity of accounting for the climate system is attenuated by small-scale MAR being a

9 Kumar et al. (2020, p. 3) propose, "Researchers fail to attribute risk associated with climate stress and variability since the features of the climatic system are complex and interconnected with other economic and social phenomena."

10 Elshafei et al. (2014, p. 2,142) write: "Finally, the specific vulnerability and responsiveness that the hydrological coupled system displays in regard to climate change (Ribeiro Neto et al., 2014) presents an additional challenge."

bottom-up intervention that can be considered a community-based adaptation strategy (see Blöschl et al., 2013; Basel et al., 2020b). Community-based adaptations are intended to increase the capacity of the system to resist a range of possible hazards, without the functionality of the system fundamentally changing. Endogenizing the climate system into the sociohydrological framework does not then require incorporating precise climate models. Climate trends (e.g., intensity of precipitation events, distribution of precipitation throughout the year, heat waves, and high temperature averages) are key limiting and determining factors in the quantity of water recharged and thresholds that will lead to flooding and drought. Regional long-term trends and extremes must be incorporated into the design of interventions, if interventions are to be effective within the extreme ranges of possible climate conditions (e.g., extreme rainfall events and how much water structures should be able to retain/resist; or evaporation trends and scarce rainfall that prevent structures from capturing sufficient water to raise water tables). Interventions may be ineffectual if they are designed for the current state and function of the biophysical and social system, without accounting for how both of these systems may be altered by changing climatic conditions, extreme events, and social interventions.

As a community-based adaptation strategy and Nature-based Solution, small-scale MAR interventions specifically increase the functionality of both the biophysical and social systems across potential climate extremes (i.e., reducing drought, flooding, soil erosion, and preserving ecosystem and hydrological function). For example, surface water runoff that has been redirected to recharge the aquifer may also reduce local evaporation rates, compounding the positive long-term effect on local water balances over time (Steenbergen et al., 2010). When small-scale MAR is implemented through collective action, the same collective action to implement small-scale MAR (discussed below) may also strengthen social systems, including identity, knowledge and social cohesion, which may further drive collective action and implementation of interventions (Basel et al., 2020a).

Climate trends and extremes within the sociohydrological system must further be contextualized across both temporal and spatial scales. At the temporal scale, the interplay between fast and slow variables may create both positive and negative system feedback processes. For example, industry, policy, and the cumulative effect of personal decisions determine macro-scale climate trends. There is a significant lag time, however, between emissions (or emissions reductions) and climate impacts. The effects of policy and individual behavior on emissions are therefore temporarily disconnected from the experience of subsequent climate-related impacts on both the biophysical (e.g., hydrological and ecosystem function) and social systems (e.g., increased risk due to increased probability of hazard occurrence). This disconnection may result in a lack of concentrated action to mitigate greenhouse gas emissions. Contrarily, a sudden climate-related disaster event may also spur a population to implement small-scale MAR interventions, directly impacting the biophysical subsystem.

The interaction between spatial scales also has implications. Higher groundwater levels may affect the local and regional climate, creating microclimates that alter ambient humidity, air temperatures, and local precipitation (Keune et al., 2016). Such shifts may make the local biophysical system more able to withstand macro-scale climatic extremes, and may even mitigate (to some extent) the local experience of drought. The implementation of small-scale MAR may therefore support positive feedback processes that moderate local climates. Scale is also important for the potential impact of social system variables on climate (and biophysical systems). The sum total of political and personal choices determines the total possible impact of the social system on the local climate system.

Drawing on these illustrative scenarios, climate trends and their relationship with economic, socio-political, and biophysical factors adds yet more complexity to an already dynamic sociohydrological system. However, assessing the potential effectiveness of small-scale MAR interventions and their implementation, depends on explicitly accounting for the climate subsystem. This requires not only using historical records for planning, but conducting climate vulnerability assessments, including how the climate regime is likely to shift, and incorporating temperature/precipitation trends, extremes, and seasonality into small-scale MAR designs.[11]

The social subsystem: Key variables and drivers

People and power work in tandem with hydrogeology to direct the flow of water. The social system causes cascading and dynamic effects throughout the biophysical and climate systems where small-scale MAR is implemented. Regardless, as the title of Savelli et al. (2021) "Don't Blame the Rain" eloquently illustrates, the experience of drought is often blamed on erratic weather and climate change. While climate trends are increasing the frequency and intensity of drought (IPCC, 2021), blaming the rain allows us to ignore that the modern experience of drought is often a result of inequitable and/or inefficient distribution of water (Savelli et al., 2021). Using this understanding as a point of departure, we conceptualize

11 Illustrating the importance of the temporal shift in precipitation: Even while the same amount of rain may fall throughout the year, it may increasingly fall in heavy rainfall events instead of being evening distributed (as per the historical record). As a result, rainfall concentrates as surface runoff, flood risk increases, and natural recharge is reduced, resulting in hydrological drought even at the same annual rate of precipitation.

the social aspects of the sociohydrological system, including factors that may enable or inhibit self-organization and collective action for small-scale MAR. We aim to explore this issue by addressing the following interrelated questions: Do higher scales of governance enable or undermine local action? What variables may increase the likelihood that people will act?

Do higher scales of governance enable or undermine local action?

Do people have the power to act? As a bottom-up solution, implementing small-scale MAR suggests the need for self-organization and collective action. These literatures are highly developed and will be further explored below. Action does not happen in a vacuum, but within a setting of "contextual factors and referential environment" (Vos et al., 2020, p. 5). The flow of water and the legal right to implement small-scale MAR are both dependent on economics, politics, and resource competition: local actors are subject to an array of external factors that may support or impede small-scale MAR initiatives and success. Vos et al. (2020, p. 5) suggest that key components of this broader setting include strength and involvement of the state bureaucracy, academic and epistemological environment, strength of civil society and room to maneuver, techno-physical and agro-ecological environment, and the functioning of capitalist markets in the water sector.

Central to understanding small-scale MAR within this context is the nature of water as a common-pool resource (CPR) "for which exclusion of users is difficult to achieve and for which joint use reduces the availability of benefits derived from the resource for others" (Steins and Edwards, 1999, p. 539). Water is vied for and contested. Water is also the lynchpin in supporting growing populations, urbanization, industrialization, and neoliberal development. The needs of numerous stakeholders, with various levels of influence, overlap creating complex interactions and competition (Hoogesteger and Wester, 2015). The interaction between stakeholders determines water governance, which simultaneously occurs at multiple levels through policies and measures, while water flows into and out of local systems. These policies and measures are a key driver affecting biophysical, climate, and social subsystems. While the role of governance and decision making is often highlighted within sociohydrological models (as an example see Penny and Goddard, 2018), the complexity of these interactions is arguably underestimated. Water governance and existing sociohydrological models/frameworks are largely based on neoliberal socio-economic productive models that may not be applicable to the cultural values of populations in question and may exacerbate injustice (Zwarteveen and Boelens, 2014; Vos and Boelens, 2018). Additionally, while tension between state and local governance may be circumstantial, Molle et al. (2009, p. 340) highlight that "Centralized water bureaucracies are also threatened by decentralization of power to the regional or local levels…" The bottom-up nature of small-scale MAR initiatives may make recharge undesirable by those in power, as it may be perceived as threatening their control over resource management. Local action to implement small-scale MAR (and benefit from increased water availability) may be prevented, limited, or regulated by state or federal legal frameworks (Cruz-Ayala and Megdal, 2020). Alternatively, downstream populations might believe that upstream small-scale MAR is stealing their water, further resulting in policies and regulations that prevent small-scale MAR; meanwhile, MAR infrastructure might actually be benefiting downstream populations with flood/drought mitigation and increased groundwater levels.

Conversely, the top-down involvement of government authorities in supporting local small-scale MAR initiatives may even undermine processes of self-organization and collective action. Top-down policy making tends to ignore the complexity and diversity of local water management systems (Boelens, 2009), potentially undermining the functionality of local systems. State recognition of local initiatives might paradoxically delegitimize local systems as effective square pegs of local management do not fit in the round whole of state discourse. Recognition and "equality" may translate into a process of "disciplining" of diverse systems of water management; through being recognized and accepted, diverse approaches to managing water must adapt to the system that has endogenized them, potentially undermining the prior effectiveness of the water management system (Boelens, 2009).

Government interventions in local initiatives can unknowingly contradict what the implementing population construes as equitable benefits (e.g., distributing water to people who did not do the work) potentially creating conflict and undermining the system of cooperation and collective action that made the intervention possible (Hoogesteger, 2015; Basel et al., 2020b; Dupuits et al., 2020).

"Well-intended" state and market interventions may push local production systems toward overexploitation of resources (i.e., water) that results in reduced resource access by underserved populations, resulting in further resource exploitation by these populations, increased environmental degradation, and reduced ecosystem services, impacting livelihoods and further exacerbating poverty (Robbins, 2012; Hoogesteger and Wester, 2017). Both the biophysical and social systems are impacted. This trend may be especially pronounced when state governments privatize previously collective land/resource rights or impose external governance systems on local actors (Trawick, 2003; Boelens et al., 2015; Hall, 2015). Among state and market interventions is a growing national and international focus on efficiency. State/non-profit initiatives to address water crises are often based on these efficiency discourses, which direct the flow of water toward the most efficient users and those that deliver the greatest economic benefit to the state (e.g., large-scale export producers or mining). The focus on using water "efficiently" effectively diverts water away from small-scale users that could be the most likely to implement small-scale MAR, while simultaneously disempowering local management, rights, and leaving local populations dispossessed of agricultural lands, livelihoods, and cultural identity (Mehta et al., 2012; Dell'Angelo et al., 2018; Vos and Boelens, 2018). Ironically, more "efficient" water users may effectively drain limited local water resources and drive local water crises with virtual water exports (Vos and Boelens, 2018).

These governance-related factors demonstrate paradoxes that may further drive community vulnerability to drought, while decreasing the likelihood of collective action and the implementation of small-scale MAR. Larger-scale governance can help avoid such paradoxes and enable local implementation of small-scale MAR (while increasing cooperation, collective action, and water justice) by (1) seeking to understand diversity, including recognizing and allowing for the different ways people understand and manage water; (2) taking a full inventory of the externalities of efficiency discourses; (3) external governance structures or policy makers taking the role of facilitator instead of expert; and (4) building on organizational structures that already exist (Hoogesteger and Verzijl, 2015).

What variables may increase the likelihood that people will act?

> *"... impacts and perceptions of natural hazards influence sociotechnical vulnerabilities, governance, and institutions, while at the same time social behavior, technical measures, and policy interventions alter the frequency, magnitude, and spatial distribution of natural hazards. Reciprocal effects at the local scale are also influenced by global drivers. Climate and environmental change can alter the frequency and severity of extreme weather events, while socioeconomic trends (including population growth, urbanization, and interdependent infrastructures) can increase exposure to natural hazards."* Di Baldassarre et al. (2018, p. 307).

Even if people have the power to act, will they? "Change (whether drastic or incremental) acts as a catalyst to response" (Elshafei et al., 2014, p. 2,143; Roobavannan et al., 2017). Populations act when conditions (e.g., drought) become sufficiently extreme, resulting in direct experience of the hazard, a shared memory of the experience, and/or perceived risk (Di Baldassarre et al., 2013; Viglione et al., 2014; Hale et al., 2015; Kuil et al., 2016; Penny and Goddard, 2018). While experiencing a hazard directly drives people to action to safeguard themselves, collective memory draws on local and social knowledge of previous experience to recognize biophysical thresholds and respond to emerging conditions (Kuil et al., 2016). Such collective memory is strongest immediately after experiencing the hazard and erodes over time, only to be renewed when the event is again experienced (Di Baldassarre et al., 2013; Viglione et al., 2014; Kuil et al., 2016). Collective memory increases social pressure to cooperate (Penny and Goddard, 2018), while eroded memory reduces the impetus for collective action. Social pressure may also be self-reinforcing: a behavior (e.g., action to address drought) is more likely to become widely adopted once 10% of the population has adopted the behavior (Elshafei et al., 2014). Perception of risk is rooted in the local context and individual/group understanding of the surrounding world (determined by cultural, agroecological, economic, political, and social factors) (Bebbington, 1996; Viglione et al., 2014; Hale et al., 2015; Penny and Goddard, 2018). Ostrom (2000, 2009) refer to this as Mental Models and Knowledge of the Social-ecological System, Haugaard (2012) as the sum of practical and discursive consciousness, Zwarteveen and Boelens (2014) as situated knowledge, and Feindt and Oels (2005) as discourse. Social connectivity and spaces for dialogue facilitate the development of shared understanding, including perception of risk, that can drive action (Benford and Snow, 2000; Ostrom, 2009; Penny and Goddard, 2018). Such understandings determine what is considered reasonable, possible, desirable, and important - and consequently influence how a population acts (and knows how to act) to address a problem (Kuil et al., 2016). Understandings may actually perpetuate inaction or result in actions that appear paradoxical (Bebbington, 1996; Cleaver, 2018). Factors that determine perception of risk are not static but constantly in flux as people adapt to changing conditions and contexts (Bebbington, 1996). When concerning small-scale MAR, factors of experience, memory, and perceived risk apply across governance scales, influencing policies and measures, individual behavior, and collective action (Elshafei et al., 2014; Hale et al., 2015; Di Baldassarre et al., 2019; Basel et al., 2020a; Kumar et al., 2020).

These factors interplay with social variables for enabling self-organization for small-scale MAR as a strategy for community-based adaptation highlighted by Basel et al. (2020b) and drawn from Ostrom (2009). Bottom-up and collective-action for small-scale MAR may be more likely among populations that have generational and situated knowledge with groundwater, established spaces or mechanisms for engaging in dialogue and debate, the opportunity for individuals to directly participate in building small-scale MAR infrastructure (allowing them to learn first-hand about the purpose and value of such activities), and access to technical and practical information about interventions (Basel et al., 2020a). Referred to by Ostrom (2009) as collective-choice rules, people are more likely to act if they are able to directly participate in resource governance, have political representation, and have access to information, tools, and funding for implementing small-scale MAR interventions (Penny and Goddard, 2018; Basel et al., 2020b). Self-organization for collective action is further enabled or inhibited by the number of water users. Users must be well-matched for the carrying capacity of the biophysical system (Kuil et al., 2016), having a large enough population both to contribute to organized/voluntary labor for building infrastructure, and to consolidate into a network that can access government support (Basel et al., 2020b). Simultaneously a population must be small enough to be able to engage directly in decision-making (see collective-choice rules) and feel that their participation makes a difference in the outcome (Basel et al., 2020b). As such, populations may also be unified by a shared challenge and believing that small-scale MAR will be effective (and is worth the effort invested) (Basel et al., 2020b). The lag time between intervention and benefit (resulting from the biophysical system described above) might reduce the will and social pressure to act. Belief in potential success, however, may be driven by implementing small-scale MAR in an iterative process that aims for short-term wins (Basel et al., 2020a).

When small-scale MAR is not already part of existing mental models and discourse, strong leadership, paired with an openness to experimentation and learning, supports action (Penny and Goddard, 2018; Basel et al., 2020b). Norms and social capital translate into connective processes that allow for organizational structures, social interaction and cooperation, shared awareness, social/political cohesion, and community participation (Elshafei et al., 2014; Hale et al., 2015; Penny and Goddard, 2018; Basel et al., 2020b). Norms and social capital based on shared values, reciprocity between people and with nature, and shared work, may further support implementation of small-scale MAR (Basel et al., 2020b).

Financial drivers within this system may result in paradoxes. For example, if livelihoods depend on groundwater-irrigated agriculture and demand for agricultural production increases, the area of land developed for agriculture may expand (Roobavannan et al., 2017). As a result, water use may increase, reducing local groundwater levels and driving the implementation of MAR. In turn, MAR may then support further increased agricultural development and production, resulting in further increased groundwater use. When small-scale MAR is driven strictly by financial drivers without being tempered with other considerations, interventions could paradoxically increase local vulnerability to drought (Basel et al., 2020b). Furthermore, Elshafei et al. (2014) link low per person gross domestic product (GDP) to reduced resilience and increased sensitivity; the experience in Oaxaca Basel et al. (2020b) and the arguments above suggest this correlation may be biased to neoliberal economic models. While such models certainly apply in certain socio-economic and cultural contexts, the implementation of small-scale MAR and resulting social and ecological benefits may result from water being important for social/cultural reasons instead of purely economic ones (Basel et al., 2020b).

Discussion and conclusions

In this paper we have conceptualized the sociohydrological system in which small-scale MAR interventions are implemented to increase groundwater availability in small or upper catchments. To do so, we have drawn on, consolidated, and advanced existing conceptualizations of the sociohydrological system. Sociohydrology addresses how humans affect hydrological regimes and how, in turn, water resources and water-related hazards influence human behavior including water management. The approach is solutions-oriented, seeking to understand these human-water interactions to identify effective responses to water resource challenges and hazards. Responses to water related problems, such as small-scale MAR, are not neutral phenomenon but are implemented by people: factors including who has decision-making power, who benefits, who loses, and the discourses that drive these decisions, influence how, when, by whom, and with what results small-scale MAR is implemented. In the conceptualization of the sociohydrological system presented in here, we have brought to light complex interplay between biophysical, climate, and social systems, accounting for social institutions, practices, and norms to make this research power-sensitive.

In the interplay between biophysical, climate, and social systems, water moves through the biophysical system guided by geomorphology, ecological processes, and human interventions. The climate system cycles water into and out of local landscapes. People and power within the social system guide the flow of water and are changing the climate system. Within this dynamic context, fast and slow changing factors intersect with spatial and governance scales. The dynamics among and between these systems can result in positive or negative feedback processes or paradoxes (unintended consequences), decreasing or increasing the local experience of drought. By conceptualizing the system and exploring the interplay between these three systems, we can identify important considerations, opportunities for engagement and learning, and possible paradoxes.

The structure and state of the biophysical system determine ecosystem function, including hydrological flows. Ecosystem functions benefit human populations, including through the provision of water resources, food, livelihoods, and the regulation of floods and drought. The relationship between people and the surrounding landscape also supports and influences place-based knowledge, social dynamics, and identity that enable or inhibit the implementation of small-scale MAR. The biophysical system is not static or only subject to the laws of the natural sciences, but is plastic: both climatic processes and the normative goals and political choices of the people managing and interacting with the biophysical system help determine the state of the landscape and resulting ecosystem function.

Interplay between biophysical, climate, and social systems is unfolding within the context of increasing hydroclimatic extremes, including droughts and floods, related to climate change. Historical climate data are no longer representative for understanding system dynamics and planning small-scale MAR interventions. Climate molds the biophysical system, which in turn helps regulate both local climates and the global climate system. Climate also indisputably affects society, while people are driving changing climate trends across both global and microclimate scales. As a community-based adaptation strategy and Nature-based Solution, small-scale MAR interventions specifically increase the ability of both the biophysical and social systems to weather climate extremes (e.g., mitigating drought and flooding, preserving ecosystem/hydrological function, and reinforcing social factors that enable collective action).

The profound influence of climate on the interplay between biophysical, climate, and social systems indicates that assessing the potential effectiveness of small-scale MAR interventions and their implementation depends on explicitly accounting for the climate system. Designing small-scale MAR in the current context of climate change requires not only using historical records for planning, but conducting climate vulnerability assessments, including how the climate regime is likely to shift including incorporating temperature/precipitation trends, extremes, and shifting seasonality.

Meanwhile, society often blames drought on climate change and erratic weather. Climate trends are increasing and intensifying drought events. The social system also informs the state and functionality of both biophysical and climate systems in a myriad of ways. The social system moreover drives the experience of drought through inequitable and/or inefficient water management. The implementation of small-scale MAR, occurs within this broader socio-political context in which water is a contested resource. The complexity of governance and decision-making is routinely under recognized, while having ricocheting effects not only on the implementation of small-scale MAR interventions and water use, but throughout the entire sociohydrological system described in this paper. Higher-level governance may enable or inhibit action to address drought (e.g., small-scale MAR). Even when the state aims to support action, state involvement may inadvertently deteriorate or delegitimize the social capital that support the implementation of MAR, or push the sociohydrological system toward overexploitation of water resources, weakening the biophysical system, fueling climate change, and exacerbating poverty.

People will be more prone to implement small-scale MAR when biophysical, climatic conditions, and inequitable distribution of water become sufficiently extreme, resulting in the experience, recent and collective memory, or perceived risk of drought. These factors combine with social pressure to act; cultural, agroecological, socio-economic, and political factors; framing and discourse about the problem and perceived potential for action; and the principles for self-organization for small-scale MAR (see Basel et al., 2020b). While livelihoods and economic trends may drive implementation, implementation of small-scale MAR may actually be driven by water being important for social/cultural reasons linked to the landscape, instead of financial ones.

Despite the promise of small-scale MAR, applying a critical lens to understanding the interplay between biophysical, climate, and social systems and resulting feedback processes and paradoxes, allows us to not overestimate or oversimplify small-scale MAR as a bottom-up solution and community-based adaptation strategy. Within the parameters of climate trends, small-scale MAR may serve to increase the functionality of ecosystems and reduce the impact of climate extremes, while protecting livelihoods and supporting society. In an additional positive feedback loop, small-scale MAR may both reduce the biophysical likelihood of experiencing drought (and mitigate flooding) while simultaneously increasing the social ability to further cope with or avoid drought. Paradoxes and negative feedback processes, however, must be avoided.

Specific factors, and how such factors interplay, will be different in each context where small-scale MAR is implemented. Conceptualizing the sociohydrological system in which small-scale MAR is implemented, including explicitly accounting for climate trends and using a power-sensitive approach, allows us to recognize and account for the complexity of this system. Important considerations, positive and negative feedback processes, and possible paradoxes can be identified. Applying these understandings to case studies offers a rich opportunity for future research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

BB and JH conceptualized the paper and the methodology. BB performed the literature review, curated the data, conducted the formal analysis, and wrote the first draft of the manuscript. BB, JH, and PH reviewed and edited the first draft before submission and throughout the peer-review process.

Acknowledgments

We would like to thank the Delft International Conference on Sociohydrology and Frontiers for the opportunity to present our preliminary research at the conference and for supporting the open-access publication of this manuscript. We would like to further thank our colleagues working with sociohydrology for their time and for many valuable discussions which contributed to the development and refinement of the conceptualization presented in this paper. Finally, we would like to thank the reviewers for their time and insightful comments that helped us to improve this manuscript.

Conflict of interest

Author BB is the founder of Ecothropic and co-founder of Ecothropic México A.C.

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Basel, B., Goby, G., and Johnson, J. (2020a). Community-based adaptation to climate change in villages of Western Province, Solomon Islands. *Mar. Poll. Bulletin*. 156, 111266. doi: 10.1016/j.marpolbul.2020.111266

Basel, B., Hernández Quiroz, N., Velasco Herrera, R., Santiago Alonso, C., and Hoogesteger, J. (2020b). Bee mietii rak rkabni nis (the people know how to seed water): a Zapotec experience in adapting to water scarcity and drought. *Climate Dev*. 13, 792–806. doi: 10.1080/17565529.2020.1855100

Bebbington, A. (1996). "Movements, modernizations, and markets: indigenous organizations and agrarian strategies in Ecuador," in *Liberation Ecologies. Environment, Development, Social Movements*, eds R. Peet and M. Watts (London; New York, NY: Routledge), 86–109.

Benford, R. D., and Snow, D. A. (2000). Framing processes and social movements: an overview and assessment. *Ann. Rev. Sociol.* 26, 611–639. doi: 10.1146/annurev.soc.26.1.611

Berkes, F., and Armitage, D. (2010). Co-management institutions, knowledge, and learning: adapting to change in the Arctic. *Études/Inuit/Studies* 34, 109–131. doi: 10.7202/045407ar

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., et al. (2012). Toward principles for enhancing the resilience of Ecosystem Services. *Ann. Rev. Environ. Resour*. 37, 421–448. doi: 10.1146/annurev-environ-051211-123836

Blöschl, G., Viglione, A., and Montanari, A. (2013). *Emerging Approaches to Hydrological Risk Management in a Changing World. Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*. (Elsevier Inc.; Academic Press), 3–10. ISBN: 9780123847034. doi: 10.1016/B978-0-12-384703-4.00505-0

Boelens, R. (2009). The politics of disciplining water rights'. *Dev. Change* 40, 307–331. doi: 10.1111/j.1467-7660.2009.01516.x

Boelens, R. (2014). Cultural politics and the hydrosocial cycle: water, power and identity in the Andean highlands. *Geoforum* 57, 234–247. doi: 10.1016/j.geoforum.2013.02.008

Boelens, R., Hoogesteger, J., and Baud, M. (2015). Water reform governmentality in Ecuador: neoliberalism, centralization, and the restraining of polycentric authority and community rule-making. *Geoforum* 64, 281–291. doi: 10.1016/j.geoforum.2013.07.005

Boelens, R., Hoogesteger, J., Swyngedouw, E., Vos, J., and Wester, P. (2016). Hydrosocial territories: a political ecology perspective. *Water Int.* 41, 1–14. doi: 10.1080/02508060.2016.1134898

Bohensky, E. L., Evans, L. S., Anderies, J. M., Biggs, D., and Fabricius, C. (2015). *Principle 4—Foster Complex Adaptive Systems Thinking. Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems*. Cambridge: Cambridge University Press, 142–173. doi: 10.1017/CBO9781316014240.007

Boillat, S., and Berkes, F. (2013). Perception and interpretation of climate change among Quechua farmers of Bolivia: indigenous knowledge as a resource for adaptive capacity. *Ecol. Soc.* 18, 421. doi: 10.5751/ES-05894-180421

Clark, W. C., and Harley, A. G. (2020). Sustainability science: toward a synthesis. *Ann. Rev. Environ. Resour.* 45, 331–386. doi: 10.1146/annurev-environ-012420-043621

Cleaver, F. (2018). "Everyday water injustice and the politics of accommodation," in *Water Justice*, eds R. Boelens, T. Perreault, and J. Vos (Cambridge: Cambridge University Press), 246–258. doi: 10.1017/9781316831847.016

Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). *Nature-Based Solutions to Address Global Societal Challenges*. Gland: IUCN, xiii + 97. doi: 10.2305/IUCN.CH.2016.13.en

Cruz-Ayala, M. B., and Megdal, S. B. (2020). An overview of managed aquifer recharge in Mexico and its legal framework. *Water* 12, 474. doi: 10.3390/w12020474

Dell'Angelo, J., Rulli, M. C., and D'Odorico, P. (2018). The global water grabbing syndrome. *Ecol. Econ.* 143, 276–285. doi: 10.1016/j.ecolecon.2017.06.033

Di Baldassarre, G., Nohrstedt, D. J., Burchardt, S., Albin, C., and Bondesson, S. (2018). An integrative research framework to unravel the interplay of natural hazards and vulnerabilities. *Earth's Fut.* 6, 305–310. doi: 10.1002/2017EF000764

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., et al. (2019). Sociohydrology: scientific challenges in addressing the sustainable development goals. *Water Resour. Res.* 55, 6327–6355. doi: 10.1029/2018WR023901

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., and Blöschl, G. (2013). Socio-hydrology: conceptualising human-flood interactions. *Hydrol. Earth Syst. Sci.* 17, 3295–3303. doi: 10.5194/hess-17-3295-2013

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., et al. (2015). Debates—perspectives on socio-hydrology: capturing feedbacks between physical and social processes. *Water Resour. Res.* 51, 4770–4781. doi: 10.1002/2014WR016416

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R. D. G., Jain, R. C., et al. (2019). Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* 27, 1–30. doi: 10.1007/s10040-018-1841-z

Dupuits, E., Baud, M., Boelens, R., de Castro, F., and Hogenboom, B. (2020). Scaling up but losing out? Water commons' dilemmas between transnational movements and grassroots struggles in Latin America. *Ecol. Econ.* 172, 106625. doi: 10.1016/j.ecolecon.2020.106625

Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R. (2014). A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrol. Earth Syst. Sci.* 18, 2141–2166. doi: 10.5194/hess-18-2141-2014

Feindt, P. H., and Oels, A. (2005). Does discourse matter? Discourse analysis in environmental policy making. *J. Environ. Pol. Plan.* 7, 161–173. doi: 10.1080/15239080500339638

Gleick, P., and Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *Proc. Natl. Acad. Sci. U.S.A.* 107, 11155–11162. doi: 10.1073/pnas.1004812107

Guyennon, N., Salerno, F., Portoghese, I., and Romano, E. (2017). Climate change adaptation in a Mediterranean semi-arid catchment: testing managed aquifer recharge and increased surface reservoir capacity. *Water* 9, 1–18. doi: 10.3390/w9090689

Hale, R. L., Armstrong, A., Baker, M. A., Bedingfield, S., Betts, D., Buahin, C., et al. (2015). iSAW: integrating structure, actors, and water to study socio-hydro-ecological systems. *Earth's Fut.* 3, 2014EF000295. doi: 10.1002/2014EF000295

Hall, R. J. (2015). Divide and conquer: privatizing indigenous land ownership as capital accumulation. *Stud. Polit. Econ.* 96, 23–46. doi: 10.1080/19187033.2015.11674936

Haugaard, M. (2012). Rethinking the four dimensions of power: domination and empowerment. *J. Polit. Power* 5, 33–54. doi: 10.1080/2158379X.2012.660810

Hommes, L., and Boelens, R. (2017). Urbanizing rural waters: rural-urban water transfers and the reconfiguration of hydrosocial territories in Lima. *Polit. Geogr.* 57, 71–80. doi: 10.1016/j.polgeo.2016.12.002

Hommes, L., Boelens, R., Harris, L. M., and Veldwisch, G. J. (2019). Rural–urban water struggles: urbanizing hydrosocial territories and evolving connections, discourses and identities. *Water Int.* 44, 81–94. doi: 10.1080/02508060.2019.1583311

Hoogesteger, J. (2015). Normative structures, collaboration and conflict in irrigation; a case study of the Pillaro North Canal Irrigation System, Ecuadorian Highlands. *Int. J. Commons.* 9, 398–415. doi: 10.18352/ijc.521

Hoogesteger, J. (2022). Regulating agricultural groundwater use in arid and semi-arid regions of the Global South: challenges and socio-environmental impacts. *Curr. Opin. Environ. Sci. Health* 2022, 100341. doi: 10.1016/j.coesh.2022.100341

Hoogesteger, J., and Verzijl, A. (2015). Grassroots scalar politics: insights from peasant water struggles in the Ecuadorian and Peruvian Andes. *Geoforum* 62, 13–23. doi: 10.1016/j.geoforum.2015.03.013

Hoogesteger, J., and Wester, P. (2015). Intensive groundwater use and (in) equity: Processes and governance challenges. *Environ. Sci. Policy* 51, 117–124. doi: 10.1016/j.envsci.2015.04.004

Hoogesteger, J., and Wester, P. (2017). Regulating groundwater use: The challenges of policy implementation in Guanajuato, Central Mexico. *Environ. Sci. Policy* 77, 107–113. doi: 10.1016/j.envsci.2017.08.002

Hulme, M. (2011). Meet the humanities. *Nat. Climate Change* 1, 177–179. doi: 10.1038/nclimate1150

International Groundwater Assessment Centre (2020). *Managed Aquifer Recharge (MAR)*. Available online at: https://www.un-igrac.org/areas-expertise/managed-aquifer-recharge-mar (accessed June 9 2020).

IPCC. (2021). "Summary for policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Cambridge University Press).

Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., et al. (2014). "Freshwater resources," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Cambridge: Cambridge University Press), 229–269.

Kallis, G. (2010). Coevolution in water resource development: The vicious cycle of water supply and demand in Athens, Greece. *Ecol. Econ.* 69, 796–809. doi: 10.1016/j.ecolecon.2008.07.025

Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., and Sivapalan, M. (2014). Socio-hydrologic drivers of the pendulum swing between agriculture development and environmental health: A case study from Murrumbidgee river basin, Australia. *Hydrol. Earth Syst. Sci.* 18, 1027–1041. doi: 10.5194/hess-18-1027-2014

Kates, R. W., Colten, C. E., Laska, S., and Leatherman, S. P. (2006). Reconstruction of New Orleans after Hurricane Katrina: A research perspective. *Proc. Natl. Acad. Sci. U.S.A.* 103, 14653–14660. doi: 10.1073/pnas.0605726103

Kennedy, D. (1995). Water supply and use in the southern Hauran, Jordan. *J. Field Archaeol.* 22, 275–290. doi: 10.1179/009346995791974198

Keune, J., Gasper, F., Goergen, K., Hense, A., Shrestha, P., Sulis, M., et al. (2016). Studying the influence of groundwater representations on land surface-atmosphere feedbacks during the European heat wave in 2003. *J. Geophys. Res. Atmos.* 121, 2016JD025426. doi: 10.1002/2016JD025426

Kuil, L., Carr, G., Viglione, A., Prskawetz, A., and Blöschl, G. (2016). Conceptualizing socio-hydrological drought processes: the case of the Maya collapse. *Water Resour. Res.* 52, 6222–6242. doi: 10.1002/2015WR018298

Kumar, P., Avtar, R., Dasgupta, R., Johnson, B. A., Mukherjee, A., Ahsan, M. N., et al. (2020). Socio-hydrology: a key approach for adaptation to water scarcity and achieving human wellbeing in large riverine islands. *Progr. Disast. Sci.* 8, 100134. doi: 10.1016/j.pdisas.2020.100134

Lasage, R., Aerts, J. C. J. H., Verburg, P. H., and Sileshi, A. S. (2015). The role of small scale sand dams in securing water supply under climate change in Ethiopia. *Mitig. Adapt. Strateg. Glob. Change.* 20, 317–339. doi: 10.1007/s11027-013-9493-8

Lasage, R., and Verburg, P. H. (2015). Evaluation of small scale water harvesting techniques for semi-arid environments. *J. Arid Environ.* 118, 48–57. doi: 10.1016/j.jaridenv.2015.02.019

Linton, J., and Budds, J. (2014). The hydrosocial cycle: defining and mobilizing a relational-dialectical approach to water. *Geoforum* 57, 170–180. doi: 10.1016/j.geoforum.2013.10.008

Madani, K., and Shafiee-Jood, M. (2020). Socio-hydrology: a new understanding to unite or a new science to divide? *Water* 12, 1941. doi: 10.3390/w12071941

Malik, R., Giordano, M., and Sharma, V. (2014). Examining farm-level perceptions, costs, and benefits of small water harvesting structures in Dewas, Madhya Pradesh. *Agri. Water Manag.* 131, 204–211. doi: 10.1016/j.agwat.2013.07.002

Mao, F., Clark, J., Karpouzoglou, T., Dewulf, A., Buytaert, W., and Hannah, D. (2017). HESS Opinions: a conceptual framework for assessing socio-hydrological resilience under change. *Hydrol. Earth Syst. Sci.* 21, 3655–3670. doi: 10.5194/hess-21-3655-2017

Mehta, L., Veldwisch, G. J., and Franco, J. (2012). Introduction to the Special Issue: water grabbing? Focus on the (re)appropriation of finite water resources. *Water Alternativ.* 5, 193–207. Available online at: https://www.water-alternatives.org/index.php/tp1-2/1881-vol5/213-issue5-2

Melsen, L. A., Vos, J., and Boelens, R. (2018). What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world". *Hydrolog. Sci. J.* 63, 1435–1443. doi: 10.1080/02626667.2018.1499025

Molle, F., and Berkoff, J. (2009). Cities vs. agriculture: a review of intersectoral water re-allocation. *Nat. Resour. For.* 33, 6–18. doi: 10.1111/j.1477-8947.2009.01204.x

Molle, F., Mollinga, P. P., and Wester, P. (2009). Hydraulic bureaucracies and the hydraulic mission: flows of water, flows of power. *Water Alternativ.* 2, 328–349.

Molle, F., Wester, P., and Hirsch, P. (2010). River basin closure: processes, implications and responses. *Agri. Water Manag.* 97, 569–577. doi: 10.1016/j.agwat.2009.01.004

Ochoa-Tocachi, B. F., Bardales, J. D., Antiporta, J., Pérez, K., Acosta, L., Mao, F., et al. (2019). Potential contributions of pre-Inca infiltration infrastructure to Andean water security. *Nat. Sustainabil.* 2, 584–593. doi: 10.1038/s41893-019-0307-1

Olson, M. (1965).The Logic of Collective Action: Public Goods and the Theory of Groups. Cambridge, MA: Harvard University Press.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action (Cambridge, MA: Cambridge University Press), 271. doi: 10.1017/CBO9780511807763

Ostrom, E. (2000). Reformulating the commons. *Swiss Polit. Sci. Rev.* 6, 29–52. doi: 10.1002/j.1662-6370.2000.tb00285.x

Ostrom, E. (2009). A general framework for analyzing sustainability ofsocial-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Ostrom, E., Janssen, M. A., and Anderies, J. M. (2007). Going beyond panaceas. *Proc. Natl. Acad. Sci. U. S. A.* 104, 15176–15178. doi: 10.1073/pnas.0701886104

Otieno, V. O., and Anyah, R. O. (2012). Effects of land use changes on climate in the Greater Horn of Africa. *Climate Res.* 52, 77–95. doi: 10.3354/cr01050

Pande, S., and Sivapalan, M. (2016). Progress in socio-hydrology: a meta-analysis of challenges and opportunities. *WIREs Water* 4, 1193. doi: 10.1002/wat2.1193

Pandey, D. N., Gupta, A. K., and Anderson, D. M. (2003). Rainwater harvesting as an adaptation to climate change. *Curr. Sci.* 85, 46–59. Available online at: http://www.jstor.org/stable/24107712

Patel, N. G., and Prabhakar, A. M. (2012). Analysis of rain water harvesting system for artificial recharge of groundwater for Gandhinagar District, Gujarat. *Paripex Ind. J. Res.* 3, 215–216. doi: 10.15373/22501991/July2014/83

Penny, G., and Goddard, J. J. (2018). Resilience principles in socio-hydrology: a case-study review. *Water Secur.* 4, 37–43. doi: 10.1016/j.wasec.2018.11.003

Reid, H. (2016). Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate Dev.* 8, 4–9. doi: 10.1080/17565529.2015.1034233

Renganayaki, S. P., and Elango, L. (2013). A review on managed aquifer recharge by check dams: a case study Near Chennai, India. *Int. J. Res. Eng. Technol.* 2, 416–423. doi: 10.15623/ijret.2013.0204002

Ribeiro Neto, A., Scott, C. A., Lima, E. A., Montenegro, S. M. G. L., and Cirilo, J. A. (2014). Infrastructure sufficiency in meeting water demand under climate-induced socio-hydrological transition in the urbanizing Capibaribe River basin–Brazil. *Hydrol. Earth Syst. Sci.* 18, 3449–3459. doi: 10.5194/hess-18-3449-2014

Ribeiro, L. (2020). *The Role of Ancestral Groundwater Techniques as Nature Based Solutions for Managing Water. EGU General Assembly 2020. Online, 4–8 May 2020, EGU2020-5959, 2020.* doi: 10.5194/egusphere-egu2020-5959

Robbins, P. (2012). "Political vs. apolitical ecologies," in *Political Ecology: A Critical Introduction, 2nd Edn, Chapter 1*. (Oxford: Wiley-Blackwell), 11–23.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., et al. (2014). The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability. *Ecohydrology* 7, 1249–1261. doi: 10.1002/eco.1562

Roobavannan, M., Kandasamy, J.,Pande, S., Vigneswaran, S., and Sivapalan, M. (2017). Role of sectoraltransformation in the evolution ofwater management norms inagricultural catchments: asociohydrologic modeling analysis. *Water Resour. Res.* 53, 8344–8365. doi: 10.1002/2017WR020671

Ross, A., and Chang, H. (2020). Socio-hydrology with Hydrosocial Theory: two sides of the same coin? *Hydrolog. Sci. J.* 65, 1443–1457. doi: 10.1080/02626667.2020.1761023

Rusca, M., and Di Baldassarre, G. (2019). Interdisciplinary critical geographies of water: capturing the mutual shaping of society and hydrological flows. *Water* 11, 1973. doi: 10.3390/w11101973

Sadoff, C. W., Hall, J. W., Grey, D., Aerts, J. C. J. H., Ait-Kadi, M., Brown, C., et al. (2015). *Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth*. (Oxford: University of Oxford), 180.

Savelli, E., Rusca, M., Cloke, H., and Di Baldassarre, G. (2021). Don't blame the rain: social power and the 2015–2017 drought in Cape Town. *J. Hydrol*. 594, 125953. doi: 10.1016/j.jhydrol.2020.125953

Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., and Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. Royal Soc. B* 375, 20190120. doi: 10.1098/rstb.2019.0120

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environ. Res. Lett*. 4, 035005. doi: 10.1088/1748-9326/4/3/035005

Sivapalan, M. M., Konar, V., Srinivasan,A., Chhatre, A., Wutich, C. A., Scott,J. L., et al. (2014). Socio-hydrology: use-inspired water sustainability science for the Anthropocene. *Earth's Fut*. 2, 225–230. doi: 10.1002/2013EF0 00164

Steenbergen, F., van Tuinhof, A., and van Beusekom, M.. (2010). *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. Available online at: https://www.bebuffered.com/downloads/3r_managing_the_water_buffer_2009.pdf

Steins, N. A., and Edwards, V. M. (1999). Collective action in common-pool resource management: the contribution of a social constructivist perspective to existing theory. *Soc. Nat. Resour*. 12, 539–557. doi: 10.1080/089419299279434

Trawick, P. (2003). Against the privatization of water: an indigenous model for improving existing laws and successfully Governing the commons. *World Dev*. 31, 977–996. doi: 10.1016/S0305-750X(03)00049-4

Vanelli, F. M., and Kobiyama, M. (2021). How can socio-hydrology contribute to natural disaster risk reduction? *Hydrolog. Sci. J.* 66, 1758–1766. doi: 10.1080/02626667.2021.1967356

Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., et al. (2014). Insights from socio-hydrology modelling on dealing with flood risk–roles of collective memory, risk-taking attitude and trust. *J. Hydrol*. 518, 71–82. doi: 10.1016/j.jhydrol.2014.01.018

Vos, J., and Boelens, R. (2018). "Neoliberal water governmentalities, virtual water trade, and contestations," in *Water Justice*, eds R. Boelens, T. Perreault, and J. Vos (Cambridge: Cambridge University Press), 283–301. doi: 10.1017/9781316831847.019

Vos, J., Boelens, R., Venot, J.-P., and Kuper, M. (2020). Rooted water collectives: towards an analytical framework. *Ecolog. Econ*. 173, 106651. doi: 10.1016/j.ecolecon.2020.106651

Wesselinck, A., Kooy, M., and Warner, J. (2017). Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. *WIREs Water* 4, e1196. doi: 10.1002/wat2.1196

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., et al. (2017). Engaging with the politics of water governance. *Wiley Interdiscip. Rev. Water* 4:e1245. doi: 10.1002/wat2.1245

Zwarteveen, M. Z., and Boelens, R. (2014). Defining, researching and struggling for water justice: some conceptual building blocks for research and action. *Water Int*. 39, 143–158. doi: 10.1080/02508060.2014.891168

frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 21 February 2023
DOI 10.3389/frwa.2023.1070644

OPEN ACCESS

EDITED BY
Marcus Nüsser,
Heidelberg University, Germany

REVIEWED BY
Melissa Haeffner,
Portland State University, United States
Judith Müller,
Karlsruhe Institute of Technology (KIT), Germany

*CORRESPONDENCE
Shreyashi Bhattacharya
✉ shreyashi.b123@gmail.com

SPECIALTY SECTION
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

RECEIVED 15 October 2022
ACCEPTED 31 January 2023
PUBLISHED 21 February 2023

CITATION
Bhattacharya S, Mukherjee J, Choudry A and Ghosh R (2023) Reifying "river": Unpacking pluriversal possibilities in rejuvenation surrounding the Adi Ganga of Kolkata. *Front. Water* 5:1070644. doi: 10.3389/frwa.2023.1070644

Reifying "river": Unpacking pluriversal possibilities in rejuvenation surrounding the Adi Ganga of Kolkata

Shreyashi Bhattacharya[1]*, Jenia Mukherjee[2], Anuradha Choudry[2] and Raktima Ghosh[1]

[1]Rekhi Centre of Excellence for the Science of Happiness, Indian Institute of Technology Kharagpur, Kharagpur, India, [2]Department of Humanities and Social Sciences, Indian Institute of Technology Kharagpur, Kharagpur, India

Using the River Adi Ganga as the case study and implementing the historical urban political ecology (HUPE) framework, in this article we demonstrate multiple trends and trajectories that comprise city-river relationships. We explore coeval ontologies framing "river," "riverine space" and "river rejuvenation" schemes, encapsulating "storylines" through the deployment of multi-modal (qualitative) research methodologies to trace and document plural perceptions on the river that was declared to be "dead"—the pillaged stretch that embodied the construction of the metro pillars. Media journalists and activists' narrative, that this act had slaughtered the river and robbed her of her original flows and services, has crafted a deep imprint on the citizens of Kolkata who consider the river as a stinking sink, offering minimal sewerage facilities to the city. Our paper challenges this linear depiction and weaves together positive moments, events and actions that keep the river flowing—shaping and in turn being shaped by (more-than)human actors across long temporal units and scales. We integrate the numerous agential and stakeholder voices attached to the river, shedding light on various (un)successful attempts to revive the river beyond global conceptualizations of what a "river" should be. We believe that the unfolding of this "pluriverse" will forge sustainable understandings of the river's current challenges and existing opportunities toward a collaborative blueprint through knowledge coproduction, stakeholder mobilization and actions. While our empirical frame of reference focuses on micro-realities surrounding a particular river on a specific urban hydroscape, our theoretical conceptualization framings and methodological applications will have potentials to be implemented at scales.

KEYWORDS

river, rejuvenation, pluriverse, historical urban political ecology (HUPE), Adi Ganga, Kolkata

1. Introduction

Academic discourses on water have witnessed both conflicting and collaborative exchanges in recent decades, with the evolution of water's definition from its chemical analysis to its varied ecological, social and economic aspects. This finds special importance in the context of South Asia, whose topography riddled with tumultuous waterscapes and tampered by British colonists, exposed the imperial mindset of perceiving rivers as transactional objects. For them, rivers were nothing but a line on the map, identified through its hydrology that could be analyzed, tamed and manipulated for revenue generation 17 (Lahiri-Dutt, 2015). This posited the direct conflict existing on a river's identity as perceived between the river prepotent and river participants, with the former recognizing the waterscapes through its transactional benefits and the latter appreciating the river's societal contributions, gathered through human-water interactions over centuries (Swyngedouw, 1999; Karpouzoglou and Vij, 2017). A brief glance at our ancient history would reflect upon the importance of rivers in nurturing civilizations, with the flowing waters leading to development of agriculture, commerce and urbanization at different places and paces of time. The development of modern cities however, witnessed the various purposes served by water in an urban space, with its flows being engineered to dispose of urban waste, while simultaneously providing shelter to marginalized communities on its banks. Despite the dynamicity of a river's physical form, with her untethered movements challenging anthropocentric boundaries, the rigidity surrounding the concept of "space" around a river's shoreline, that often shelters vulnerable communities, exposes the fragility of urban diasporas in metropolitan centers. Rivers in South Asian urban spaces, despite their different geomorphological, social and political challenges, now continue to share certain similarities seated in developmental or urbanization practices, through butchering of waterbodies and overwhelming of shorelines with skyscrapers.

This emerging trend of flaunting "progress," often under the guise of river restoration, rejuvenation and corrections, comes across as a front for anthropological manipulation of urban water, catering to state legitimization of corporate practices on ecological bodies. In many cases of urban waterbodies, especially rivers in India, prominent streams have been converted into either sewage arteries for the increasing urban demographic, or tamed for infrastructural transformations such as dams, bridges, real estate, thus continuing the colonial legacy of ecological abstraction in South Asian. The impact of these practices, increases by manifold when ideas such as river rejuvenation or restoration are disengaged from the hydrosocial aspects of water and are based on socio-political hierarchical decision making. The case of River Adi Ganga in Kolkata (see Figure 1), showcases the contemporary challenges of an urban waterscapes in the global South, impacted by socio-political and infrastructural practices that are deeply rooted in "colonial hydrology" (D'Souza, 2006), a case that is reflective of the situation of most South Asian rivers, and yet unique with the region's place-based narratives.

We believe that the colonial period was watershed in terms of evolution of networked infrastructures of Kolkata–the Adi Ganga–Tolly's Canal being the first major hydraulic engineering intervention in this regard, yet, the river encountered many cycles of physical-political transformations, serving as an input and output to the shifting needs and aspirations of the city. We have analyzed the role of the river in trade-transportation-drainage-sewerage-sanitation, its material impacts on the urban waterscape, and how solutions to tackle the deterioration of riverine stretches should be designed from comprehensive-inclusive perspectives along a scoping exercise on the historical-social biography of the river. Thus, this historical narrative, we think is important in terms of placing the significance of temporality in understanding rivers, river-city interactions, and planning historically and culturally contingent solutions.

We use place based narratives to explore the water complexities of the urban river Adi Ganga in Kolkata. The challenges of Adi Ganga, a river enmeshed with centuries of heritage, has been analyzed with the Historical Urban Political Ecology (HUPE) framework to understand the multiple narratives of city-nature codependency and explore the many "storylines" existing on/upon the river's varied spatial stretch. These storylines probe into a deeper understanding of "modern water," dissecting the diverse connotations of urban water abstraction, which is jotted with history, socio-cultural transformations and political aspirations that have shaped the river and vice versa (Linton, 2010). By exploring these many meanings of this river and the multiple narratives and practices surrounding restorative efforts, we unpack and validate "pluriversal possibilities" (Escobar, 2011) as a theoretical-empirical traction toward solution-oriented interventions for South Asian urban waterscapes. The river encountered many cycles of physical-political transformations, serving as an input and output to the shifting needs and aspirations of the city. We have analyzed the role of the river in trade-transportation-drainage-sewerage-sanitation, its material impacts on the urban waterscape, and how solutions to tackle the deterioration of riverine stretches should be designed from comprehensive-inclusive perspectives along a scoping exercise on the historical-social biography of the river. Thus, this historical narrative, we think is important in terms of placing the significance of temporality in understanding rivers, river-city interactions, and planning historically and culturally contingent solutions.

1.1. Scholarships on south Asian water: A brief review

The importance of water in the global south's societal ethos has long been discussed, whether through a deterministic approach of hydraulic society (Wittfogel, 1957) or witnessed in the flexible and evolving human-non human interactions, as exclaimed aptly by Lahiri-Dutt (2000, p. 2396), that "the river is neither outside society, nor is it just a thing out there in nature." The case of Adi Ganga, whose cultural significance keeps evolving from a site of religious patronage to a transactional route, to a habitat for refugees that keeps absorbing and disseminating changes, stands true to this testament. This messy reality of water, shaped by various social relations was explored early by political ecologists (Swyngedouw, 1999, 2005, 2009; Bakker, 2003, 2004, 2013; Baviskar, 2007,

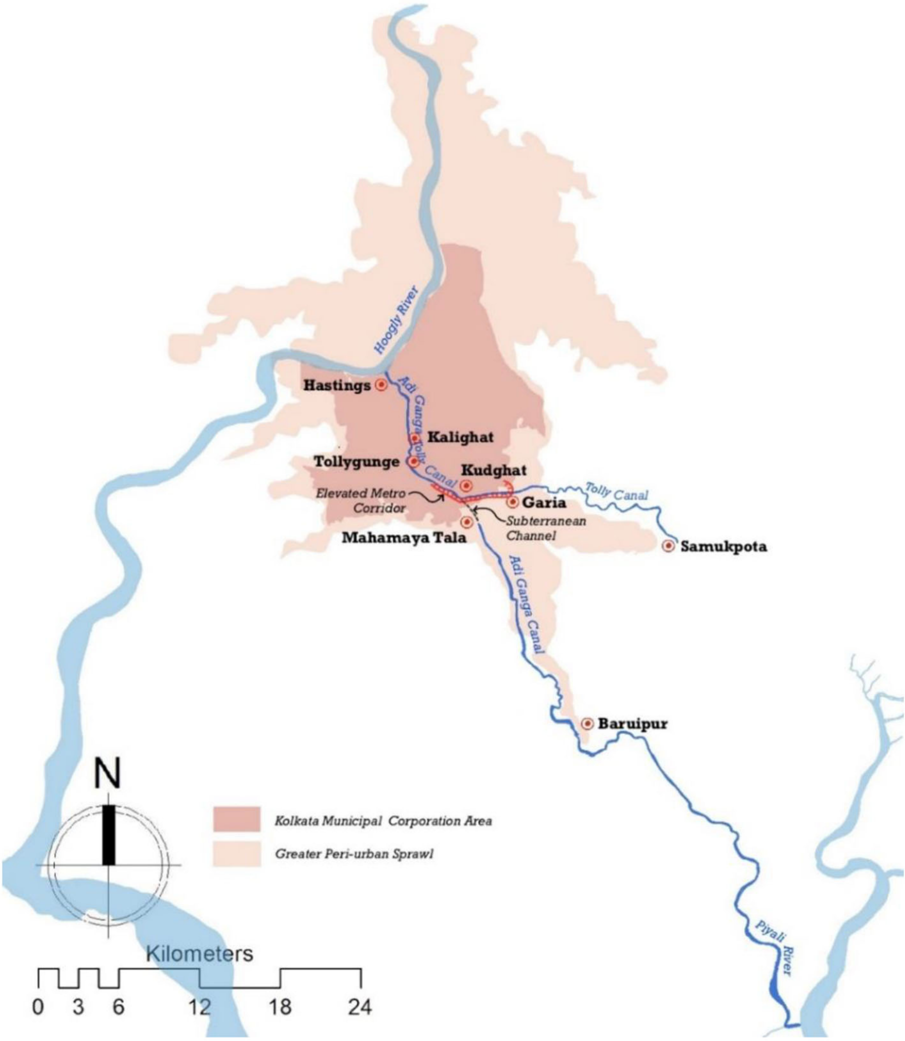


FIGURE 1
River Adi Ganga, Kolkata 2021 Source: Developed by Debika Banerji and Shreyashi Bhattacharya (Mukherjee et al., 2022).

2009), focusing on the power equations surrounding urban water dynamics and its immersion into the scalability of urban water governance (Swyngedouw, 2005, 2009; Gandy, 2008; McFarlane, 2008; Bakker, 2011; Rattu and Véron, 2015).

Linton and Budds (2014) explained this further with the "hydrosocial" paradigm that had emerged out of political ecology of water, on "how water and society make and remake each other, over space and time," harnessing on the hybridity between water and humans which is signified by the omission of the hyphen in "hydrosocial," just as in a socionatural system where the two elements "socio" and "natural" cannot be separated or even distinguished (Wesselink et al., 2017). These pluralities of South Asian urbanity has played a major role in developing the eco-political and socio-environmental practices on and around Adi Ganga, with citizens historically and politically claiming and "inventing" spaces around the river (Miraftab, 2004). This also contributes to the discourse on materiality's surrounding the river, where the marginalized have been "othered" as contributors of unsanitary, polluting practices and criminality (Véron, 2006; Ghertner, 2011, 2012; Truelove and Mawdsley, 2011; Zimmer, 2012, 2015; Follmann, 2015).

The socio-political backdrop of river Adi Ganga, with the banks offering shelter to millions of refugees post partition (1947), Bangladesh Liberation War in 1971 and a space from migration of the city's informal workforce against the colonial space of hydrological interventions and bourgeoisie environmentalism (Baviskar, 2003), is a testament to the water's unruly dynamics, of "what is legal and what is legitimate" in urban waterscapes (Acharya, 2015). This core discourses, exploring the socio-political hegemonies surrounding "flows, allocation, infrastructure, institutions and framings" or "instances" of water (Budds, 2013, p. 303) can be redefined further by understanding the otherness of urban waterscapes that involves cultural connotations, consumption dynamics and place-based understandings through transgressions of disciplinary boundaries (Bryant, 1999).

The media and activists' portrayal of the decline and death of the river also fits within the larger urban (political) ecological scholarship on hydrological engineering and urban ordering of the statecraft and its simultaneous impact upon local ecologies and social displacements (Gandy, 2004; Baviskar, 2011; Castonguay and Evenden, 2012; Coelho and Raman, 2013; Singh et al., 2018; Coelho, 2020; Chitra, 2021). Mukherjee's exploration of the Historical Urban Political Ecology (HUPE) framework offers a historical perspective to the manipulated and evolving colonial ecosystem infrastructures surrounding the city and the river, exposing the micro-realities of eco-social multistakeholder collaborations in maintaining future sustainability of deltaic riskscapes such as Kolkata, where Adi Ganga's drainage network serves a prominent role in maintaining the flood relief balance for the city's municipal area. We have advanced Mukherjee's (2020) HUPE to trace urban riverine dynamicity's across historical human interventions, simultaneously with more-than-human interactions. Ranging from the "tidalectics" (DeLoughrey, 2007) governing the water's flow pattern to the multispecies interactions on the riverscape, HUPE offered a detailed understanding of the evolving drivers of climate change and vulnerability in the delta and also shedding light on socio-ecological resilience of Kolkata based on an integrated (more-than) "humans in nature" (Berkes and Folke, 1998) approach of the city's urbanization process, such as population growth and density, coping abilities of the ecological system with focus on social disadvantages surrounding marginalized groups sharing its resources (Dang et al., 2011; Noble et al., 2014).

2. Why Adi Ganga? Rationalizing the case study

River Adi Ganga originates at Hastings as a distributary of River Hooghly and flows southwards across the city of Kolkata to meet the Piyali river, which falls into the Bay of Bengal. Like River Hooghly, which is an eastern distributary of River Ganges, Adi Ganga is also revered in Hinduism due to her connection to River Ganga/Ganges. As per Hindu mythology, an ancient King Bhagirath had prayed to Goddess Ganga to purify the souls of his ancestors, who were cursed by Sage Kapil due to a misunderstanding. Goddess Ganga was considered the epitome of purity in Hinduism and thus it was suggested that only her touch could provide them salvation. It was Sagar's great grandson Bhagirath, who prayed to the Goddess and convinced her to descend upon the mortal realm in the form of a river. Interestingly, the goddess in her worldly form lost her way and couldn't find the location of the ashes. However, to fulfill her promise to Bhagirath, she branched herself into multiple channels or distributaries, that met the sea, thus forming the Ganga delta. As one of various branches met the ashes hidden in a cave, the souls of Bhagirath's ancestors were freed of the curse, which today is popularly known as the Legend of Sagar (Mukherjee, 2020). Even today, the Ganges and her various distributaries are considered as "*Ma Ganga*" or "Mother Ganga," signifying the enmeshed natural-cultural agency of the river that has nurtured the city's evolution over centuries.

During the colonial period, besides being a major trade route between Calcutta and the Sundarbans, River Adi Ganga was molded into a servicing the drainage of the region as well, with her natural tidal regime offering cost effective solutions in consolidating the colonial regime. The subsequent degradation of the channel, after colonizers prioritized the railways over water transportation, affected the river sustainability, with increasing urbanization around her banks and lessening investments on her maintenance. This led to the complete transformation of the once heritage river into a foul, murky and defunct channel, presently reduced to a *nullah*, a sewage conduit (see Figure 2).

FIGURE 2
The polluted Adi Ganga-Tolly Nullah stretch. Source: Author.

While the construction of the metro railway on a section of her stretch significantly affected her flow and ecology, the channel still plays an important role in maintaining the flood line balance of the southern municipalities of Kolkata. With majority of the river choked under untreated sewage, sediments and inorganic pollution, the region faces tremendous ecological hazards in the form of floods during monsoons. As most of the riverbank settlers are from marginalized communities, they face severe material and physical losses during these floods. Being a deltaic city, the role of waterscapes in the survival of Kolkata is paramount and the protection of an urban ecological heritage river such as Adi Ganga that transects across one of the densest localities of the city, is necessary in this regard.

The case of Adi Ganga, thus presents an interesting amalgamation of history and cultural ecology shaped by constantly evolving human-nature interactions rooted in a region's socio-geo-political context. Probing into these narratives and using the historical/archival approach to explore socionatural entanglements in the past, offer city-nature practitioners a temporal analysis of a cultural-ecological resource and its intangible heritage. The stories surrounding River Adi Ganga ranging from mythological accounts to contemporary oral narratives of childhood nostalgia, can steer the discourse on exploitation of urban waters toward water sustainability and inculcating transdisciplinary understandings of a riverscape into sculpting implementable solutions.

3. Methodology

3.1. Research design

Research and discussion on Adi Ganga aren't new in the Bengal's ecological context, with the river's pivotal role in the city's flood balance and the continual tampering with her flows since the construction of the metro railway on a section of her stretch. However, the lack of convergence of multidisciplinary

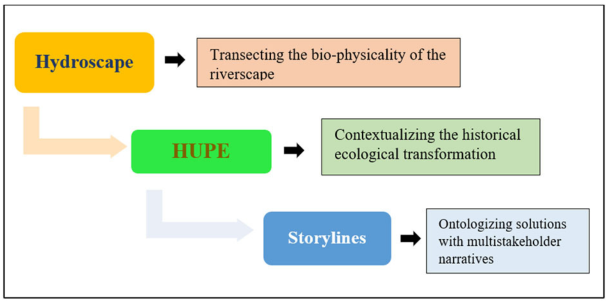


FIGURE 3
Research design. Source: Authors.

discussions on the river's socio-ecological sustainability continued to create the schism among her stakeholders, academicians and the policymakers. The agenda of our team, comprising of people from different disciplinary backgrounds and interests, such as history, political ecology, geomorphology and cultural studies was to bring in our own understandings from understanding the messy hydroscape (Lord, 2014; Baetan and Lave, 2020) and her socio-political entanglements to analyzing the symbolism and cultural heritage associated in the river's volatile ecological existence by incorporating the HUPE and Storylines approach to relearn the varied perceptions surrounding the river's rejuvenation. The "storylines" approach implies the conveyance of "dominant, counter, and even suppressed" narratives for specific socio-ecological spaces that demand granular probing and analyses (Moore, 2007, p. 23). We explored the various narratives on Adi Ganga, through her history and from her different stretches and her varied sets of participants to analyze the different challenges for the river on her socio-spatial scales that through the involvement of her multiple stakeholder interactions and exchanges can converge to successful participatory governance (see Figure 3).

3.2. Methods

As we integrated the HUPE and Storyline approaches to study the Adi Ganga's case we have explored three qualitative methods to extrapolate our data, i.e., (1) Archival Research (2) Transect Walk, (3) Ethnography, and (4) Participant Observation. The archival research consisted of detailed accounting of primary accounts and secondary literatures, while our field explorations can be categorized into Transect Walks and Ethnographical methods to analyze the river from a geomorphological and socio-political perspective. We have combined and applied these methods to convey "storylines" on the Adi Ganga. While archives provided us with the edge to incorporate shifting temporalities on the life-cycle of the river, ethnography enabled us to map contemporary realties including more-than human interaction dotting this urban waterscape. The transect walk enabled us to understand the physicality-materiality of Adi Ganga across her many stretches enmeshed with budding tangible and intangible storylines.

TABLE 1 Archival explorations.

Source	Document type
West Bengal State Archives	Colonial era revenue, maintenance, miscellaneous, Toll accounts and legal documents
Kolkata Town Hall	Colonia era maps, canalization plans, reports from officers
National Library	Colonial era accounts of officers (diary entries, gazetteers) and pre-colonial era vernacular literature

3.2.1. Archival research

We have consulted various archives (Table 1)—colonial and vernacular, to connect and comprehend multiple snippets on the river, transforming across dynamic trajectories. The use of primary documents from West Bengal State Archives, Kolkata Town Hall Archives, National Library and secondary literatures have allowed us to revisit the route, travels and interactions on Adi Ganga across various temporal scales. Primary accounts from the archives include revenue and miscellaneous reports on the canal's excavation and maintenance, correspondences, diary entries and notes detailing the canal's legal ownership and statements from company officials. The primary accounts also provided us with plans and maps for further canalization projects proposed on the canal. Colonial accounts on the journey of Adi Ganga had also been documented by James Rennell, Hunter and O'Malley (Mukherjee, 2020) where the channel was portrayed to be draining into the Bidyadhari River below Baruipur, along with reports on Adi Ganga-Tolly Nullah's revenue generation, maintenance of the river and further plans for her canalization. Even before the British colonization, Adi Ganga found mention in the sixteenth and seventeenth century cartographic projections by Portuguese cartographers like Jao de Barros and Van Den Brouke as an important trade route in south Bengal.

Medieval era vernacular literature such as the *Manasamangal* by BipradasPipilai, the *Chandimangal* by KabikankanMukundaram Chakrabarti, the *Raymangal* by Krishnaram Das and other works like the *Satyanarayan Katha* by Ayodhya Ram, *Shitalamangal* by Harideb and *Kalu Rayer Geet* by Dwija Nityananda as well as Vaishnavite Saint Shri Chaitanya's journey on the river Adi Ganga in the *Chaitanya Bhagabat* have mentions of Adi Ganga as an important route of trade and travel in Bengal's socio-economical history (Bandyopadhyay, 1996; Mukherjee, 2016, 2020).

3.2.2. Transect walk[1]

We have conducted transect walks along the entire river stretch from her junction at Hastings to her canalized stretch at Samookpota that was designed to fall into River Bidyadhari as well as her original route up to Surjyapur where it currently diverges into different branches to meet the Piyali river. The transect walk has allowed us to observe the flows and shoreline interactions

1 Transect walk is an interdisciplinary information gathering method applied to show, study and describe a land/waterscape, its features, resources and varieties, by identifying and diagramming the given transect route.

of the river across her original stretch that was canalized and turned into a sewer, the stretch that has been pillarized by the metro railway and the section of the river that turned into a paleochannel and finally emerged as a cleaner section at the fringes of Kolkata. The walk allowed us to observe the spatial planning surrounding the river that was transformed into a drainage network for Kolkata's southern municipality, to explore the religious-cultural connotations surrounding the river near pilgrimage sites such as Kalighat or the *Rashbaris*, and the lives of marginalized communities ranging from migrant squatters to prostitutes finding shelter in her banks and noticed local government initiatives on the river clean-up against lack of ecological awareness among the local community.

3.2.3. Ethnography

We interviewed and held formal-informal discussions with residents from the different stretches, varying from different socio-economical strata. We have interviewed houseowners (old and new) and their perspectives on the river's transformation, the perspective of the squatter communities across different stretches who have been evicted and since resettled on the banks and their reactions to living alongside a filthy river. The prostitutes living across different stretches of the river allowed us to observe their micro-realities of existing alongside a holy river which people and state continue to contaminate. Interviews were held with state apparatuses managing the river stretch at different level, ranging from officers at Irrigation and Waterways Department, Pollution control Board and municipal governance officials from Kolkata Municipal Corporation and local youth engaged in the river cleanup. We held onsite Focus Group Discussions with elderly men and women, shopkeepers, priests and local club members living on the banks on their attachment to the river, oral histories, current challenges and their hopes for Adi Ganga.

3.2.4. Participant observation

We observed the flows and obstructions of the river at different spatial stretches along with the water's different interactions with the participants. From Adi Ganga's free flowing emergence at Hasting's to her sacrality induced abstraction at the pilgrimage sites, and the local governance practices in cleaning up the channel, the multiple synergies existing on the river's spatial stretch was observed and analyzed by our team of researchers. We also witnessed the various riverfront inequalities and evolving stakeholder understanding of the river's social-ecological problems that impacts Adi Ganga's current existence.

4. One river, numerous challenges, multiple timeframes: An empirical discovery

The story of Adi Ganga's journey, from a river of religious-social importance to a transactional route and finally a sewer struggling to survive, contextualizes the need to understand modern South Asian urban rivers through a lens of historical-political analysis, where colonial legacies continue to play a significant role in an ecological resources' contemporary struggle. The application of the HUPE framework in the study of Adi Ganga, offers a detailed understanding of the river's transformative challenges and helps in identifying her needs in the context of increasing anthropocentric threats. The threats posed from climate vulnerability such as floods and concurrent diseases affect both human-non human participants, that are significantly enhanced with present social and state practices. The continuation of the colonial hydrological system against the changing geomorphological and urban needs are combatted with the social practices stemmed in ecological non-awareness.

The HUPE analysis of Adi Ganga points toward (1) Climate Vulnerability (2) Social Practices and (3) Outdated Apparatuses, as broader but major challenges of the river, which can further be categorized into various sub-challenges that shed light on micro-realities on the waterscape, shaped by local socio-ecological and political turnabouts (see Figure 4). However, the interconnected nature of the socio-ecological challenges as well as the political nature of Adi Ganga's degenerative state, require a deeper inspection of these complex riverine issues, in order to highlight the scope for implementable and sustainable solutions in future. These challenges and sub-challenges have thus, been further sectioned into three prominent issues, i.e., (a) Drainage Network, (b) Intra-Institutional Impediments, and the (c) Metro Railway, in order to probe in the diverse yet situated narratives on and around Adi Ganga.

4.1. Historical drainage networks

The river Adi Ganga played an important part in the intricate colonial drainage network system of the city that was developed three centuries ago keeping in mind the geography and fluvial dynamics of the deltaic terrain of erstwhile Calcutta. The naturally "bowl shaped" feature of the city, with the central locations of Kolkata at a lower elevation, made it prominent to pump out the sewage from these locations to different outfall channels, under the colonial "Town system." This system was developed by crafting around the tidal nature of the city's rivers and her various channels, such as River Hooghly and her distributary known as Adi Ganga, that was manipulated into carrying out the sewage of the southern stretch of Calcutta (Mukherjee, 2020). This old bed of the Ganges was re-excavated by William Tolly from Hastings to Samukpota in 1775–1777, leading to her new identity as Tolly's Nullah or Tolly's Canal. The Nullah was not provided with any sluices or lock gates due to her tidal nature, leading to deposition of silt over the years. The colonial government would facilitate the channel's regular clean-up and maintenance through dredging, clearing up of silts on the banks, prohibiting dumping of human waste, animal carcasses etc., but over the years, the shifting priorities to the railways and defuncting hydrological apparatuses, urban development agendas along shorelines and political turmoil leading to increase in squatters on the banks, Adi Ganga-Tolly Nullah over the years, turned into a waste dumping ground for the state and the locals, like most South Asian urban rivers. The river Adi Ganga at present, is part of the Tolly Nullah basin that takes care

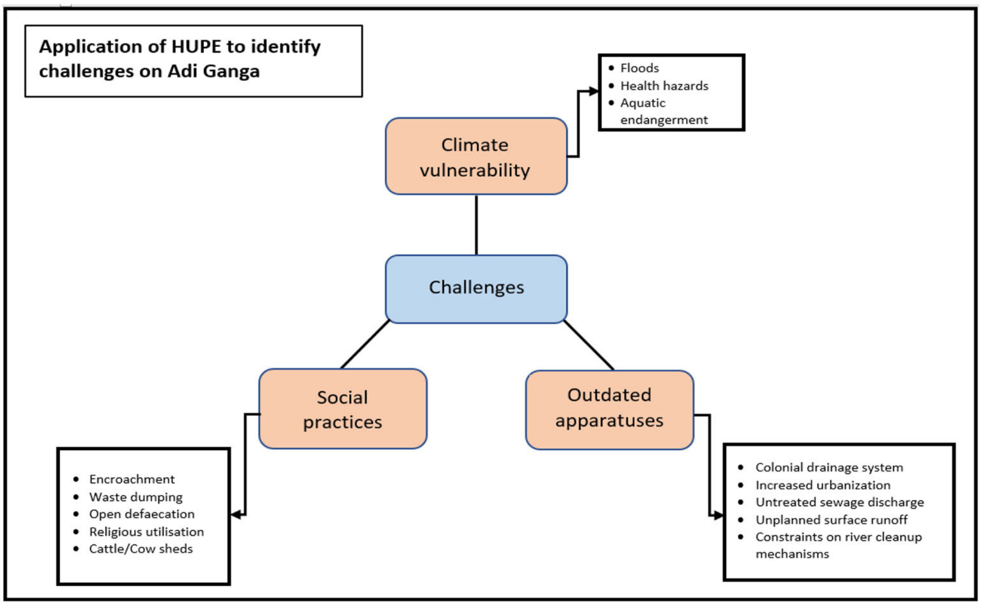


FIGURE 4
Challenges on the river: A HUPE Analysis. Source: Authors.

TABLE 2 Tolly Nullah drainage basin-canal system with area coverage under KMC.

Tolly Nullah: basin, network and area coverage		
Canals and branch channels of Tolly Nullah drainage basin		Tolly's Nullah, Boat Canal, Keorapukur Canal, Western Channel, Renia Canal
Boroughs covered		IX (part), X, XI (part), XIII (part)
Wards covered	Full	70–78, 81–85, 87–89, 97, 111–118, 120–121
	Part	69, 79, 86, 90, 93–95, 98, 100, 119, 122, 123
Areas served		Bhawanipore, Alipore, Chetla, Kalighat, etc.

Source: Developed from Mukherjee (2020).

of the drainage of several heavily residential districts of southern Kolkata and that falls under the supervision of Kolkata Municipal Corporation (see Table 2), where over the last century, the river had been dealing with the region's dry and storm weather flow (see Figure 5).

The accumulation of untreated sewage and plastics on her heavily silted banks, makes the place risky, especially during the monsoons, when the heavily silted river banks fail to balance the flood line causing flash floods across southern Kolkata and induce recurring material as well as physical damages for the communities living on the banks (see Figure 6). Beside the natural and man-made challenges faced by the canal, the problems lying in the historic interventions of the drainage system that were deemed as revolutionary once, now present subsequent hurdles in the hydrological management of the basins. The drainage system that was designed to tackle immediate urbanization on the banks now face challenges with unchecked urban sprawls, encroachment, lack of ecological awareness, pollution, inadequate maintenance and "developmentalist interventions" over the past decades. The unplanned diversion of surface runoff from one subbasin to another cause overloading on the existing drains, leading to flash floods (Mukherjee, 2020). A study conducted in 2015 by the Kolkata Municipal Corporation (KMC) and British Deputy High Commission showed flooding in various parts of the city in rainfall of 300–400 mm in 25 h under 3 and 5 m storm surge during high tides [Kolkata Municipal Corporation (KMC) British Deputy High Commission, 2017; Mukherjee and Bardhan, 2021].

The increased haphazard dumping of garbage on riverfront by locals, ranging from flowers, household discards, plastic packets and in certain cases carcasses from the nearby slaughterhouses (revealing the lack of ecological awareness among local communities), has also put extreme pressure on the age-old drainage system that is already struggling with malfunctioning locks and pumps, or systems with reduced pumping capacity. The lack of maintenance of the canal outlets, outfall structures which are in dire need of repair and absence of any working sewage treatment plants (STPs) existing on the river has raised the canal bed due to silt accumulation, leading to 15%-50% reduction in carrying capacity of Tolly's Nullah and the entire canal system of the city (Mukherjee and Bardhan, 2021).

4.2. Intra-institutional impediments

At present, the river has been demarcated separately as Adi Ganga (Garia-Samukpota and Garia-Surjyapur stretch) and Tolly Nullah (Hastings-Garia stretch) with the Irrigation and Waterways Department of West Bengal (IW&D) managing "Adi Ganga" and Kolkata Municipal Corporation (KMC) and Kolkata Metropolitan Development Authority (KMDA) managing "Tolly Nullah." As the river stretch managed by the KMC falls under heavily residential

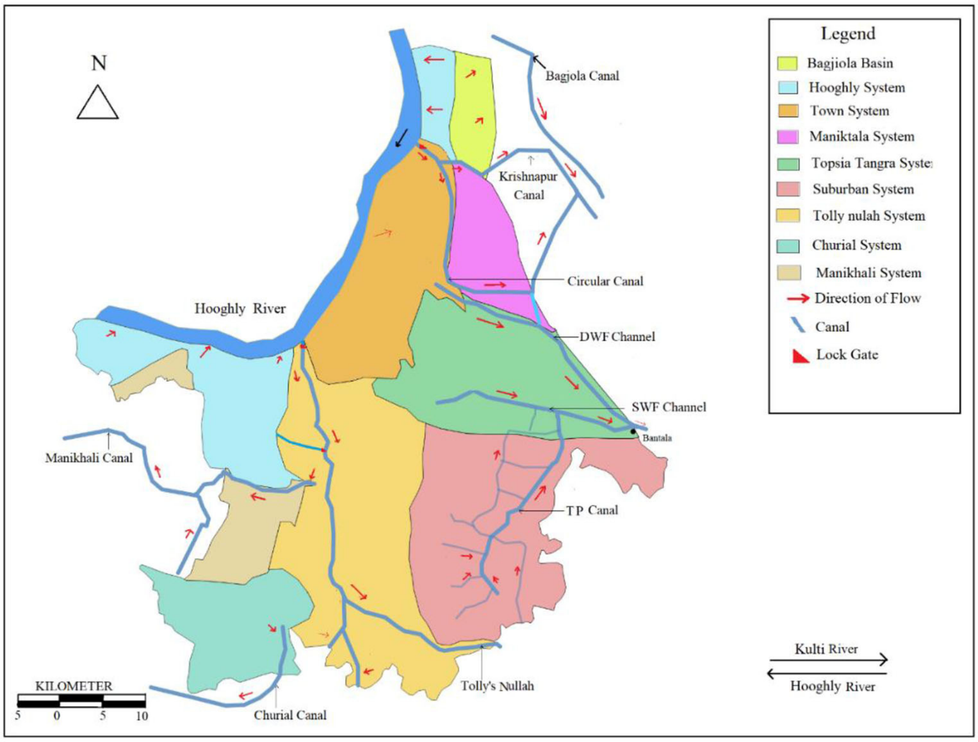


FIGURE 5
Major drainage systems of Kolkata. Source: Mukherjee (2020).

zones, the agency faces various difficulties in managing their respective stretches, ranging from infrastructural limitations to socio-cultural obstacles, as discussed in the following:

4.2.1. Ecological unawareness

The dilemma surrounding Adi Ganga's revival or rejuvenation depends on the dual identity of the river crafted by cultural and statist developments. Kalighat, one of the most densely populated localities of Kolkata had been built around the Kali temple, an important pilgrimage shrine of Hinduism, which rests on the bank of Adi Ganga. The sacrality surrounding the region has turned the river channel in to a common space for throwing away of flowers, incense sticks, ritual offerings along with the increasing load of sewage in this densely urbanized space. Similarly in the locality of Kudghat, the construction of metro pillars has affected not only the natural flow of the channel but also concretized the channel's identity as a *nullah* in the minds of locals, where residents throw daily garbage into the river, justifying their actions by suggesting that the channel is already a sewer. Awareness campaigns have been organized by the KMC, where the agency has put up banners on the river banks prohibiting the drinking, storing or utilization of the river water, dumping of household garbage as well as religious offerings and bathing or defecating on the river banks. Heritage walks alongside the river stretch have also been organized by the agency to elicit some awareness among the residents on the river's heritage, but to no avail.

4.2.2. Pollution

The unchecked urbanization around the river stretch along with construction of the metro railway at present has put immense pressure on the colonial era canal system, turning this important channel into a toxic waste filler. KEIIP report on the chemical analysis of Tolly's Nullah water quality has showed high to moderate levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and coliform in the water over the past years (Table 3).

The tidal regime of the river also affects the quality of water in the channel, as shown in the differing sets of sample data recently collected from different stretches of the river (Table 4). The BOD, COD and coliform bacteria count in the river water significantly increases during low tide, while the oxygen level is found to be negligent at almost every stretch which suggests that no life can exist on the river. Tolly Nullah-Adi Ganga at Kalighat proves to be the most unsanitary stretch with the highest total coliform count during the entire tidal regime.

4.2.3. Technological restraints

Many of the KMC workers employed contractually for river clean up navigate the channel on small boats and pick up flowers, plastics and other inorganic waste from the river, at regular intervals. While garbage arresters are placed at certain spots in the channel to catch bulk amounts of floating waste, the workers are provided some gloves and makeshift equipment made from bamboos to pick up plastics manually from the river. Recent

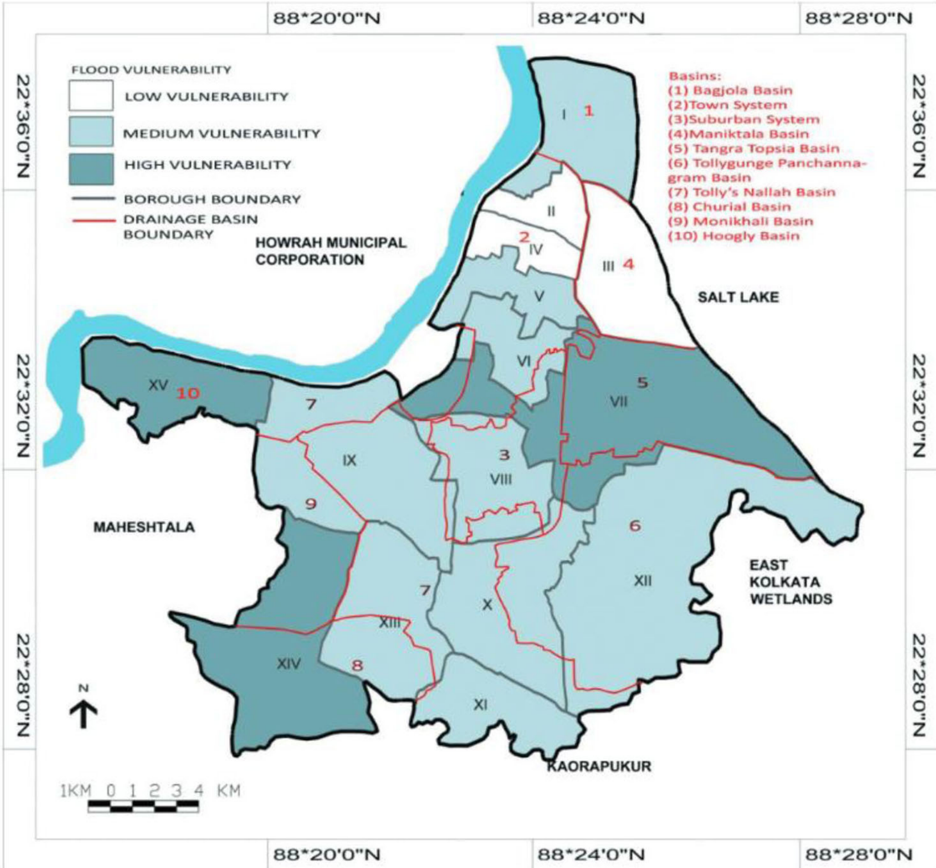


FIGURE 6
Borough wise flood vulnerability map of KMC. Source: Mukherjee and Bardhan (2021).

TABLE 3 Water quality of Tolly Nullah.

Parameters	2012 (sampling date)	2017 (sampling date)
BOD (mg/l)	40.0	27.08
COD (mg/l)	150.00	58.00
Dissolved O_2 (DO) (mg/l)	4.8	NIL
Fecal coliform	3.4×10^6 (MPN/100 ml)	3,000,000 (mg/l)
pH	6.52	7.27
Temperature (°C)	32.5	34
Total suspended solids (TSS) (mg/l)	68.00	30.00

mg/l = milligram per liter, MPN/100 ml= Most Probable Number per one hundred milliliters, °C = Degree Celsius.
Source: Prepared from KEIIP Sewerage and Drainage Network Reports (Tranche 3), Kolkata Environmental Improvement Investment Program (2018, 2019).

interim measures taken up by the KMC to check polluting of the river stretch are [WD and MA memo no. 89-JS (NG), Department of Urban Development Municipal Affairs Government of West Bengal, 2021]:

- Urgent dredging at the most polluted stretch of the upstream of Tollys Nullah-Adi Ganga upto 4.6 km.
- Demolition of makeshift toilets on the river banks and construction of 77 community sanitary latrines.
- Demolition/Eviction of *khatals* (cow and cattle sheds) on the river bank.
- Temporarily fencing vulnerable spaces at Borough X and XI for 2 kms, restricting access to the river bank and minimizing manual dumping of garbage in the river.
- Installing 10 floating garbage arresters, 4 organic composters and carried out awareness campaigns.

Despite the above measures, officers supervising the channel's clean-up have expressed their dismay at working on the river with limited tools, as untreated waste water continue to spill in to the river. The tidal regime of the river also restricts the use of bioremediation practices, thus highlighting the need for sewage treatment plants on the river bank to check the river's pollution and her subsequent revival.

4.3. "Metro"-politan river: Post-colonial challenges

After the independence of India, with changing political situations across the state and especially in Kolkata which was still

TABLE 4 Water quality of Adi Ganga at different tidal regimes.

Parameters	BOD (mg/l)		COD (mg/l)		Fecal coliform (MPN/100 ml)		pH		Temperature (°C)		Fecal coliform (MPN/100 ml)		Dissolved O_2 (mg/l)		Total suspended solids (mg/l)	
	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide
Jirat Bridge	2.80	13.10	14	48	780,000	1,300,000	7.30	7.32	27	30	1,100,000	3,300,000	5.00	NIL	78	156
Kalighat	9.88	11.09	35	40	2,300,000	7,000,000	7.27	7.38	27	30	7,000,000	14,000,000	NIL	NIL	36	64
Karunamoyee	9.13	9.84	34	40	3,300,000	4,900,000	7.40	7.38	28	30	7,000,000	11,000,000	NIL	NIL	34	30
Kudghat	10.16	12.81	40	45	1,700,000	2,300,000	7.34	7.31	30	31	4,900,000	7,000,000	NIL	NIL	28	38
Bansdroni	10	11.25	36	42	1,700,000	2,100,000	7.35	7.27	30	31	3,900,000	4,600,000	NIL	NIL	28	32
Shahid Khudiram	8.75	9.58	34	36	7,80,000	1,700,000	7.45	7.53	30	31	2,100,000	4,600,000	NIL	NIL	30	36

Source: Developed from data samples by West Bengal Pollution Control Board, 2022. Accessed online from http://emis.wbpcb.gov.in/waterquality/showwqprevdatachoosedist.do.

TABLE 5 Adi Ganga revival plans before the metro construction.

Activity	Participants
1981–1982: The TDC made repeated attempts to reach out to the I&WD and KMDA officials for the revival of Adi Ganga-Tolly Nullah. Plans were formulated but none were materialized into action	• Tollygunge Development Council (TDC) • Mohit Ray
1996: Petition filed by for the revival of the river stretch was to be heard by the Green Bench of Kolkata High Court	Rebati Ranjan Bhattacharya
1996: Government directives to clean up the river by forming a committee of multiple state agencies A recommendation of INR 40 crore for the canal restoration scheme was requested to the National River Conservation Directorate (NRCD) **1998:** A revised plan requesting INR 29 crore and 50 lakh was submitted to the NRCD, but the plan never materialized	• Chief Secretary of the state • Chief engineer of Kolkata Metropolitan Development Authority (KMDA) • Commissioner of Kolkata Municipal Corporation (KMC) • Secretary of Irrigation &Waterways Department, West Bengal (I&WD)
1997: CEMSAP's seminal report entitled *Management of East Kolkata Wetland and Canal Syatem* showed the interdependency between the wetlands of Kolkata and her canal system and proposed to connect the Samukpota stretch of River Adi Ganga-Tolly Nullah to the decaying Bidyadhari-Piyali river basin, to have controlled release of flushing doses of water from Hooghly River and simultaneously integrating transportation and eco-tourism practices around the struggling river. The plan didn't materialize due to the metro rail construction on the river	Calcutta Environmental Management Strategy and Action Plan (CEMSAP)

Source: Developed from Mukherjee (2016, 2020).

reeling from influx of refugees after the Indian partition in 1947 and the Bangladesh Liberation War in 1971, the river front became a place of shelter for the marginalized communities trying to find livelihood opportunities in a megapolis. Simultaneously, the river's condition began to worsen with the increasing flow of untreated waste from drainage systems, transforming her into a local toxic and hazardous dumping ground, leading to various calls for Adi Ganga's clean up in the last decades of the twentieth century by different agencies (see Table 5).

In 1999, the plan for construction of the metro railway on the riverbed between Tollygunge to Garia was floated by the then state government, causing a stir among prominent environmental activists who deemed the project as unscientific and illegal. However, a petition filed by activist Subhash Dutta against the metro extension scheme in the Kolkata High Court failed to stop the project when the court gave verdict in favor of the State under the Section 11 of the Railways Act 1989.[2]

2 Based on the archaic colonial Act of 1890, it gave railways imprimatur to construct in or upon, across, under or over river, canals, brooks, streams or other waters as it thinks proper.

In 2001, the construction work began on the river bed by embedding 300 pillars on the riverbed of the already choked waterbody, which led to the brutal eviction of more than 40 thousand squatters and slum dwellers who had been living on the river stretch for decades, while grassroot organizations such as the *Ucched Bachao Jukta Mancha* (UBJM), Manthan, Association for Protection of Democratic Rights, *Nari Nirjatan Pratirodhn Mancha, Sanlap*, All India Progressive Women's Association, and *Maitree* mobilized protests and demanded the squatters rehabilitation (Mukherjee et al., 2023). The eviction started on September 22, 2001 and continued in phases, with Rapid Task Forces being used to violently suppress the protests as bulldozers demolished makeshift houses of these vulnerable communities. Community kitchens that were organized for the evicted squatters, stood up as a symbol of hope for reclaiming of their riverine stretches and thus were soon followed by the state police shutting them down (Mukherjee, 2020).

4.3.1. The dying river

The aftermath of the metro rail project on the river, witnessed gradually despondent and lessening mobilizations surrounding the revival of Adi Ganga, which was declared "dead" by many of the activists. The metro stretch has hindered the natural flow of the channel and with the added debris, sewage and siltation, the centuries old drainage network that was designed to hold 100 mm of water per day, now gets flooded easily, when torrential rain and tropical cyclones exceed the water limit to upto 200 mm per day (Chatterjee, 2020). Besides, over time many of the squatter families have relocated to other parts of the same river stretch, which has become more ecologically at risk over time. At present, 49,000 people now live in the slums on the banks of Tolly's Nullah, which is almost 20% of the population of the region (Mukherjee and Bardhan, 2021), putting them in a vulnerable state of existence.

This casual acceptance of the Adi Ganga-Tolly Nullah as a waste disposal ground among the state and local community, transcending the cultural ethos surrounding her heritage and ecological importance blatantly exposes the continuation of colonial water legacy, that consists of not only the hydrological system but also the policy of segregation and exclusion of the non-state stakeholders whose agential undertakings are still not taken into consideration while exploring river conservation. Declaring river policies without exploring these differing and changing hydrosocial understandings, cutting across the intra state rankings have resulted in Adi Ganga's current struggling existence and will continue to do so if shared accountability and collaborative practices are not given immediate platforms for Adi Ganga's survival in future.

4.3.2. Blurring bourgeoisie environmentalist notions

While colonial hydrological may have significantly altered the future of South Asian rivers by dissecting water's social and economic values, the continuing practices of water hierarchy in post-colonial India played a major role in decline of most urban rivers, especially Adi Ganga. The development of the metro plan and its implementation against divided forms of activism was reflective of the various conflicts existing on Adi Ganga's shorelines regarding her "ownership." Even in the pre-metro phase, the river restoration protests for Adi Ganga saw two different forms of activism surrounding the river, consisting of the environmentally aware middle class who were concerned in protecting the ecological heritage and personal nostalgia attached to the river and the other consisting of grassroot mobilizations where the focus was meant upon the lives and livelihood scenarios shared by the marginalized communities living on the river banks for decades and yet reduced to invisible actors with no agency on the river.

These diverging narratives of river protection affected Adi Ganga's future severely, with no common ground being explored among these multiple stakeholders on necessary steps required for the river's survival. The lack of seamless communication strategies on the river's importance, challenges and steps for conservation among these stakeholders allow the continuation of hydrosocial malpractices on Adi Ganga. Our interactions with different sets of respondents ranging from river participants, activists and policymakers reflect upon the challenges faced by each respondent, rooted in their historical-political understanding and experience of the river and the possible remedies as perceived by them (Table 6).

The shoreline participants, consisting of residents, business owners, club members and temple authorities, share their perceptions on Adi Ganga by engaging with an individualistic approach. Families who have lived here for many generations offer a nostalgic approach toward the river's revival, as they lament of their fading childhood memories around the river. The local club committees, consisting of local residents belonging to "reputed backgrounds" share same sentiments surrounding cultural practices on the river. Almost all of them blame the squatters for turning the river into a sewer channel, suggesting their unsanitary practices as a direct contributor to the river's detrimental state. The squatters, while vehemently denying this, state that they are the worst sufferers of the channel's poor state. Beside living with the foul smell and murky water, they are forced to live with this unsanitary water when it floods their homes during monsoons, posing serious health hazards to the residents.

The idea of Adi Ganga's sacrality and sanitation is however, presents an interesting conundrum among religious community surrounding the river. Despite announcements and warnings from authorities, pilgrims continue to take bath in the river, citing the water's religious significance among Hindu community. Few priests from the Kalighat temple blamed the government for turning the "holy river" into a sewage channel, but implored that it didn't affect Adi Ganga's sacredness. A quick discussion with the state agencies as well as activists reveals that using the cultural prominence of the river to dissuade people from throwing garbage into the river have been proven unsuccessful over the years, with the lack of concrete sewage treatment measures and transparent river rejuvenation policies from the government.

5. Weaving "storylines" toward solutions through HUPE

The integration of HUPE analysis for the river Adi Ganga offers a broad overview of the identified challenges and its complexities from multistakeholder (both human and non-human) narratives, thus positing a platform to address them through

TABLE 6 Adi Ganga stakeholder narratives.

Stakeholders		Narratives from the field
Shoreline participants	Squatters Old families Business owners Local club members Temple authorities	*"Ungodly sight and foul odor makes it difficult for us to live beside the river"* *"The river overflows during the monsoon, flooding entire localities. This increases chances of diseases, especially among us slum dwellers"* *"This was and will be a 'holy river', nothing can change it!"* *"I heard stories from my father about the river's heritage... I remember boats passing on the river even 10-15 years ago. Now everything is gone... it's just a sewer now."*
Government	KMC KMDA IWD CPCB	*"Locals need to understand the importance of river, what do their children learn when they see parents throwing garbage into the waterbody?... implementing fines cannot be a long term solution"* *"This Nullah was excavated centuries ago! Since then population as well as sewage load has increased. We need better tools or new plans for treating the sewage"* *"The river has cultural value as well... We need local's cooperation in maintain the river's heritage"*
Activists	NGOs Journalists Academics	*"The river can be revived... there are many examples from the western countries of river rejuvenation"* *"Regular initiatives on the river's cleanup, encroachment drives and pollution abatement is necessary"* *"Transparency on river policies is necessary to ensure local-state cooperation"*

Source: Authors.

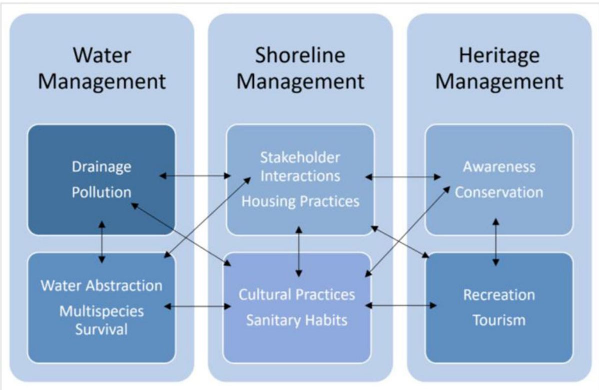


FIGURE 7
Storylines for solutions. Source: Authors.

seamless storylines. The HUPE storyline has reflected upon the divisions existing among Adi Ganga's management practices, namely ecological, socio-cultural and political. In order to revive the river under the current circumstances, or to posit her a chance of survival, these divisions need to be blurred. Our interactions on the river have recognized the need for specialized understanding of Adi Ganga's water, shoreline and heritage management, which require entangled-integrated practices for the river's rejuvenation (Figure 7). The challenges of pollution, abstraction and defunct apparatuses blur the land-water binaries and hierarchies, with the integration of ecology based social-cultural practices rooted in awareness generation, socially just housing and other infrastructural development, and introduction of innovative ideas for conservation of the river's heritage by entangling water practices with recreational livelihoods.

Elaborating upon the above illustration, one can notice the cross fertilization of opportunities that can be crafted into solutions. Combating the challenge of outdated drainage and increasing pollution on the river, it is imperative to restrict the untreated sewage falling into the river. As the tidal regime of Adi Ganga refuses bioremediation procedures, it is necessary to install STPs for the drainage or find a new a new drainage outfall for the region. Besides, the eviction of marginalized communities on a recurring basis against the blatant conversion of the riverscape into a real estate honeycomb for affluent classes that has been increasing the waste discharge presents the continuation of colonial era practices of discrimination and exploitation. This necessitates the need for transparent and community friendly river practices where unsanitary, exploitative practices water practices are combatted with infrastructural innovation and cultural integration.

The first step in this process would be recognizing and dissemination the importance of "waste" among the local community who often engage in illegal and unsanitary practices of waste promotion (Table 7). Regulation of infrastructural development on the riverscape, creating and implementing strict norms for dumping of plastic wastes, installing STPs across the river stretch and preparing a revised drainage basin for the region is necessary to facilitate trust and accountability among all the river stakeholders. The maintenance of the river stretch should also be treated as joint responsibility between state and all her actors by raising awareness surrounding the river's heritage and ecological importance to combat pollution from domestic discharge and religious tourism by introducing modules on waste segregation, river ecology, importance of city-river's interconnected drainage-climate change scenario among local schools, colleges, clubs and cultural associations on a long-term scale.

The highly intervened stretch requires extensive river care and maintenance from the state as well as the community through incorporations of scientific expertise and citizen science. While the KMC, KMDA, IW&D, and PCB float the various norms and regulations for river clean-up, local participants of the policies such as supervisors, contractors and youth employed by them have better understanding of local ethos and practices. Besides training these workers with innovative and modern technologies, it is also important to recognize their opinions on maintaining the river, which can contribute immensely in engaging more community participation. Creating a database for local-state interactions also offers citizens a better understanding of their stakeholdership and making them more engaged in the river's survival.

The need for multidisciplinary-collaborative platform to explore and understand the riverine ecology of urban Kolkata

TABLE 7 Problems and solutions on Adi Ganga.

Problems	Solutions
• Increasing encroachment from squatters, slaughter houses and high rise apartments putting pressure on the drainage discharge • Religious tourism contributing to river pollution • Open defecation, unsanitary practices, odor and discoloration of water • Metro pillars affecting the river flow • River quality deemed as hazardous • Lack of ecological awareness • River turns into a paleochannel at certain stretches	• Regulation of infrastructural development and its contribution to water pollution • Installations of STPs and revision of the colonial drainage structure • Training the ground-level workers with modern techniques for river maintenance and giving them more agency on local cleanup strategies • Creating a local-state database for the respective river maintenance authorities and experts • Increasing state-community participations by engaging youth in waste segregation, river-city ecology and heritage workshops • Developing an interdisciplinary panel on Kolkata's ecology consisting of experts from history, sociologists, environmental science, NGOs, legal teams and state officers to discuss and disseminate sustainable policy scenarios with community participants on a feedback loop and restructure its implementation accordingly

Source: Authors.

is evident, where various aspects of the city's socio-ecological scenario is studied, analyzed and interpreted through innovative dissemination strategies. The lucid understanding of these scenarios can offer the various stakeholders, opportunities to circulate the diverse complexities of the river to their respective agencies and offer a holistic space for curating discussion-based decisions. Awareness campaigns, educational curriculums, technical apparatuses and development of heritage based recreational tourism can offer implementable urban riverine policy suggestions that can contribute in successful application of participatory governance on Adi Ganga.

6. Conclusion

The deeply embedded socio-ecological complexities surrounding the riverscape of Adi Ganga has made it pertinent to develop "solutions" that comprehends its extensive array of interpretations, such as solutions for whom and solutions by whom? The empirics surrounding Adi Ganga's history and political ecology have evidenced the interplay of political-ecological-social transformations encompassing the river, where the city and nature's interdependency has been exploited by colonial masters and later state mechanisms, while ignoring the agencies of various "others" living on and by the river. Thus, the need for reifying Adi Ganga, cannot be summarized under the vague objective of neo liberal rejuvenation practices, where soft capitalism and bourgeoisie environmentalism overwhelms the ineradicable contributions of the vulnerable participants of the river. The task of resuscitating Adi Ganga, would require the knowledge of her legacy not only through her historicity but also in appreciating her ecological heritage, that has been shaped by various spatio-temporal interactions with her many participants. The intricate human-non human linkages existing and evolving on Adi Ganga, expresses the dynamicity of interactions across her multiple stakeholders, that is captured aptly by the "storylines" approach. The compilation and evaluation of the archival voices as well as silences, along with the present narratives and counter narratives from stakeholders, whose voices are often suppressed or unheard, bring forth a comprehensive understanding of Adi Ganga, as a part of Kolkata's "living system infrastructure" and posits a platform for transitioning from knowledge accumulation to action policy (Mukherjee, 2022).

It is crucial to combat the impact of the anthropocene on Adi Ganga, considering the continued degradation of flood efficacy of Kolkata's fluvial systems and the increasing climate change induced vulnerabilities in the delta. Investigating the root of this problem, would first necessitate the discarding of the colonial demarcation of South Asian rivers as "chaotic" and "unruly" and the continuance of colonial hydrological practices against indigenous knowledge. Rerouting the Adi Ganga's ecological legacy would remain only a buzzword unless her current demographic challenges are addressed with a deeper ontological understanding. Replacing the current Eurocentric model with popular and local scientific knowledge, and integration of the cross-sectoral understanding of the river's management can provide a glimpse of the pluriversal possibilities in rejuvenating Adi Ganga that voices the role of the "many worlds" existing beyond western hydro science in river discourses (Escobar, 2020). These practices reflect the various river epistemologies of the global south, where post-colonial waters can be unchoked of the political hubris and impediments, to move toward a socio-ecologically just and sustainable future. These can be attained by analyzing the river-society interactions from a multiscalar perspective and collaborating the technical expertise with the regional stakeholder "co-flows," that can assist in developing long term river conservation-management strategies for South Asian urbanscapes.[3]

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

3 The concept of urbanscapes has emerged and evolved across multiple disciplines, with focus on broader concepts such as urban design, architecture, landscape architecture and landscape urbanism that contribute toward the development of sustainable solutions. Recent works on the concept, now focus beyond the physical demarcations and include the social aspects that are shaped by multiple spatio-temporal variables (Sheih et al., 2017; Shamlou et al., 2018).

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants (legal guardian/next of kin) provided written informed consent to participate in this study.

Author contributions

SB conceptualized and designed the research, conducted data collection and analysis, and led the writing. JM conducted overall research supervision, provided advice on research design, data analysis, and contributed to writing. AC contributed to conceptualization of research, development of data collection methods, and advised on writing certain sections. RG contributed in research design, data analysis, and reviewing the manuscript. All authors contributed substantively to the manuscript and approved the submitted version.

Acknowledgments

We extend our gratitude toward the people living and working on/beside Adi Ganga, the state and non-profit agencies, for dedicating their time and participating in the data collection process. We are also thankful toward the EU-ICSSR funded EqUIP Project—Towards a Fluid Governance: Hydrosocial Analysis of Flood Paradigms and Management Practices in Rhone and Ganges Basins (India, France, and Switzerland) in supporting the field research for this study.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Acharya, A. (2015). "The cultural politics of waterscapes," in *The International Handbook of Political Ecology*, ed. R. L. Bryant (Cheltenham: Edward Elgar Publishing Limited). doi: 10.4337/9780857936172.00036

Baetan, J., and Lave, R. (2020). Retracing rivers and drawing swamps: using a drawing tablet to reconstruct an historical hydroscape from army corps survey maps. *Hist. Methods* 53, 182–198. doi: 10.1080/01615440.2020.1748151

Bakker, K. (2003). Political ecologies of water privatization. *Stud. Polit. Econ.* 70, 35–58. doi: 10.1080/07078552.2003.11827129

Bakker, K. (2004). *An Uncooperative Commodity*. Oxford: Oxford University Press.

Bakker, K. (2011). "Commons versus commodities: political ecologies of water privatization," in *Global Political Ecology*, eds R. Peet, P. Robbins and M. J. Watts (London: Routledge), 347–370.

Bakker, K. (2013). Neoliberal versus post-neoliberal water: geographies of privatization and resistance. *Ann. Assoc. Am. Geogr.* 103, 253–260. doi: 10.1080/00045608.2013.756246

Bandyopadhyay, S. (1996). Location of the Adi Ganga palaeochannel, South 24 Parganas, West Bengal: a review. *Geogr. Rev. India.* 58, 93–109.

Baviskar, A. (2003). Between violence and desire: space, power, and identity in the making of metropolitan Delhi. *Int. Soc. Sci. J.* 55, 89–98. doi: 10.1111/1468-2451.5501009

Baviskar, A. (2007). "Introduction: waterscapes: the cultural politics of a natural resource," in *Waterscapes*, ed. A. Baviskar (Delhi: Permanent Black), 1–11.

Baviskar, A. (2009). For a cultural politics of natural resources. *Econ. Polit. Week.* 38, 5051–5055.

Baviskar, A. (2011). What the eye does not see: the Yamuna in the imagination of Delhi. *Econ. Polit. Week.* 46, 45–53.

Berkes, F., and Folke, C. (1998). "Linking social and ecological systems for resilience and sustainability," in *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*, eds F. Berkes, C. Folke and J. Colding (Cambridge: Cambridge University Press).

Bryant, R. L. (1999). A political ecology for developing countries? Progress and paradox in the evolution of a research field. *J. Econ. Geogr.* 43, 148–157. doi: 10.1515/zfw.1999.0010

Budds, J. (2013). Water, power and the production of neoliberalism in Chile, 1973–2005. *Environ. Plan. D.* 31, 301–318. doi: 10.1068/d9511

Castonguay, S., and Evenden, M. (2012). *Urban Rivers: Remaking Rivers, Cities, and Space in Europe and North America.* Pittsburgh: University of Pittsburgh Press. doi: 10.2307/j.ctv10tq43d

Chatterjee, A. (2020). *The Cyclone Amphan and Its Impact in the City Kolkata.* Available online at: https://medium.com/@anjan.chatterjee/the-cyclone-amphan-and-its-impact-in-the-city-kolkata-c63aadc51dfa (accessed July 18, 2022).

Chitra, V. (2021). Remembering the river: flood, memory and infrastructural ecologies of stormwater drainage in Mumbai. *Urban Stud.* 59, 1855–1871. doi: 10.1177/00420980211023381

Coelho, K. (2020). Lines in the mud: tank eco-restoration and boundary contestations in Chennai. *Urbanisation* 5, 121–139. doi: 10.1177/2455747120965508

Coelho, K., and Raman, N. (2013). "From the frying-pan to the floodplain: negotiating land, water and fire in Chennai's development," in *Ecologies of Urbanism in India: Metropolitan Civility and Sustainability*, eds A. Rademacher and K. Sivaramakrishnan (Hong Kong: Hong Kong University Press), 145–168. doi: 10.5790/hongkong/9789888139767.003.0006

Dang, N. M., Babel, M. S., and Luong, H. T. (2011). Evaluation of food risk parameters in the Day River Flood Diversion Area, Red River Delta, Vietnam. *Nat Hazards*. 56, 169–194. doi: 10.1007/s11069-010-9558-x

DeLoughrey, E. (2007). *Tidalectics: Navigating Repeating Islands in Introduction to Routes and Roots*. Honolulu: University of Hawai'i Press.

Department of Urban Development and Municipal Affairs Government of West Bengal (2021). *Submission of Quarterly Progress Report for the Period From March 2021 to May 2021 in Compliance With the Order of Hon'ble NGT Under OA-200/2018.* Memo no 89-JS (NG). Department of Urban Development and Municipal Affairs Government of West Bengal.

D'Souza, R. (2006). Water in British India: the making of a colonial hydrology. *Hist. Compass* 4, 621–628. doi: 10.1111/j.1478-0542.2006.00336.x

Escobar, A. (2011). Sustainability: Design for the plriverse. *Development.* 54, 137–140. doi: 10.1057/dev.2011.28

Escobar, A. (2020). *Pluriversal Politics: The Real and the Possible.* Transl. by David Frye. Duke: Duke University Press. doi: 10.2307/j.ctv11315v0

Follmann, A. (2015). Urban mega-projects for a 'world-class' riverfront—the interplay of informality, flexibility and exceptionality along the Yamuna in Delhi, India. *Habitat Int.* 45, 213–222. doi: 10.1016/j.habitatint.2014.02.007

Gandy, M. (2004). Rethinking urban metabolism: water, space and the modern city. *City*. 8, 363–379. doi: 10.1080/1360481042000313509

Gandy, M. (2008). Landscapes of disaster: water, modernity, and urban fragmentation in Mumbai. *Environ. Plan. A*. 40, 108–130. doi: 10.1068/a3994

Ghertner, A. (2011). "Green evictions: environmental discourses of a "slum-free" Delhi," in *Global Political Ecology*, eds R. Peet, P. Robbins, and M. Watts (London: Routledge), 145–165.

Ghertner, A. (2012). Nuisance talk and the propriety of property: middle class discourses of a slum-free Delhi. *Antipode*. 44, 1161–1187. doi: 10.1111/j.1467-8330.2011.00956.x

Karpouzoglou, T., and Vij, S. (2017). Waterscape: a perspective for understanding the contested geography of water. *WIREs Water* 4, e1210. doi: 10.1002/wat2.1210

Kolkata Environmental Improvement Investment Program (2018). *Kolkata Environmental Improvement Investment Program Tranche 3—Sewerage and Drainage Network (SD31). Initial Environmental Examination*. Available online at: https://www.keiip.in/pdf/42266-026-iee-en.pdf (accessed August 05, 2022).

Kolkata Environmental Improvement Investment Program (2019). *Kolkata Environmental Improvement Investment Program Tranche 3—Sewerage and Drainage Network. Initial Environmental Examination*. Available online at: https://www.keiip.in/pdf/42266-026-iee-en_2.pdf (accessed August 05, 2022).

Kolkata Municipal Corporation (KMC) and British Deputy High Commission (2017). *Road Map to Low Carbon and Climate Resilient City*. PWC.

Lahiri-Dutt, K. (2000). Imagining rivers. *Econ. Polit. Weekly* 34, 2395–2397+2399-2400.

Lahiri-Dutt, K. (2015). "Towards a more comprehensive understanding of rivers," in *Living Rivers, Dying Rivers*, eds R. R. Iyer (New Delhi: Oxford University Press).

Linton, J. (2010). *What is Water? The History of a Modern Abstraction*. Vancouver, TN: UBC Press.

Linton, J., and Budds, J. (2014). The hydrosocial cycle: defining and mobilizing a relational-dialectical approach to water. *Geoforum*. 57, 170–178. doi: 10.1016/j.geoforum.2013.10.008

Lord, A. (2014). Making a hydropower nation: subjectivity, mobility, and work in the nepalese hydroscape. *Himalaya* 34, 13.

McFarlane, C. (2008). Governing the contaminated city: infrastructure and sanitation in colonial and post-colonial Bombay. *Int. J. Urban Reg. Res.* 32, 415–435. doi: 10.1111/j.1468-2427.2008.00793.x

Miraftab, F. (2004). Invited and invented spaces of participation: neoliberal citizenship and feminists' expanded notion of politics. *Wagadu* 1, 1–7.

Moore, S. A. (2007). *Alternative Routes to the Sustainable City*. Lanham: Lexington Books.

Mukherjee, A. B., and Bardhan, S. (2021). Flood vulnerability and slum concentration mapping in the Indian city of Kolkata: a post-Amphan analysis. *Water Sci.* 35, 109–126. doi: 10.1080/23570008.2021.1957641

Mukherjee, J. (2016). The Adi Ganga: a forgotten river in Bengal. *Econ. Politic. Weekly* 51, 17.

Mukherjee, J. (2020). *Blue Infrastructures of Kolkata: Natural History. Political Ecology and Urban Development in Kolkata*. Singapore: Springer.

Mukherjee, J. (2022). "Living systems infrastructure" of Kolkata: exploring co-production of urban nature using historical urban political ecology (HUPE). *Environ. Urban.* 34, 32–51. doi: 10.1177/09562478221084560

Mukherjee, J., Bhattacharya, S., and Bose, L. (2023). "Heritage or basic human rights? Politics of environmentalism surrounding the Adi Ganga in Kolkata," in *Regional Political Ecologies and Environmental Conflicts in India*. eds S. Pattnaik and A. Sen (London; New York, NY: Routledge). doi: 10.4324/9780367486433-2

Mukherjee, J., Bhattacharya, S., Ghosh, R., Pathak, S., and Choudry, A. (2022). "Environment, society and sustainability: The transdisciplinary exigency for a desirable anthropocene," in *Social Morphology, Human Welfare and Sustainability*, ed M. I. Hassan (Springer Nature). doi: 10.1007/978-3-030-96760-4_2

Noble, I. R., Huq, S., Anokhin, Y. A., Carmin, J., Goudou, D., Lansigan, F. P., et al. (2014). *Adaptation needs and options. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University, Cambridge University Press, 833–868.

Rattu, P., and Véron, R. (2015). How to govern the urban hydrosocial cycle: archaeo-genealogy of hydromentalities in the Swiss urban water sector between 1850 and 1950. *Geogr. Helvet*. 70, 33–44. doi: 10.5194/gh-70-33-2015

Shamlou, S., Nagizadeh, M., and Habib, F. (2018). Urban-scape: an analysis of the approach and theoretical background to develope a conceptual framework. *ARMANSHAHR Architect. Urban Dev. J. Architect. Urban Design Urban Plan*. 11, 197–209.

Sheih, E., Behzadfar, M., and Ali, N. A. (2017). Theoretical framework Codification for urban scape using "the production of space" theory and influential forces on scape. *Motaleate Shahri*. 6, 81–94

Singh, N., Parthasarathy, D., and Narayanan, N. C. (2018). "Contested urban waterscape of Udaipur," in *Sustainable Urbanization in India: Challenges and Opportunities*, ed J. Mukherjee (Singapore: Springer).

Swyngedouw, E. (1999). Modernity and hybridity: nature, regeneracionismo, and the production of the Spanish waterscape. *Ann. Assoc. Am. Geogr*. 89, 443–465. doi: 10.1111/0004-5608.00157

Swyngedouw, E. (2005). Dispossessing H_2O: the contested terrain of water privatization. *Capital. Nat. Social.* 16, 81–98. doi: 10.1080/1045575052000335384

Swyngedouw, E. (2009). The political economy and the political ecology of the hydro-social cycle. *J. Contemp. Water Res. Educ*. 142, 56–60. doi: 10.1111/j.1936-704X.2009.00054.x

Truelove, Y., and Mawdsley, E. (2011). "Class and water: discourses of citizenship and criminality in clean, green Delhi," in *A Companion to the Anthropology of India*, ed I. Clark-Deces (Chichester: Wiley-Blackwell), pp. 407–425. doi: 10.1002/9781444390599.ch22

Véron, R. (2006). Remaking urban environments: the political ecology of air pollution in Delhi. *Environ. Plan. A*. 38, 2093–2109. doi: 10.1068/a37449

Wesselink, A., Kooy, M., and Warner, J. (2017), Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. *WIREs Water*. 4, e1196. doi: 10.1002/wat2.1196

Wittfogel, K. A. (1957). *Oriental Despotism. A Comparative Study of Total Power*. New Haven: Yale University Press.

Zimmer, A. (2012). *Everyday Governance of the Waste Waterscapes*. Bonn, Germany: Universitäts-und Landesbibliothek Bonn.

Zimmer, A. (2015). "Urban political ecology 'beyond the West': engaging with South Asian urban studies," in *The International Handbook of Political Ecology*, ed R. L. Bryant (Cheltenham, Northampton: Edward Elgar Publishing Limited).

frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 04 May 2023
DOI 10.3389/frwa.2023.1051336

OPEN ACCESS

EDITED BY
Jenia Mukherjee,
Indian Institute of Technology Kharagpur, India

REVIEWED BY
Brighton Austin Chunga,
Mzuzu University, Malawi
Innocent Nojiyeza,
University of Zululand, South Africa

*CORRESPONDENCE
Soma Sarkar
✉ somasarkar1990@gmail.com

SPECIALTY SECTION
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

RECEIVED 22 September 2022
ACCEPTED 06 March 2023
PUBLISHED 04 May 2023

CITATION
Sarkar S (2023) Urban water crisis and the promise of infrastructure: a case study of Shimla, India. *Front. Water* 5:1051336.
doi: 10.3389/frwa.2023.1051336

Urban water crisis and the promise of infrastructure: a case study of Shimla, India

Soma Sarkar*

School of Development Studies, Tata Institute of Social Sciences, Mumbai, India

Urban water configurations evolve through synergetic relationships that are non-linear, spatially variable, and temporally contingent. As urban development grows in complexity, dense water flow networks intensify within the urban landscape and pose a major challenge to urban water governance. At this junction, this study takes up the specific case study of the water crisis in Shimla, a city situated in the Western Himalayas, which was once the summer capital of British India. Shimla witnessed two significant episodes of a severe water crisis in 2016 and 2018, respectively. While the mainstream discourses identified erratic rainfall due to climate change, urban growth, and tourism as the prime causes, the crisis was not marked by absolute scarcity. Multitude configurations of infrastructure politics, distribution, and access produced scarcity, which differentially impacted the people in the city and continues to do so. Marginalized social groups (class, caste, gender, and religion) and people living on the periphery, such as slum dwellers, daily wage laborers, and informal sector workers with inadequate economic and social safety nets seem to have been missing from the discourse. In addition, the crisis events in Shimla have led to institutional changes in the governance of water by establishing a parastatal body for a water utility in the city and the proposal of mega water infrastructure projects for the bulk supply of water from the Sutlej River. Deriving from a situated urban political ecology approach, this study presents an in-depth empirical understanding of the complex urban waterscape of Shimla city, where the tourism industry is a major stakeholder, and a critical analysis of the emerging "new" politics of water, which is also a politics of infrastructure in Shimla's post-crisis phase. It adopts a qualitative research design involving in-depth interviews with different stakeholders in urban water governance in Shimla and a neighborhood-level case study to understand the post-crisis water scenario in the city. Locating the Shimla case study within the broader planetary geography, this study argues that the water crisis, as a context, is dialectical. Despite the implementation of several hydraulic projects and the financialization of nature, the inherent fissures of inequality within the city that cause differential access to water remain.

KEYWORDS

water crisis, infrastructure, institutional reforms, financialization, equity

1. Introduction

Water has become a pressing concern in the Anthropocene for billions of people across the globe, as it threatens the survival of humankind in the next century. In the Global South, millions of people (mostly the poor and children) die annually due to inadequate access to clean water (Mollinga et al., 2007; Enqvist and Gina, 2019; Enqvist et al., 2022). Approximately 785 million people lack even a basic drinking water service, including 144 million people who are dependent on surface water (World Health Organization., 2019). It is a prime urban challenge since infrastructural and spatial planning often falls behind the rapid scale of urbanization (Bakker, 2010). However, the urban water challenges resulting from urbanization are not absolute scarcities but are often primarily the question of distribution (Mehta, 2005). There is an agenda setting and framing of a "crisis" discourse to usher in large infrastructural developments (Giglioli and Erik, 2008). Along these lines, studies in urban political ecology have explored the material flows that unevenly shape the urbanization process while focusing on objects in the context of capitalist power relations. Large infrastructure networks, mainly water infrastructure, have been a frequent site of inquiry (Swyngedouw, 1997, 2004, 2006; Gandy, 2004; Kaika, 2004; Loftus, 2012). Going back in time, we see that water and urban environments have co-evolved continuously through intricate interrelationships that are temporally contingent and spatially variable, moving across non-linear progressions leading to unceasingly embryonic urban and resource configurations. However, in recent times, these relationships have intensified because of the urban communities' increasing dependence on water to first satisfy their own basic needs and then feed into the increasing large-scale production and consumption of water-based goods and services (Castro, 2013). Over the years, however, the scholarship on water has shifted from viewing water as a material substance to an understanding of the complex assemblages that water forms, linking the social, political, economic, and cultural systems, which then govern the different flows of water through societies, thereby shaping urban environments (Cook and Erik, 2012). As new urban development grows in complexity, dense networks of water flows intensify within the urban tissue and pose a major challenge to urban water governance.

Water crises have become frequent in recent times in cities around the world (e.g., Bangalore, Chennai, Mexico City, and Cape Town), as they struggle with over-extraction of water, contamination, shortages, and flood risks (Colven, 2022). With reference to Cape Town's "day zero", scholars have argued that the water crisis of 2015 to 2018 cannot be understood outside its already precarious and contradictory water governance system, which is defined by multi-scalar fractures in conjunction with historical and persistent inequality (race and class) (Enqvist and Gina, 2019). Rather, the crisis was situated within an existing reliance on the path that was shaped by a conflicting paradigm of governance, one characterized by ongoing tensions between imperatives of ecology, economics, and equity (Bigger and Nate, 2020). In Cape Town, the transformations were commensurate with that of the corporatization of water services by establishing a competitive atmosphere, performance-based management, and cost recovery policies aimed at reducing public sector inefficiencies (Smith and Susan, 2003). In the context of the Flint water crisis, critics argued that the relics of segregation and discrimination present in Flint made it an exclusive target, and this would not have been the case if Flint had been wealthier and white (Anand, 2017). In São Paulo, water shortages were felt across the city in 2015, and cuts in the supply of water were felt overwhelmingly by low-income residents and those living outside the urban center. Although, in the urban outskirts of São Paulo, there was no systematic rationing of water, the combination of less water storage space, further distance from treatment centers, and more insecure hook-ups meant that peripheral residents experienced longer periods of scarcity (Millington, 2018).

In India, water is listed in the Indian Constitution as a state subject, and with the state, the executive control over the production and management of water resources is concentrated. The state can legislate on who should have ownership, access, and user rights and what should be the mechanisms for distribution. This arrangement changed after the 74th constitutional amendment; thereby, municipality bodies are in charge of the above activities but with state control mechanisms. Among the previous studies, Zérah (2000) illustrated the differences between the water network connection and supply adequacy in New Delhi, highlighting that 50% of Delhi's residents do not have a reliable water supply despite having piped water connection. Anand (2011, 2012) explored the hydraulic infrastructural practices in Mumbai and the critical role of pumps, pipes, pressure, and water expertise in managing the city. Biswas and Druti (2021) further argued that groundwater will be extracted and depleted more in Delhi if the percentage of piped water network does not increase in tandem with the rapid urban transformation. However, Drew (2020) argues for a shift from "pipe politics" to "catchment politics" or the "politics of water capture" in her case study of the Hauz Khas Lake in New Delhi. Such explorations are possible in regions where traditional water management infrastructures are considered to be wiser ways of using resources.

In the context of Chennai, Niranjana (2021) explored the role of water works engineers within the fragmented water infrastructure of the city and highlights the fragmentary and pluralistic epistemologies that make up modern infrastructures. On the other hand, Coelho (2022) conceives urban waterlines as dynamic assemblages that employ water circulations in projects of transmuting territories and re-valuing urban nature and also as an analytical tool to capture the dialectic hybridity of water and society that reflects the power relations of capitalist development. In India, research has focused on big coastal cities such as Mumbai (Shaban and Sharma, 2007; Cooper, 2011; Ranganathan, 2014a,b; Anand, 2017), Kolkata (Das, 2009; Allen et al., 2017), and Chennai (Coelho and Venkat, 2009; Srinivasan et al., 2013), but there has also been an emerging focus on the small and intermediate level towns. Chatterjee and Kundu (2022) explore the changing power relations between actors within the locality (which they call "para") and their differential access to water services in their case study of Baruipur town, in West Bengal, India. They critically engage with the two cases of the stand post and the packaged drinking water in analyzing the relationship between public actors and private water vendors in the town. Sarkar (2022) problematizes water as a socioecological space of caste and gender and explores the differential access to water within communities at the level of neighborhoods (para) in the Purulia district of West Bengal, India.

Despite the huge spectrum of water research in India, most of it focuses on the plains or coastal plains. Only a few studies have explored urbanization and the urban waterscape in mountain cities (Boelens, 2014; Dame et al., 2019). In addition to the challenges of the landscape, this is important because of two aspects:

verticality and seasonality. Verticality in the relational production of space is of significance in the mountains. Negi et al. (2017) call this "contoured urbanism", where upward mobility entails new susceptibilities and where the everyday negotiations with inherited hierarchies through practices produce geographically situated forms of urbanization in parts of the Himalayas. In this vertical contoured urbanscape, water is a perennial challenge that is compounded by the neglect of traditional water systems, such as stone spouts and springs (Wester et al., 2019), outdated and poorly constructed water distribution systems that get superimposed on traditional water systems, pipe leakages, and poor governance that puts primacy on piped water supply over other time-tested and sustainable sources. In Darjeeling, private water tankers provide water to millions of residents.

Second, there is a sense of seasonality attached to the mountain cities in India. In Mussoorie, for example, the number of tourists increases to 200,000 during the peak months of May and June, and this has, directly and indirectly, affected the region (Madan and Laxmi, 2000; Koner and Gopa, 2021). In this regard, scholars have argued that tourism-led urban water use can significantly impact the regional level since it is concentrated in time and space (Gössling et al., 2012). This is particularly the case with the Himalayan cities, which attract a large number of tourists amidst their dwindling water supply. It results in more urbanization and newer water-consuming urban amenities (swimming pool, western flush toilet, showers, etc.). This results in new uses, production, practices, management, and control of urban water flows, which pose a challenge to the current governance mechanisms. The Global Water Partnership rooted in the experiences of the United Nations Development Programme (UNDP) — World Bank Water and Sanitation Program (WSP) has been providing developing countries with technical assistance aimed toward the urban use of water (Rana and Lauren, 2004). On the other hand, Biswas (2008) is critical of this partnership and the ambiguity around the concept of "integration" in Integrated Water Resource Management (IWRM). He argues that its application to better manage macroscale and mesoscale water policies, programs, and projects has a dismal track record. Synthesizing the existing literature, this study argues that the flows of water in a city are complex in nature and the interconnected dimensions of the social, cultural, economic, environmental, political, and topographical arenas in which water is embedded need to be considered. Due to the lack of this holistic approach, discourse on the water crisis has often been recognized as a crisis of governance. This study furthers this argument by situating the Shimla water crisis within the broader planetary geography.

Shimla, the erstwhile summer capital of colonial India, has witnessed two major incidences of the water crisis in recent times. In 2015–16, contamination in Ashwani Khad, one of the major water sources of the city, caused a hepatitis outbreak affecting many lives. It also disrupted the water supply because a major source was cut off. This was followed by another incidence of the water crisis in the peak summer of 2018, when the city nearly reached "day zero", as the water supply was disrupted for more than 2 weeks. In both incidences, the tourism industry was badly impacted, but the latter garnered immense social media attention as the residents urged the tourists not to visit Shimla that summer. These water shortages affect men, women, and marginalized communities differently. In most areas, the poor who live in marginal areas within the city, especially in the peri-urban areas outside the municipal water supply limits, pay a higher price for buying water from informal sources (Wester et al., 2019). The same is true for residents who rent accommodation, even in the core city center—they often do not have guaranteed rights to use the municipal connection, which is reserved for the house owner, and end up paying more than double for water (Wester et al., 2019). In Shimla, there have been major institutional shifts in the governance of water in the post-crisis phase.

Taking this as the point of departure, this study explores the complex urban mountain waterscape of Shimla city to understand the nature of the water crisis in the city, how it led to specific interventions and institutional responses, and how people's relationship with water in the city changed/evolved as Shimla underwent shifts in the water governance structure. Using an urban political ecology framework, it presents a critical analysis of the emerging "new" politics of water in Shimla's post-crisis phase. Urban political ecology investigates how a particular urban environment is produced and who gains and who loses due to particular power relations influencing changes within the urban environment and in the coproduction of urban society and environment (Swyngedouw, 1996, 1997; Braun and Castree, 1998; Swyngedouw and Heynen, 2003; Kaika, 2005; Heynen et al., 2006). More recent studies have also applied this framework for understanding nuances of water in smart city environments (Drew, 2020), urban waterlines (Coelho, 2022), and differential access to water (Chatterjee and Kundu, 2022).

2. Materials and methods

The study followed a qualitative research design involving in-depth interviews with different stakeholders in urban water governance in Shimla. A total of 45 in-depth interviews were conducted with key government officials, elected political representatives, consultants, residents, migrants, representatives from the hotel associations, business owners, academicians, media representatives, and lawyers. In addition to this, 50 semi-structured interviews and two focus group discussions were conducted at the neighborhood level of the Krishnanagar municipal ward as a case study. The participants for the study were selected using the snowball method. The fieldwork was conducted in 2021 amidst COVID-19 challenges, taking all precautionary measures. The interviews were conducted in English and Hindi, which were later transcribed and translated into English. After identifying the broad themes from the narrative threads, an interpretive analysis was conducted. In this study, pseudonyms are used for the names of the participants. The transect walk method was used in mapping the different water practices in the localities, understanding pipe networks, and also understanding people's perceptions of the water infrastructures. The secondary data include gazettes, government reports, project DPRs (Detailed Project Reports), popular articles, and a rigorous content analysis of all the proceedings of the house of the Shimla Municipal Corporation from 2015 to 2021.

3. Results and discussion

3.1. Situating Shimla's waterscape

The erstwhile summer capital of British India, Shimla, is situated on a transverse spur in the shape of an irregular crescent in the lower Himalayas, at a mean elevation of ~7,100 feet above sea level. In 1851, Shimla was first constituted as Municipal Committee and became a class I Municipality in 1871. In 1874, it was brought under the Punjab Municipal Act of 1873. After becoming a part of Himachal Pradesh and by the Himachal Pradesh Development and Regulation Act 1968, Shimla Municipal Committee was converted into a corporation in 1969. With the promulgation of the Himachal Pradesh Municipal Corporation Act of 1994, the number of wards was delimited to 21, and elections were conducted (Kanwar, 1990). The main functions of the corporation included ensuring sufficient water supply, maintaining sewerage and drainage systems, preventing the spread of seasonal diseases and epidemics, and undertaking the construction of civic infrastructure facilities such as roads, bridges, schools, health centers, and commercial complexes. The number of wards later rose to 25 after some nearby areas were included in the municipality, and as of 2016, Shimla has 34 municipal wards.

The history of water supply in Shimla relates to great engineering feats. The city has one of the oldest lift water supply systems in India, which is 135 years old and pumps at an average head of 1,470 meters. Before British settlement in Shimla, the region depended on its 17 baolis and natural springs for water. As the demand for water grew, a water supply system, planned by the British, was set up in 1875 to cater to 16,000 people. In 1880, 15,000 acres of land were converted into a catchment forest in Seog, and a gravity scheme was introduced. In 1893, the catchment forest was extended and pumping engines were installed at Cherot Nallah. In 1899, this was further augmented. In 1914, electricity was introduced, and the Gumma Water Lift Scheme was introduced on the Nauti Khad between 1919 and 1924. It was the highest water lift scheme in the world at that time (Buck, 1904). In total, two more rounds of augmentation were performed post-independence — first at Ashwani Khad in 1992 with an installed capacity of 10.8 MLD (millions of liters per day); second at Giri in 2007–2008 with an installed capacity of 61.3 MLD, taking the total installed capacity of the system to 61.2 MLD. In addition to this, the Municipal Corporation has 11 borewells providing 3–4 MLD of water and a buffer water scheme from Chaba with an installed capacity of 10 MLD.

At present, the drinking water for Shimla is lifted from seven sources, which are then treated in four water treatment plants. The treated water is sent through the network to the five major service reservoirs and then to 25 overhead tanks through gravity. The water from these overhead tanks is then supplied to the water connections in the city. The approximate capacity of water at the source is 51.5 MLD. Of the seven water sources, only two (Gumma and Giri) are reliable and contribute to more than 73% of the total water production. The following, Figures 1, 2, show the transmission of water from the source to the tank of the Gumma and Giri scheme.

The socioecological configuration of water is complex in Shimla because of the terrain. The increase in population, urban expansion of the city, and the incoming tourist influx have put additional pressure on the existing water systems. Shimla was built to cater to the needs of a maximum of 25,000 (British) people, who considered the place their summer haven. Since then, the population has increased to ~1.7 lakhs or 0.17 million (as per the 2011 census), but the infrastructure has not been augmented accordingly. This results in Shimla often facing a shortage of piped water supply during the peak of summer, which is also the peak tourist season. There have been two peak water crisis scenarios in Shimla, in 2015–16 and 2018, and after each one of them, there were major institutional shifts in the governance of water in Shimla city.

3.2. Hepatitis outbreak and water crisis of 2015–16

Contamination in the Ashwani Khad in January 2016, which is the major water source of Shimla, caused a widespread outbreak of hepatitis in Shimla, infecting ~6,000–10,000 people. Before this, Shimla experienced episodes of contamination almost every other year (2007, 2009, 2013, and 2016), but the cause was not identified and the one in 2016 affected a significant portion of the population in Shimla and the neighboring districts of Solan. Several assessment reports have often highlighted the issue of contamination risk from untreated water and sewage. For many residents of Shimla, the term "water crisis" is still used to refer to the hepatitis outbreak of 2015–16.

Ashwani Khad is a major source of water for the residents of Shimla, providing 10.8 MLD of water, which is ~20% of Shimla's water requirement. It became operational in 1994. In 2005, a sewerage treatment plant was constructed 5 kilometers upstream of the water treatment plant in Malyana. In 2015–16, the Malyana Sewage Treatment Plant malfunctioned and discharged sludge into the Ashwani Khad. This led to an outbreak of hepatitis, mostly affecting the localities of Kasumpati, Vikas Nagar, Panthaghati, Chotta Shimla, New Shimla, and Khalini, and later spread to the entire city (Sharma et al., 2021). After the contamination, a special investigation committee was constituted for inspection. Some of the main observations after visiting the Malyana Sewerage Treatment Plant were as follows:

1. The sewerage treatment plant at Malyana was underutilized and not functioning properly.
2. There is no approach road to the plant, causing difficulties in the lifting of sludge that was lying there.
3. Since there was no power backup, the plant becomes non-functional during a power failure, causing raw effluent to be discharged.

Due to this, the High Court ordered the Irrigation and Public Health Department (now Jal Shakti Vibhag) to stop lifting water from Ashwani Khad until the quality of water is improved to the drinking level. The general public was advised to clean their water storage tanks. Since a major water supply source was cut off, the city experienced severe water shortages for months. Water from only Koti and Brandi Nallah was tapped for potable purposes. Regular water testing was mandated.

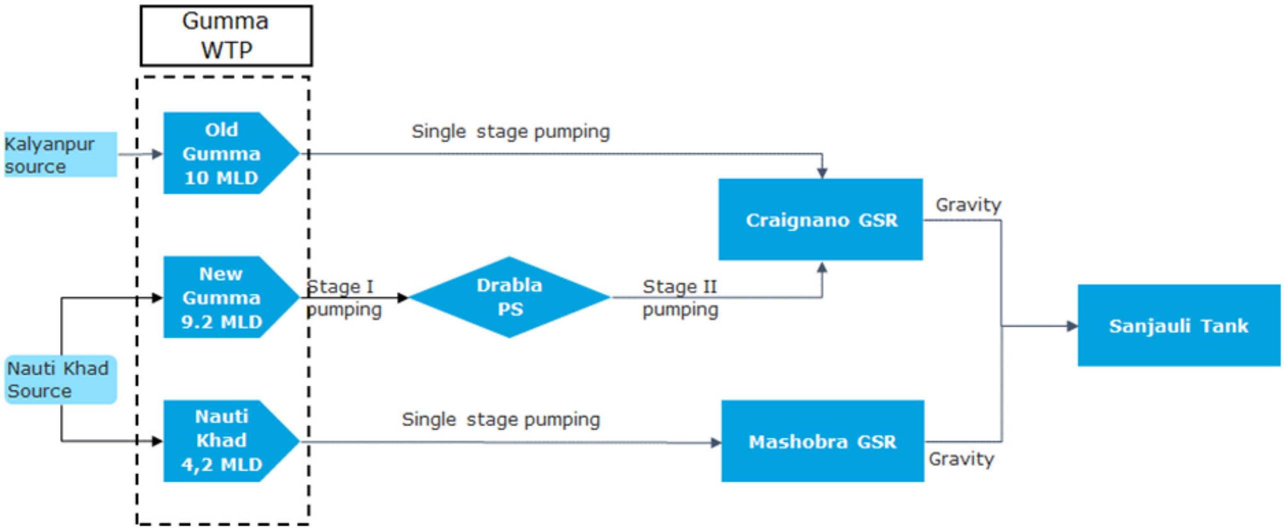


FIGURE 1
An outline of the Gumma water sourcing scheme. Source: Situation analysis report, 2018. Greater shimla water supply and sewage circle (GSWSSC), Shimla (Deloitte Touche Tohmatsu India LLP., 2018).

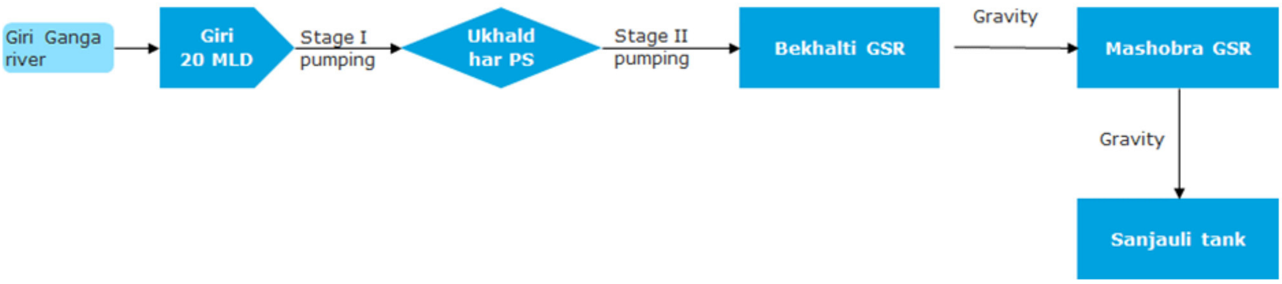


FIGURE 2
An outline of the Giri water sourcing scheme. Source: Situation analysis report, 2018. Greater shimla water supply and sewage circle (GSWSSC), Shimla (Deloitte Touche Tohmatsu India LLP., 2018).

What followed was a blame game between different authorities involved in the water lifting and distribution process. As per the institutional structure, the Irrigation and Public Health Department was responsible for lifting raw water and its treatment, along with the operation and maintenance of the transmission system, and the Shimla Municipal Corporation was responsible for the distribution, billing, and grievance redressal. Major questions of accountability, misgovernance, and failure of institutions were raised after the outbreak. Due to all this chaos, the city council demanded a change in the governance structure so that the entire water supply system could be handed over to the municipality. There was a change in the governance structure with the establishment of the Greater Shimla Water Supply and Sewage Circle (GSWSSC).

3.3. The urban conquest of water in the crisis of 2018

Shimla reached "day zero" at the peak of the shortage of piped water supply in May 2018, with several localities going without water supply for ∼10–15 days. While the closure of Ashwani Khad in 2016 and the lack of precipitation are often cited as the triggers for this crisis, one cannot deny the role of the tourist influx, inefficient infrastructure, poor governance of the water supply system, and inequitable distribution. For many reasons, this crisis garnered extensive media and social media attention across the country and world and came to be known as the "Shimla Water Crisis" of 2018.

The official response from the water authorities attributed the water crisis to climate change, meaning less snowfall in the winter and scanty rainfall resulting in a shortage of water at the source itself. In doing so, they cast nature into pole position to explain scarcity. It is, thus, presented in a way where "nature" becomes the principal cause of water scarcity and not the existing political–economic configurations that lead to the urbanization of water in selective and uneven ways (Kaika, 2004). This eventually results in "scarcity" of the poor and powerless and water abundance for the socioeconomic and political elites. Apart from the shortage of water due to the Ashwani Khad closure and scanty rainfall, the 24 h power cut near the Giri and Gumma pumping stations further aggravated the situation. The Giri and Gumma are major water sources in the city's supply. In the absence of power backup, it is a vulnerable dependency of the water-lifting process on electricity. The pumping of water is also affected during heavy rains because of high turbidity and over-siltation. However, that was not the case in the 2018 crisis. The 2018 crisis was instrumental in exposing the sectoral and spatial inequities in the water supply system of Shimla.

With regard to the commercial sector, the hotel industry incurred severe financial losses in the summer of 2018 due to tourists canceling their reservations due to the water situation. While interviewing members of the hotel association, it was found that none admitted to having water shortages in their hotels in 2018. It was informed that the hotel industry remains ever-prepared for the water uncertainties in the city and relies on private water tankers to suffice their needs. Many of the hotel owners had their own business of water tankers. These were used for their own needs and were also available for hire by the municipality when required. This crisis also brought to the forefront the networking of these tankers and people's gullible dependence on them. Transect walks in the Lower Bazaar neighborhood also revealed that some of the commercial water pipelines connecting the hotels had water running throughout the day, while those connecting the domestic connections had water for a limited time. The keyman in charge of the particular locality plays a significant role in this process.

Spatially, Shimla is divided into six water zones based on the areas under each overhead tank — Chaura maidan zone, Central Zone, Lakkar Bazaar Zone, Chotta Shimla Zone, New Shimla Zone, and Sanjauli zone (Figure 3).

During the crisis, not all localities were impacted in a similar way. In one of the field interviews, a professor commented, *"the whole city does not experience water crisis in the same way nor does [sic] all sections of people. The elite localities and the hotels did not run out of water. The university guest houses and faculty quarters had sufficient water while the hostels had an erratic water supply."*

He was referring to inter-locality and intra-locality inequities in the water supply referring to the university located in the Summerhill area. In addition, the pertinent question that arises here is who is prioritized over whom? Similar narratives of inequitable distribution were found all over the town. Higher-income neighborhoods get a regular water supply. Lower-income neighborhoods, on the other hand, get water at intervals. Even within one single municipal ward, water supply frequency and pressure vary with localities. The reasons cited for this discrepancy were manifold. While the authorities concerned (SJPNL and the Municipal Corporation) blamed gravity, inaccessibility (no roads for tankers), congestion, and other technical glitches, there were a group of people who blamed the vested interests of the political party leaders who got water themselves and diverted the remaining water to the hotels.

This was also the time when several officials (Engineers to Keymen) who were in charge of the water supply and distribution and were handling it for many years were routinely transferred to other departments. Managing the water supply and distribution in a mountain city requires experience because it all rests on a delicate balance of which valve is to be opened and when, otherwise all the water will gush downstream due to gravity. This would result in neighborhoods located on the higher side of the mountain slope not getting water. The new appointees were unaware of this and could not manage the peak summer water demand in the city. As households went without water for weeks, many women took to the streets expressing their disappointment and demanding water. There were several protests and many were arrested. Mostly, it was women, who were at the forefront of the protests. In one such protest for water in the Bolieuganj locality, cases were filed against several women. The cases were heard at the Chakkar District Court on 9 September 2021. After the hearing, one of the women, aged 51 years old, who was also a shopkeeper by profession, shared, *"we absolutely did not have water in the house. What could we do? After reaching out to the councilor[sic], one water tanker was provided, but one water tanker was not sufficient for the whole neighborhood. Many women protested because we were not able to run our households. Cooking, bathing, washing, and everything else were on halt because we barely had water to drink."* It is evident from this that the issue of water is a personal issue for women because it disrupts the private sphere of the "household". The 2018 water crisis exposed many fissures of inequality within the existing system, but most importantly brought the plight of women into the discourse.

3.4. Institutional shifts in response to the crises

In India, water governance is decentralized at the state level. The state governments receive financial support from the central government to implement national-level projects. In their administrative and physical borders, the states are in charge of developing and managing water resources. To develop and manage water resources, states have a variety of institutions at their disposal, including regulatory bodies, water departments, gram panchayats, irrigation departments, and public work departments (Ahmed and Araral, 2019). Rural and urban areas have different water management systems at the state level. Water management in urban areas is handled by a variety of political and administrative institutions, including municipalities and districts, where both elected and appointed officials carry out their duties. State-to-state variations in these arrangements are possible. The formulation, execution, and delivery of policies are the purview of these municipal- and district-level bodies. Water infrastructure construction and maintenance, water distribution, and other related tasks are all included in the provision of services *(ibid).*

In Shimla, historically, the entire water supply was managed by the municipal committee until 1979 when the Irrigation and Public Health Department (IPH) (now Jal Shakti Vibhag) was formed and took over the responsibility of creating the water supply and sewerage (WSS) infrastructure in the state of Himachal Pradesh. It was responsible for providing WSS services to the whole state, with the exception of Nagar Panchayats and Municipal Committee areas. Only bulk water was provided there. Within the city, the Shimla circle of the IPH department was responsible for asset creation (bulk water supply, distribution network, sewerage network, and sewerage treatment plants). The IPH was also responsible for providing treated bulk water and for treating sewage for the SMC area. The WSS department of the Shimla Municipal Corporation was responsible for the distribution of treated water and collection of sewage within SMC limits.

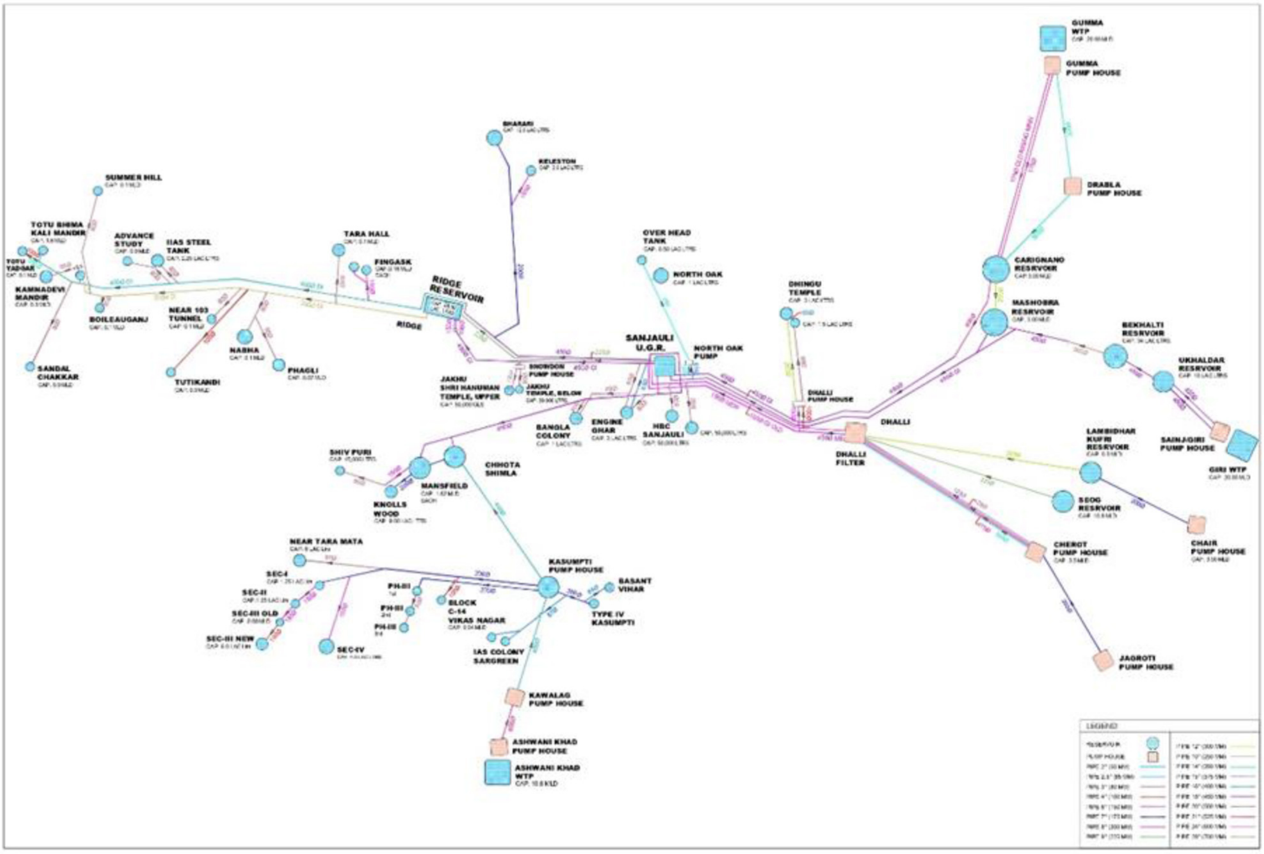


FIGURE 3
Water distribution network of Shimla. Source: Shimla Jal Prabandhan Nigam Limited (SJPNL).

The hepatitis outbreak of 2015–2016 was the outcome of poor water governance, whereby the contamination of the water source remained unnoticed for days and later, the duality between the different authorities involved in the water lifting and distribution process was blamed. There were questions of accountability, misgovernance, and failure of institutions. This incident resonates with the water contamination case of Flint when its water source was switched from Lake Huron to the Flint River. Flint River's water was acidic compared to Lake Huron, and corrosion control chemicals were not added to the water. A lack of chlorine in the water resulted in bacterial growth, causing an outbreak of Legionnaires' disease in 2014–2015, killing over 80 residents, and infecting more than 100 residents (Anand, 2017). In the hepatitis outbreak in Shimla, ~6,000–10,000 people were affected, which led to major institutional shifts in the governance of water.

After the hepatitis outbreak of 2015–2016, the Honorable High Court of Himachal Pradesh ordered reforms in the water supply and sewerage administration of the city of Shimla specifically, and the State of Himachal in general. It wanted one statutory body/post to be manned by a competent authority and members along with requisite staff to deal with the entire water supply system of Shimla town and the entire water crisis relating to the State of Himachal Pradesh. The Greater Shimla Water Supply and Sewage Circle (GSWSSC), was created under the Municipal Corporation as a separate, ring-fenced body for the delivery of all integrated services related to water supply and sewage disposal in the Greater Shimla Planning Area. It was envisioned that the accounts for the circle would be ring-fenced from the rest of the Municipal Corporation. The GSWSSC was also envisaged to have standard operating procedures for the delivery of water and sewerage services. It was envisaged that the Government of Himachal Pradesh would support all initiatives to strengthen the circle by way of adequate and qualified personnel and adequate need-based financing. The GSWSSC was functionally, financially, and operationally ring-fenced within SMC, with a separate bank account. A director, deputed from IPH, was the head of the circle and would exercise all operational powers for WSS, and the IPH provided the staff required for the functioning of the circle. Most importantly, service levels and tariffs within the entire Greater Shimla area (GSA) were mandated to be uniform. A Memorandum of Understanding (MOU) between the IPH, Urban Development Department (UDD), and SMC was required to set up the GSWSSC.

Since 2016, the GSWSSC has improved the water supply and sanitation system in the city by repairing leakages and reducing non-revenue water. However, the 2018 water crisis called for another major institutional shift in the governance of water in the city, whereby there was a shift from this ring-fenced entity to an independent utility. The GSWSSC transformed into a company called the Shimla Jal Prabandhan Nigam Limited (SJPNL). The Government of Himachal Pradesh and Shimla Municipal Corporation jointly owns the company with the corporation having a 51% shareholding in the company, representing the interests of Shimla city, and the Government of Himachal Pradesh owning a 49% shareholding in the company, representing the interests of peri-urban areas. Today, the SJPNL is responsible for the management of the city's water supply. The core performance standards, as mandated by 2025 as a part of the Medium Term WSS Program funded by the World Bank are as follows:

1. Universal access to piped water supply and sewerage will be provided to all households in the Greater Shimla area. The safe and piped water supply of 135 lpcd per person per day and sewerage connection will be provided. The water supply standards in the entire Greater Shimla area would be uniform, and there would be no difference in standards between Shimla city and the peri-urban area, nor would there be different standards of supply for low-income neighborhoods/households.
2. Continuous pressurized water supply (24 × 7) will be provided. The supply of potable water to end users through a system of pipes — comprising interlinked bulk transmission and/or distribution systems — which are continuously full and under positive pressure throughout their whole length, such that the end user may draw off the water at any time of the day or night, 24 h a day, every day of the year. Continuous pressurized supply will be accompanied by 100% metering of all households and supply points and volumetric incremental block tariff.
3. In total, 100% water quality and effluent compliance with applicable potable water and environmental standards are specified by the Central Public Health Engineering Environmental Organization (CPHEEO), the Central Pollution Control Board, and the Himachal Pradesh Pollution Control Board.

The governance of the urban hydro-social cycle, the demand aspect, in particular, operates *via* public awareness campaigns about water conservation and attempts to increase water extraction or reduce consumption by technological fixes. There is always an inclination toward engineering solutions. The 2018 water crisis in Shimla paved the way to pitch the long-withstanding Sutlej project plan in front of the World Bank. While the core performance standards under the project are much needed, the concern is around the cost recovery aspect of the project. The cost of the project, which involves augmenting the water supply to Shimla from the Sutlej with an additional 67 MLD to meet the water demand until 2050 is Rs. 1,168 Cr (1 crore = 10 million). This amount will finally be recovered from the general public itself.

In Shimla, there is going to be 100% metering of the taps, and public taps are slowly being discontinued. This resonates with the prepaid water meter case from Phiri, Soweto, a low-income community in Johannesburg. The case involved a disagreement over water provision policies and the installation of a prepaid water meter system in Phiri, pitting five impoverished residents of Phiri against the City of Johannesburg, Johannesburg Water, and the national Minister for Water Affairs and Forestry (Naidoo, 2005). The sufficiency of Johannesburg's Free Basic Water Policy, which only allowed 6,000 free liters of water per household per month, or 25 liters per person per day for a household of eight, was put to the test *(ibid)*. The case was taken to the High Court and Supreme Court and resulted in controversial shifts of legal opinions, but this was the first case where the court was forced to rule on the availability and sufficiency of water. In Shimla, the tariff for domestic water connection within the municipal area from 0 to 20 kiloliters is Rs. 17.55 per kiloliter. Water is no longer available for free. The question remains as to, in the absence of any tariff concessions for the low-income group of people in the city, how socioeconomically accessible the "new" water infrastructure is And what this entails for equity and water justice in the future. While services may become efficient under such a regime, the challenge of service delivery to the poor in urban areas remains. The following neighborhood case study further elaborates along these lines.

3.5. Life "below the Cart road": a case study of Krishnanagar

In Shimla, the British left behind a very nebulous "way of life," which was reserved for a section of Anglophiles and affluent Indians who now occupied the posh localities, which were previously only reserved for the British (Bhasin, 1992). This spatial segregation, along with class lines, is visually evident in Shimla. The settlements have developed over the years with subsequent waves of urbanization. These spatial differentiations have deeper connotations when juxtaposed with social configurations. These are particularly visible when it comes to access to resources.

Krishnanagar municipal ward is located at the core of Shimla city along the sunny slopes of the Ridge. The mountain slope is divided by Cart Road, and Krishnanagar is located below it. Shimla was built by the British as a "hill station" and sanatorium for themselves. There was a particular sense of "seasonality" attached to its ontology since the city served as the summer capital of colonial India. In Shimla, the topography was used to carry out racial segregation by the elevation difference. An average Indian was an outcast in that colonial stratosphere who was more likely to service providers such as porters, rickshaw-pullers, clerks, etc. During the British time, while the officials resided in the Ridge and present-day Jakhu area, the Indian service providers had their settlements down the slopes, that is, how this slope developed as well. A steep road down the Cart Road near Mahamaya hotel takes us to Krishnanagar. The road is narrow and steep, so much so that car drivers from only that locality can drive on that slope. Some of the localities within Krishnanagar are Ghora Sarai, Mistri Line, Valmiki Mandir, Ladakhi Mohalla, Cowshed, Slaughter House, Lalpani, Gurudwara, and Gaddikhana. Most of the localities are symbolic of the occupation of the original residents. For example, Ghora Sarai was originally inhabited by horsecart pullers during the colonial period, and horses can still be found there. These horses are now used for tourism and recreation at Mall Road.

Krishnanagar is the largest slum in Shimla. Out of 2,758 houses in the slums of Shimla, 1,213 houses are in Krishnanagar. The area is often neglected in terms of basic amenities. In addition, the general perception of this locality among the Shimla residents is quite negative. The Valmikis (untouchables), the Ravidasis (leather workers), the Ladakhis, the Punjabis, and many others who live in Krishnanagar have lived there for generations. Migrant laborers from Nepal and Indian states also call Krishnanagar their home because of the low property value. There is also a Valmiki community, which was engaged in leather processing. It was found that there are variations within the neighborhood as well. Many businessmen live in the Gaddikhana area closer to Cart Road, and their perceptions about the neighborhoods situated downhill are often biased. This neighborhood was purposively chosen to understand the contours of social and spatial hierarchy across a slope and how it limits one's access to provisions.

The neighborhood-level study of 50 households revealed that the water source choices for the people living in Krishnanagar are municipality home connections ($n = 27$), municipality joint connections ($n = 2$), public taps ($n = 6$), natural springs ($n = 4$), municipality home connections and natural spring both ($n = 9$), natural spring and public tap both ($n = 1$), and not having any connection of one's own but sharing from the neighbor ($n = 1$). In Krishnanagar, the ratio of water connections to properties is very low. This indicates that multiple properties are sharing one connection, and/or that several properties are without connection. For people depending on municipality home connections, water was received once every 3 days for a duration of 30 min to 1 h. They face a particular problem in the summer months of May and June because during that time, water is diverted to all the hotels located uphill from Krishnanagar, and much less water is given to the locality. Summer months are particularly challenging at the household level because many people have relatives/guests visiting, and the requirement for water in the house increases.

Figure 4 maps the daily water needs of the studied households in the Krishnanagar ward. Based on the amount of water they needed to run the household and the water they receive daily, they responded based on whether the water they receive is sufficient or insufficient for them. It was found that people with sufficient water needs are households of smaller family sizes who have a maximum cap of 1,000 liters requirement per day. Those with insufficient water are households of larger family sizes with an upper cap of 2,000 liters per day. Here, water sufficiency also includes their dependence on the natural springs/baolis. Springs are used alongside formal household water provisions as a backup. As the springs continue to supplement, complement, and substitute for formal piped water connections, even in households with municipality home connections, the waterscape of mountain cities such as Shimla becomes more complex (Müller et al., 2020).

In a case study of the city's waterscape in Coimbatore, Tamil Nadu, India, Biswas (2021) argued that the amount of storage available at the household level can significantly and long-lastingly affect the procurement burden placed on women in the case of intermittent water supply. Even though there is a difference in the quality of stored water and flowing water, under intermittent water supply, theoretically at least, if a household can store enough water to meet their entire water needs during the supply days, then the procurement burden on women can be minimized. In Shimla, access to storage is an important factor in water sufficiency as well. Households with sufficient water were also the ones with more than 1,000 liters of storage tanks. Such households often maintain dead storage of a minimum of 500 liters as a preparedness mechanism in anticipation of another water crisis. With regard to the 2018 water crisis, a middle-aged entrepreneur and resident of the Gaddikhana area of Krishnanagar remarked, *"we get water once every 3 days and we maintain storage of two thousand liters. With a newborn baby in the house, our water requirement is also high. It is because we maintain some water storage, we did not face many difficulties in the 2018 crisis but had to call water tankers twice."* Storage of water is essential, but not every household has access to it in a similar way. For low-income households without plumbing infrastructure, water is stored in drums, buckets, and cans, and the total storage capacity is within 250 liters. Similarly, people who reside in rented accommodations depend on their landlords for water. In many cases, even when the supply of water in the city is once every 3 days, the house owners release water to their tenants after meeting their own needs. Thus, the people without adequate storage are the first ones to be affected when there are disruptions in the city's water supply.

Apart from this, the timing of the water supply is an important factor. Water is mostly supplied in this locality between 4:00 a.m. and 5:30 a.m. The early morning timing for water is problematic for many residents whose water taps are outside the house or who are accessing public water taps. This is because the region has witnessed many human–wildlife conflicts with leopards. Since the opposite slope is forested, it becomes an easy passage for leopards to come to this locality to hunt for dogs for food. There have been incidences of attacks on children and the elderly as they come out of their houses at unusual hours (early morning or late at night) to access tap water or toilets. Being located downhill of the slope, water is first released in this locality phase by phase and then in the uphill localities. This is done to ensure that the water pressure is maintained and the uphill localities also get water. Otherwise, the entire water supply will gush downhill under gravity. This intricate balance of pressure and valves is regulated by the keyman of the locality. The timing, duration, and frequency of water supply often depend on them as they become the first point of contact for many people when it comes to grievance redressal. The keyman holds a certain level of power when it comes to the water supply in the city. Hansen and Oskar (2009) call them urban specialists or middlemen who form a bridge between the slum dwellers and the services of the city. Anand (2012) calls this "plumber raj" where the plumbers play a significant role in the water supply, where the formal water connections become complex. This is similar to the case of Shimla.

A major problem faced by the residents of Krishnanagar is getting a new water connection. Most of the constructions in this area are unauthorized and to get a water connection, the house deed is required along with proof of electricity payment. It is because of this challenge that many households in this locality are still out of the water supply network, and the role of the plumbers and keyman become significant. For many of these people and people for whom the supplied water is not sufficient, the natural springs are the only resort. After the hepatitis outbreak of 2015–2016, water testing was done in the natural springs in the city. Most of them were declared unfit for consumption. The spring upon which the people of Krishnanagar are dependent flows polluted water into

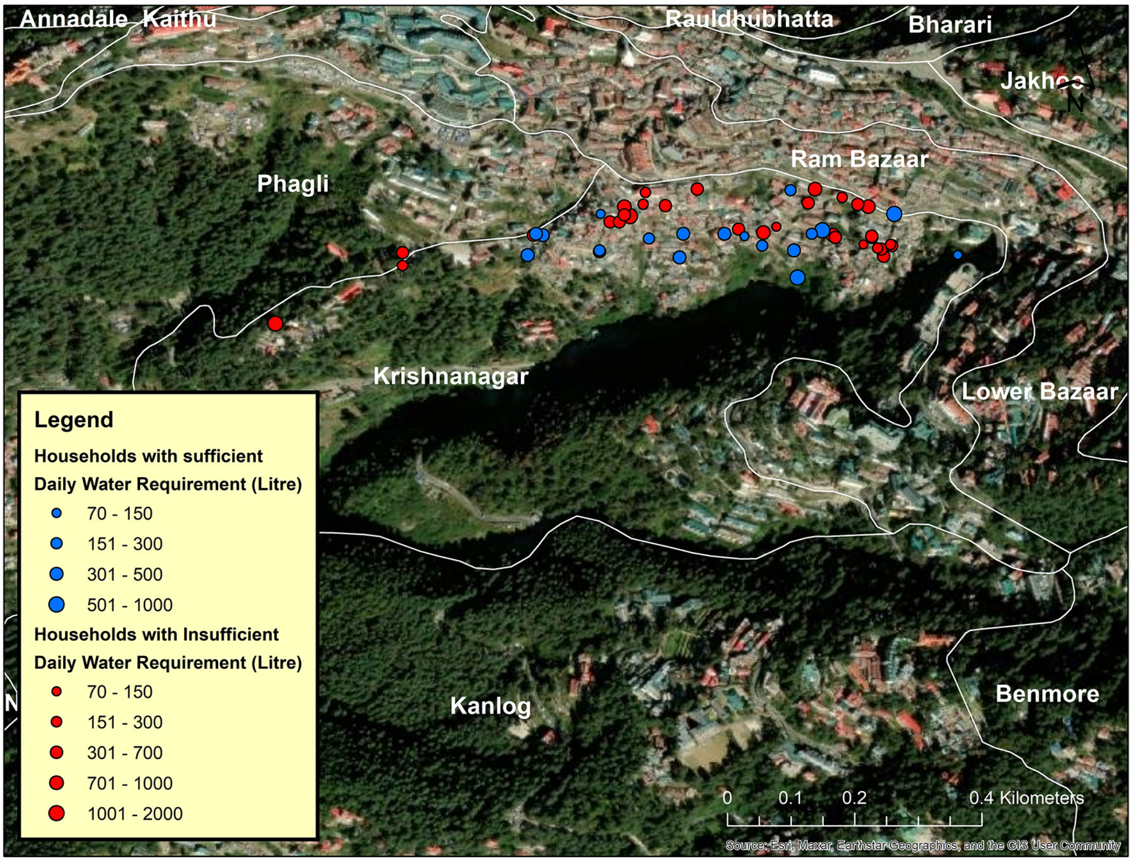


FIGURE 4
Map showing the daily water requirements of residents in Krishnanagar, Shimla, India. Source: Author.

the locality from the Mall Road above. Water from that spring is tapped through pipes and spread out within Krishnanagar, and the households depend on it for drinking, cooking, washing, and cleaning. Scholarly research engaging with urban waterscapes often overemphasize access to a particular quantity of water rather than the quality of that water for domestic use (Lavie et al., 2020). There is a need to define access and adequacy in terms of the quality and source of water too, as in the case of Shimla.

An interesting response from one of the participants highlighted that when the water crisis in Shimla happened in 2016 and 2018, many people in this ward were not greatly affected because, either way, they were dependent on the natural springs and not on the supplied water. They were already "out of the network" Being out of the network of the water supply is not just about connectivity to the infrastructure, it is also symbolic of how a particular population group is viewed by the state and produced as abject to the modern city (Anand, 2012). Hence, in Krishnanagar, we see a decentralized locally developed water alternative (natural springs) and subjectivities regarding service delivery thriving under the shadow of the large hydraulic infrastructural system. Radonic and Sarah (2015), in their case study of Sonora, found that the steep eroding slopes were covered with networks of "illegal" PVC pipes, blurring the boundaries between humans and technology. The act of carrying water containers, filling rooftop cisterns, and carrying out manual waste disposal render bodies a part of the urban infrastructural fabric. This is different from mainstream infrastructural thinking, which surrounds the state and capital as sites of governance and the role of civil society in the everyday forms of water management where the state is perceived to be absent is less explored (*ibid*).

We know that urban societies both shape and are shaped by water both materially and discursively as water embeds social relations (Gandy, 2004; Kaika, 2004; Swyngedouw, 2004; Loftus, 2012). Infrastructures also tend to reflect and reproduce social inequities within the city. Grounded case studies, such as Krishnanagar, offer a different lens to look at the production, politicization, and contestations around urban space. The "urban" provides a more nuanced understanding of urbanization, revealing how urban settings are shaped, politicized, and contested.

4. Conclusion

In the promise of infrastructure, while there has been an augmentation in the city's water infrastructure through large investments, this detailed fieldwork and literature review highlights the need to focus on the efficiency of the infrastructure and people's access to it. Despite the huge infrastructural technological fix as a solution to the city's water crisis, the water supply system of Shimla appears fragmented. The company claims to have eased out the water shortages and, to some extent, they have done so, but only in specific localities. "Geography" continues to be a barrier for certain localities. Volumetric tariffs levied as a part of cost recovery are making piped water a commodity of luxury for the marginalized and low-income groups of people without social safety nets and residing on the periphery of the city and in vertical orogeny in mountain cities. In short, the urbanization of water and the social, economic, and cultural processes associated with its domestication have brought access to and control over nature's water squarely into the realms of class, gender, cultural differentiation, and struggle. On top of that, the commodification of water incorporates the circulation of water with money circulation, and in doing so, makes access to water dependent on positions of social power.

Hence, in the case of Shimla, the "crisis", as a context, is dialectical. The specific geographical characteristics of marginal settlements — poor location, difficult topography, and obsolete infrastructure — facilitate the continuing exclusion of the urban poor by reinforcing technical arguments and blaming the lack of investment funds as the main reasons for continued water deprivation. At the same time, despite the implementation of hydraulic projects and the financialization of nature, the inherent fissures of inequality within the city that cause differential access to water remain. While infrastructure is essential for a city's growth, people's participation and inclusivity are important for the infrastructure to be effective.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

The paper is authored by SS and the research is derived from her ongoing doctoral research.

Funding

The author has been awarded the Dr. Ambedkar Doctoral Fellowship from DAIC, New Delhi, for her doctoral research. The fieldwork for this research was conducted from this grant. The author also extends her gratitude to the Frontiers Fee Support Scheme, Frontiers in Water, and TU Delft for their generous support in offering a full fee waiver for featuring this manuscript.

Acknowledgments

I am thankful to my doctoral supervisor Prof. Geetanjoy Sahu for his guidance in developing this paper.

Conflict of interest

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

Publisher's note

References

Ahmed, M., and Araral, E. (2019). Water governance in India: evidence on water law, policy, and administration from eight Indian states. *Water* 11, 2071. doi: 10.3390/w11102071

Allen, A., Hofmann, P., Mukherjee, J., and Walnycki, A. (2017). Water trajectories through non-networked infrastructure: insights from peri-urban Dar es Salaam, Cochabamba and Kolkata. *Urban Res. Pract.* 10, 22–42. doi: 10.1080/17535069.2016.1197306

Anand, N. (2011). Pressure: The politechnics of water supply in Mumbai. *Cult. Anthropol.* 26, 542–564. doi: 10.1111/j.1548-1360.2011.01111.x

Anand, N. (2012). Municipal disconnect: on abject water and its urban infrastructures. *Ethnography* 13, 487–509. doi: 10.1177/1466138111435743

Anand, N. (2017). *Hydraulic City: Water and the Infrastructures of Citizenship in Mumbai*. Durham, NC: Duke University Press.

Bakker, K. (2010). *Privatizing Water: Governance Failure and the World's Urban Water Crisis*. Ithaca, NY: Cornell University Press.

Bhasin, R. (1992). *Simla, the Summer Capital of British India*. Delhi: Rupa Publications.

Bigger, P., and Nate, M. (2020). Getting soaked? Climate crisis, adaptation finance, and racialized austerity environment and planning. *Nat. Space* 3, 601–623. doi: 10.1177/2514848619876539

Biswas, A., and Druti, G. (2021). Studying the water crisis in Delhi due to rapid urbanisation and land use transformation. *Int. J. Urban Sust. Dev.* 13, 199–213. doi: 10.1080/19463138.2020.1858423

Biswas, A. K. (2008). Integrated water resources management: is it working? *Int. J. Water Res. Dev.* 24, 5–22. doi: 10.1080/07900620701871718

Biswas, D. (2021). Navigating the city's waterscape: gendering everyday dynamics of water access from multiple sources. *Dev. Prac.* 31, 248–258. doi: 10.1080/09614524.2020.1836128

Boelens, R. (2014). Cultural politics and the hydrosocial cycle: water, power and identity in the Andean highlands. *Geoforum* 57, 234–247. doi: 10.1016/j.geoforum.2013.02.008

Braun, B., and Castree, N. (1998). *Remaking Reality: Nature at the Millennium.* London: Routledge.

Buck, E. J. (1904). *Simla Past and Present*. London: Minerva Publishers and Distributors.

Castro, J. E. (2013). Water is not (yet) a commodity: commodification and rationalization revisited. *Hum. Figurations* 2, 1. Available online at: http://hdl.handle.net/2027/spo.11217607.0002.103

Chatterjee, S., and Kundu, R. (2022). Co-Production or contested production? Complex arrangements of actors, infrastructure, and practices in everyday water provisioning in a small town in India. *Int. J. Urban Sustain Develop.* 14, 196–208. doi: 10.1080/19463138.2020.1852408

Coelho, K. (2022). Urban waterlines: socio-natural productions of indifference in an indian City. *Int. J. Urban Reg. Res.* 46, 160–181. doi: 10.1111/1468-2427.13087

Coelho, K., and Venkat, T. (2009). The politics of civil society: neighbourhood associationism in Chennai. *Econ. Polit. Weekly* 27, 358–367. Available online at: https://www.jstor.org/stable/40279795

Colven, E. (2022). A political ecology of speculative urbanism: the role of financial and environmental speculation in Jakarta's water crisis. *Environ. Plan. Econ. Space* 5, 0308518X221110883. doi: 10.1177/0308518X221110883

Cook, I. R., and Erik, S. (2012). Cities, social cohesion and the environment: towards a future research agenda. *Urban Stu.* 49, 1959–1979. doi: 10.1177/0042098012444887

Cooper, R. W. F. (2011). Municipal water schemes in a Mumbai squatter settlement: assembling space and society. *Int. J. Urban Sust. Dev.* 3, 77–92. doi: 10.1080/19463138.2011.557894

Dame, J., Schmidt, S., Müller, J., and Nüsser, M. (2019). Urbanisation and socio-ecological challenges in high mountain towns: insights from Leh (Ladakh), India. *Landscape Urban Plan.* 189, 189–199. doi: 10.1016/j.landurbplan.2019.04.017

Das, K. (2009). *Agency and Access Under Decentralized Governance: Water Supply and Sanitation in Kolkata City*. Ahmedabad: Gujarat Institute of Development Research.

Deloitte Touche Tohmatsu India LLP. (2018). *Situation Analysis Report. Submitted to: Greater Shimla Water Supply and Sewerage Circle, Municipal Corporation Shimla.*

Drew, G. (2020). Political ecologies of water capture in an Indian 'Smart City'. *Ethnos* 85, 435–453. doi: 10.1080/00141844.2018.1541918

Enqvist, J., Ziervogel, G., Metelerkamp, L., van Breda, J., Dondi, N., Lusithi, T., et al. (2022). Informality and water justice: community perspectives on water issues in Cape Town's low income neighbourhoods. *Int. J. Water Resour. Develop.* 38, 108–129. doi: 10.1080/07900627.2020.1841605

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

Gandy, M. (2004). Rethinking urban metabolism: water, space and the modern city. *City.* 8, 363–379. doi: 10.1080/1360481042000313509

Giglioli, I., and Erik, S. (2008). Let's drink to the great thirst! Water and the politics of fractured techno-natures in Sicily. *Int. J. Urban Reg. Res.* 32, 392–414. doi: 10.1111/j.1468-2427.2008.00789.x

Gössling, S., Peeters, P., Hall, C. M., Ceron. J. -P., Dubois, G., Lehmann, L. V., et al. (2012). Tourism and water use: Supply, demand, and security: An international review. *Tourism Manag.* 33, 1–15. doi: 10.1016/j.tourman.2011.03.015

Hansen, T. B., and Oskar, V. (2009). Introduction-urban charisma: on everyday mythologies in the city. *Critique Anthropol.* 29, 5–26. doi: 10.1177/0308275X08101029

Heynen, N., Kaika, M., and Swyngedouw, E. (2006). *In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism*. Abingdon: Routledge.

Kaika, M. (2004). *City of Flows: Modernity, Nature, and the City*. London: Routledge.

Kaika, M. (2005). *City of Flows: Water, Modernity and the City*. New York, NY: Routledge.

Kanwar, P. (1990). *The Political Culture of the Raj*. Oxford: Oxford University Press.

Koner, K., and Gopa, S. (2021). Urban environment and sustainable water supply: a comprehensive analysis of Darjeeling city, India. *Environ. Deve. Sust.* 23, 17459–17482. doi: 10.1007/s10668-021-01396-y

Lavie, E., Laure, C., and Anaïs, M. (2020). Reconceptualising the drinking waterscape through a grounded perspective. *Geograph. J.* 186, 224–236. doi: 10.1111/geoj.12343

Loftus, A. (2012). *Everyday Environmentalism: Creating an Urban Political Ecology*. Minneapolis, MN: University of Minnesota Press.

Madan, S., and Laxmi, R. (2000). The impacts of tourism on the environment of Mussoorie, Garhwal Himalaya, India. *Environmentalist* 20, 249–255. doi: 10.1023/A:1006760015997

Mehta, L. (2005). *The Politics and Poetics of Water*: *The Naturalisation of Scarcity in Western India*. Bangalore: Orient Blackswan.

Millington, N. (2018). Producing water scarcity in São Paulo, Brazil: the 2014-2015 water crisis and the binding politics of infrastructure. *Polit. Geography* 65, 26–34. doi: 10.1016/j.polgeo.2018.04.007

Mollinga, P. P., Ruth, S., and Douglas, J. M. (2007). Politics, plurality and problemsheds: a strategic approach for reform of agricultural water resources management. *Dev. Policy Rev.* 25, 699–719. doi: 10.1111/j.1467-7679.2007.00393.x

Müller, J., Juliane, D., and Marcus, N. (2020). Urban mountain waterscapes: the transformation of hydro-social relations in the trans-Himalayan town Leh, Ladakh, India. *Water* 12, 1698. doi: 10.3390/w12061698

Naidoo, P. (2005). The struggle for water, the struggle for life: the installation of prepaid water meters in Phiri, Soweto. *Centre Civil Soc. RASSP* 1, 155–177. Available online at: https://ccs.ukzn.ac.za/files/CCS_RASSP_0705_Report%209.pdf

Negi, V. S., Maikhuri, R. K., Pharswan, D., Thakur, S., and Dhani, P. P. (2017). Climate change impact in the Western Himalaya: people's perception and adaptive strategies. *J. Mountain Sci.* 14, 403–416. doi: 10.1007/s11629-015-3814-1

Niranjana, R. (2021). Between fragments and ordering: engineering water infrastructures in a postcolonial city. *Geoforum* 119, 1–10. doi: 10.1016/j.geoforum.2020.12.018

Radonic, L., and Sarah, K. R. (2015). Pipes and praxis: a methodological contribution to the urban political ecology of water. *J. Polit. Ecol.* 22, 389–409. doi: 10.2458/v22i1.21115

Rana, S., and Lauren, K. (2004). *The Global Water Partnership. Addressing Challenges of Globalization: An Independent Evaluation of the World Bank's Approach to Global Programs. Case Study*. Washington, DC: The World Bank, Operations Evaluation Department.

Ranganathan, M. (2014a). 'Mafias' in the waterscape: urban informality and everyday public authority in Bangalore. *Water Alternatives* 7, 1.

Ranganathan, M. (2014b). Paying for pipes, claiming citizenship: political agency and water reforms at the urban periphery. *Int. J. Urban Reg. Res.* 38, 590–608. doi: 10.1111/1468-2427.12028

Sarkar, S. (2022). Bhumij in a heterogeneous society: negotiating hierarchies and access to water in the Jungle Mahals of West Bengal. *Indig. People Nat.* 1, 241–56. doi: 10.1016/B978-0-323-91603-5.00019-1

Shaban, A., and Sharma, R. N. (2007). Water consumption patterns in domestic households in major cities. *Econ. Polit. Weekly* 9, 2190–2197.

Sharma, M. K., Rajesh, S.ingh, Omkar, S., and Durbude, D. G. (2021). *Contamination in Drinking Water Supply: A Case Study of Shimla City, Himachal Pradesh, India. Climate Impacts on Water Resources in India*. Cham: Springer, 11–20.

Smith, L., and Susan, H. (2003). Access to water for the urban poor in Cape Town: where equity meets cost recovery. *Urban Studies* 40, 1517–1548. doi: 10.1080/0042098032000094414

Srinivasan, V., Seto, K. C., Emerson, R., and Gorelick, S. M. (2013). The impact of urbanization on water vulnerability: a coupled human–environment system approach for Chennai, India. *Global Environ. Change* 23, 229–239. doi: 10.1016/j.gloenvcha.2012.10.002

Swyngedouw, E. (1996). The city as a hybrid: On nature, society and cyborg urbanization. *Capital. Nat. Social.* 7, 65–80.

Swyngedouw, E. (1997). Power, nature, and the city. The conquest of water and the political ecology of urbanization in Guayaquil, Ecuador: 1880–1990. *Environ. Plan. A.* 29, 311–332. doi: 10.1068/a290311

Swyngedouw, E. (2004). *Social Power and the Urbanization of Water: Flows of Power*. Oxford: Oxford University Press.

Swyngedouw, E. (2006). Circulations and metabolisms:(hybrid) natures and (cyborg) cities. *Sci. Cult.* 15, 105–121. doi: 10.1080/09505430600707970

Swyngedouw, E., and Heynen, N. C. (2003). Urban political ecology, justice and the politics of scale. *Antipode.* 35, 898–918.

Wester, P., Mishra, A., Mukherji, A., and Shrestha, A. B. (2019). *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Berlin: Springer Nature.

World Health Organization. (2019). *National Systems to Support Drinking-Water: Sanitation and Hygiene: Global Status Report 2019: UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water: GLAAS 2019 Report*. Geneva: World Health Organization.

Zérah, M. H. (2000). Household strategies for coping with unreliable water supplies: the case of Delhi. *Habitat Int.* 24, 295–307. doi: 10.1016/S0197-3975(99)00045-4

frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 06 July 2023
DOI 10.3389/frwa.2023.1043628

Check for updates

OPEN ACCESS

EDITED BY
Abhiroop Chowdhury,
O. P. Jindal Global University, India

REVIEWED BY
Anjana Ekka,
Delft University of Technology, Netherlands
Aliya Naz,
O. P. Jindal Global University, India

*CORRESPONDENCE
Raktima Ghosh
✉ ghosh.rak12@gmail.com

RECEIVED 15 September 2022
ACCEPTED 02 June 2023
PUBLISHED 06 July 2023

CITATION
Ghosh R, Mukherjee J, Bandyopadhyay A, Chatterjee S, Choudry A, Ghosh P, Pathak S, Sen A and Sinha P (2023) Analyzing scenarios and designing initiatives toward just transitions: coproducing knowledge with(in) the dried fish sector in the Indian Sundarbans. *Front. Water* 5:1043628.
doi: 10.3389/frwa.2023.1043628

Analyzing scenarios and designing initiatives toward just transitions: coproducing knowledge with(in) the dried fish sector in the Indian Sundarbans

Raktima Ghosh[1]*, Jenia Mukherjee[2], Aishik Bandyopadhyay[3], Subhradeep Chatterjee[2], Anuradha Choudry[2], Poulami Ghosh[1], Souradip Pathak[1], Amrita Sen[2] and Priyadarsini Sinha[2]

[1]Rekhi Centre of Excellence for the Science of Happiness, Indian Institute of Technology Kharagpur, Kharagpur, India, [2]Department of Humanities and Social Sciences, Indian Institute of Technology Kharagpur, Kharagpur, India, [3]Department of Musicology, Rabindra Bharati University, Kolkata, India

The south-western fringe of the Indian Sundarbans hosts a number of fish drying collectives that are exposed to a bundle of mutually reinforcing social-ecological-institutional risks. Despite its wide contribution to local-regional food security and livelihoods, dried fish production has received little attention in research and policy circles so far. As part of the Social Sciences and Humanities Research Council (SSHRC) sponsored Dried Fish Matters global partnership project, our research team seeks to address this lack in two ways: (i) delineating knowledge base through a systematic literature review on intersecting social-ecological and sociohydrological dimensions of integrated fisheries and fish drying practices, and (ii) employing a knowledge co-production approach that involves participation of dry-fishers, researchers, fishworkers' forum (partner organization), and scientists for meaningful understandings about the constraints and potentials in the sector. In this essay, we applied a three-step methodology to arrive at a crisscrossing conceptual, empirical, and collective understandings on the 'invisible' dried fish value chain in the Indian Sundarbans. With detailed lessons from the field, our interdisciplinary research team acts as a liaison among the groups to build a collaborative space for interactions, recognize prevalent adaptive practices and identify pathways toward short-, intermediate-, and long-term co-interventions through which fish drying practices can be more effectively improvised upon and up scaled. The essay lays out detailed insights and sensible recommendations from the knowledge co-production workshop, organized as a part of solution-focused participatory research on climate-resilient and gender-aware dried fish practices in the Indian Sundarbans. In light of the collective observations on the complex problems and reflections on needs-driven initiatives, the authors advocate for collaborative research praxes in forging just transitions for the less explored dried fish sector.

KEYWORDS

dried fish, knowledge co-production, social-ecological systems, sustainability, sociohydrology, participatory

1. Introduction

A sizeable share of marine captured fish is preserved through various fish processing techniques that include drying, salting, smoking, and fermenting—collectively known as dried fish—which is an important source of food and livelihood for a large segment of the population in South and Southeast Asia. Notably, India's total contribution to processed products including dried and unsalted fish is 2.64 lakh[1] tons, whereas West Bengal state produces 0.04 lakh tons of processed fish, placing it sixth-highest in production after Gujarat, Kerala, Maharashtra, Telangana, and Karnataka (Handbook on Fisheries Statistics, 2020). Despite its unparalleled social, cultural, nutritional, and economic significance which is strongly manifested in the involvement of people in fish production, circulation, and consumption pattern, the dried fish sector has gained disproportionately scant attention in academic fora and remained invisible in policy debates so far. The social and ecological changes experienced by the dried fish value chain that extends from marine habitat to dried fish organizations, to market and finally to consumers, coincide with the magnifying challenges of small-scale fisheries (SSF), yet the former has generated only narrower understandings about its scale, importance, threats and potentialities across research and an official dossier on a sharp contrary to the SSF. While there is a growing scholarship on food safety, nutrition, and preservation technologies associated with dried fish, a wide gap remains in locating the elements of complexity in dried fish resource systems through integrating critical, analytical frames of interdisciplinary research such as social-ecological linkages, institutional dynamics, and governance. Threatened by a host of factors including fish stock reduction, frequent cyclones, land-water pollution, social inequities, and top-down governance methods—explicitly characterizing the combined footprints of political economy and Anthropocene—dried fish today requires more collaborative research approaches that effectively address the sustainability of the sector.

In recent decades, an emerging body of transdisciplinary research along with a cluster of approaches linking action research and sustainability research, have signaled the relevance of knowledge co-production and sound collaboration among different groups of actors (researchers, community, practitioners, government organizations, civil groups), probing into various social and ecological issues at local contexts (Stange, 2017; Norström et al., 2020; Carter et al., 2022). Compared to mainstream research ideologies which tend to perceive solutions either through sacrosanct scientific modeling or theoretical projections confined within specific research groups connecting loosely with messy societal upheavals, everyday lived experiences and community ethos, knowledge co-production engages multiple disciplines, perspectives and insights for a long-term inquiry into the processes, activities, values, needs, and interests of communities over a collaborative platform that reflects upon the sustained pathways and practices for solutions.

This essay responds to the significant research gap in dried fish by contributing to the understanding of social-ecological systems (SES) in coastal fish production and highlighting the urgent menaces faced by this otherwise unsung social economy. Within the expanding realms of sociohydrology (SH) that throws light on water-society-policy interfaces for inclusive management of human-water systems (Sivapalan et al., 2012, 2014), the study advances the theoretical dialogues through coupling sociohydrological perspectives with practical nuances of the fisheries resource system. Drawing evidence from the dried fish organizations in the Indian Sundarbans, the essay explores how risk-prone ecologies shape the socioeconomic vulnerabilities and institutional contexts of dried fish. The Indian Sundarbans have been the focal area of the study because of three reasons: firstly, a great deal of coastal communities is reliant upon artisanal fishing and fish production for subsistence, making it a globally salient fish production region; secondly, the biodiversity-rich deltaic landscape who has observed the interplay of multiple legal cultures since historical times, is exposed to "disruptive risks" in the face of changing marine and deltaic environments, and thirdly, the exclusionary governance crafted within the logics of strategic self-financing methods has apparently limited the performance potentials of the fisheries economy in the Sundarbans.

Informed by our conceptual-empirical findings and with a deeper realization of the complexity emanating from changing economics and long-standing social-ecological risks to fish production, our research team employs a knowledge co-production approach as part of long-term, responsible practices for solutions. In line with facilitating a "deliberate collaboration between different people to achieve common goals" (Lemos and Morehouse, 2005; Norström et al., 2020), knowledge co-production in dried fish attempts to address health and wellbeing of fishers within an improved fish drying environment and infrastructure, forged by locally tailored initiatives. Acknowledging that this inclusive approach produces "more than just knowledge" rather they foster mutual trust, build networks, create conversations, and unveil possibilities (Wyborn and Bixler, 2013; Norström et al., 2020), a multi-stakeholder workshop was conducted with the participation of various academic and non-academic actors—collaboratively laying out solution-focused pathways for dried fish practices.

The next two sections describe the field sites and the three-step methodology applied in the present study. In the fourth section, we review the selected literature on SES and SH to situate fisheries and dried fish on their interlacing conceptual fabrics with examples from South and Southeast Asia. This is followed by a SWOT (Strength, Weakness, Opportunity, and Threat) matrix which enlists the SWOT factors, derived from the literature. We then explore fish processing activities and trade along the value chain and simultaneously, trace out social dynamics for dried fish production with regard to relationships, institutional norms, and inequities. The sixth section locates key sustainability challenges and livelihood issues within the dried fish value chain and delineates short-, intermediate- and long-term experimental roadmaps for solution-focused practices, an outcome of knowledge co-production with multi-stakeholder participation. On this front, the study implies how knowledge co-production to pin down areas seeking interventions, makes a novel entry in transdisciplinary research through its potential contributions to dried fish scholarship, policy, and practices.

1 1 lakh is equivalent to 100,000.

2. Familiarizing the field

An island archipelago with an impressive digitate configuration that hosts the world's largest mangrove forest, the Indian Sundarbans (21°30′-22°30′N and 89°-90°E) lies at the southernmost frontier of the Ganga delta in the state of West Bengal, eastern India. The Sundarbans Biosphere Reserve (SBR), as the Sundarbans is officially known in India, has assumed global attention due to its wide and exotic ensemble of biodiversity, wildlife, and marine resources. The eminence of the Royal Bengal Tiger coupled with several other wildlife species, mangrove species, and aquatic resources have acquired the region the status of a "reserved forest" since 1878. However, in recent years, climate emergencies and ecological crises have taken center stage and attracted scientists and large organizations from around the world to this conservation hotspot.

The region constitutes 48 forested and 54 inhabited islands which are connected and disconnected by a maze of rivulets, estuaries, and narrow creeks. In this shifting terrain, tidal waves reach up to three hundred kilometers inland with an average amplitude of 3.5–5 meters to dissolve the boundaries between land and sea, silt and water, people and forest. The relatively unstable, alluvial surface which mostly characterizes the "low' islands of the Sundarbans, still see the processes of being formed, fretted, and reformed through the agential functioning of tides, waves, and silts. The region's climate is characterized by high relative humidity between 70 and 88%, whereas June and January experience average temperatures of 34 and 11°C, respectively. Even though the Sundarbans experiences about 80% of annual precipitation occurring mainly during monsoon months (July–September), occasional showers prevail almost all through the year (Danda et al., 2011). Girdled by dense mangrove forest, the eastern islands are refined swampy beds whereas the western part of SBR encompassing Frasergunj, Sagardwip, Jambudwip, and Mousuni island-villages observe powerful wave actions along the extensive sandy "chars"[2] (Nishat, 2019). The distal edge of this immense archipelago, these islands are distinctly exposed to climate change impacts in the forms of cyclonic hazards, coastal erosion, soil loss, embankment failure, and flooding.

While the inhabitants of easterly islands have adopted forest-based fishing, inland freshwater aquaculture, honey, and beeswax collection as predominant livelihood options (Chacraverti, 2014), dried fish production and small-scale marine fishing are prevalent in the western part of SBR. In the Sundarbans, the networked roots of mangroves on the clayey substrate, play a pivotal role in nutrifying water and harnessing the food web with invertebrates toward acting as nursery grounds for nearly 90% of the important commercial aquatic species including fish in the entire eastern coast of India (Chandra and Sagar, 2003). After agriculture, fisheries activities have been the most common and staple livelihood options for over 4.4 million people of the Sundarbans (Danda et al., 2011; Chacraverti, 2014). The rich biophysical world endowed with sandy shorelines and waterborne *chars*, has outfit grounds for fish drying practices which involve groups of people including small-scale marine fishers, fish producers, daily-wage workers, and traders. To date, the south-western fringe of the Sundarbans harbors four dried fish production sites including Frasergunj-Bakkhali, Sagardwip, Kakdwip,[3] and Kalistan in between the mouths of the river Hugli and Harinbhanga. Each of these sites constitutes clusters of large- and small-sized dried fish camps, locally known as *shabar* (large- and medium-scale camp) and *khoti* (small-scale camp). Our study specifically focuses on three "transient" dried fish clusters in Frasergunj village, namely Lalgunj, Lakshmipur, and Baliara (see Figure 1), encompassing a large number of *shabar* and *khoti* which are separated by flexible boundaries[4] (see Table 1).

3. Methodology

The Dried Fish Matters global partnership project (www.driedfishmatters.org) is designed to bring together a diverse group of researchers and practitioners to produce landmark regional comprehension about the dried fish economy in South and Southeast Asia. As a part of the interdisciplinary team in this project, we navigated the repository of existing literature, became familiar with heterogeneous findings from case studies, delineated thematic areas for the research, and finally, incorporated these details into our core area of analysis. Over the span of 2021–2022, we carried out field surveys, collected secondary data, conducted interviews, and organized multi-stakeholder workshops to cultivate a synergistic space for interactions among different groups related, in a variety of ways, to the dried fish sector. Besides, our interdisciplinary team composition with expertise in environmental history, political ecology, human rights, cultural studies, and physical geography enabled us to capture the nuances in economic, institutional, and environmental flows shaping dried fish production and practices at the Indian Sundarbans.

We followed a three-step methodology in this research: (i) systematic literature review: fine-grained analysis of SES literature on small-scale fishing and dried fish in South Asia, facilitating a SWOT (Strength-Weakness-Opportunity-Threat) assessment for the integrated fisheries and dried fish sector, (ii) field-based ethnography: using ethnographic tools (participant observation, KIIs, focus group discussions, and focused interviews) to weigh the emerging threats, get acquainted with the people and their practices, and realize the potentials for partnerships in the field, and (iii) forge discussion on solution-oriented pathways: first-hand, participatory mapping of areas seeking solutions through multi-stakeholder engagement, knowledge co-production and practicable co-interventions (Figure 2).

In the first phase, a systematic literature survey was conducted to create a knowledge base providing theoretical guidance as well as case-specific evidence related to SES and SH dimensions of fisheries in South Asia. Four sequential steps were followed:

2 River-dominated or wave-dominated islands in making.

3 The Bengali, the word "dwip" denotes to islands. Hence, "Sagardwip" is also called Sagar Island.

4 The dried fish units remain operational during the four months of winter when fishers, fish processers and fish sorters from neighboring villages assemble and temporarily stay there. Hence, they are referred to as "transient" clusters. The camps are separated by thin bamboo fences; communication and exchanges take place among the processors of the camps. The camp arrangements and functions are discussed in Section 5.

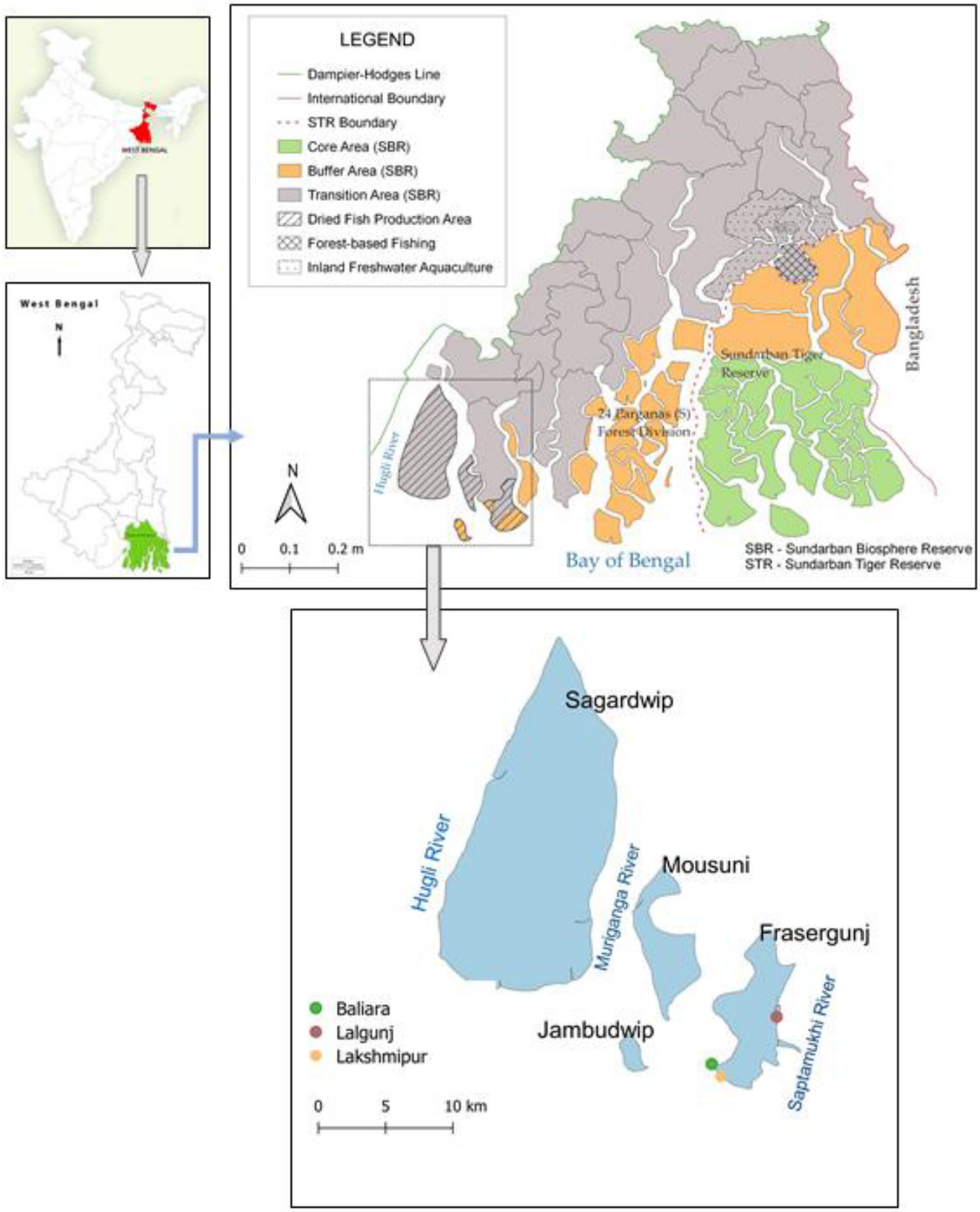


FIGURE 1
The study area and fish processing centers in Frasergunj, Indian Sundarbans. Source: Author (Ghosh).

(i) application of key words and phrases as search criteria (Table 2) to derive both academic and gray literature from Google search, Web of Science and Academia database, (ii) consulting Zotero open-source e-library of the DFM project (https://www.zotero.org/groups/2778295/dfm-v2v_west_bengal/library) to draw out publications based on seven thematic tags—social relations, ecology, governance, gender, labor, culture and value chain, (iii) sieving duplicate files, (iv) preliminary scanning of abstracts and inclusion of SES and SH literature based on methodological approaches, theoretical intersections, research findings and geographies, and (v) full-text scanning and review of the literature (Figure 3). Iterative search and subsequent filtering, finally, yielded 115 publications. Through multiple rounds of scanning, examination, and synthesis of the insights from the literature, we mapped social and ecological dynamics in the institutional context of the fisheries resource system. Because fish processing is understood as a subset of the small-scale fisheries, there are some common concerns between the two, such as livelihood struggles, political influences, and ecological damages.

Through this first step of the three-step methodology, we—(i) learned about case study specificities pertaining to practices, relationships, challenges, and conflicts; (ii) theoretically comprehended institutional linkages, feedback mechanisms, sociohydrological aspects, and gendered roles with regard to transdisciplinary intersections (stakeholder involvements, management participation, social inclusion, decision making), (iii) became acquainted with the historical backdrop, belief systems, and deltaic architecture of the study site; (iv) highlighted uncertainties, perilous threats, and opportunities as a comprehensive SWOT analysis, and (v) crafted survey designs and set questions for the interviews. With this prior vision and awareness, we embarked into the field.

Fieldwork took place in November 2021 and March 2022 at the Indian Sundarbans and Sheoraphuli (Hugli) dried fish markets, respectively. Surveys were conducted at Baliara, Lalgunj, and Lakshmipur dried fish sites in Frasergunj village by our team of eight researchers, accompanied by a representative of our partner Dakshinbanga Matsyajibi Forum (DMF), a small-scale fishworkers' forum established in the early 1990s (Table 3). As participant observers, culturally and linguistically connected to the stakeholders in the field, we initiated friendly conversations with female daily-wage dry-fishers, male contractual laborers, fishers, and young girls who are involved in fish drying activities in the *shabar* and *khoti*. Our long, colloquial exchanges at the first meeting, created a congenial atmosphere which is crucial for deepening the bonds between communities and participant researchers. We probed into focus group discussions (FGDs) in which each targeted question was asked to individuals in a specific group to carve out diverse perceptions of their everyday affairs inside and outside of the dried fish camps. Five FGDs (60–75 min each) were arranged with *shabar* owners, women *hajira* workers, and fish processors of a household; the reflections were audio- and video-recorded. The FGDs took place at the camp compound, at a local club room, at the shacks in *shabar,* or at the shop of the dry-fisher family, depending on the convenience of the respondents. All respondents provided prior verbal informed consent. The *shabar*

TABLE 1 Approximate total numbers of *shabar* and *khoti* in the fish processing clusters of Frasergunj.

Fish processing clusters	Number of *shabar*	Number of *khoti*
Lalgunj	13	20
Baliara	15	50
Lakshmipur	Nil	30

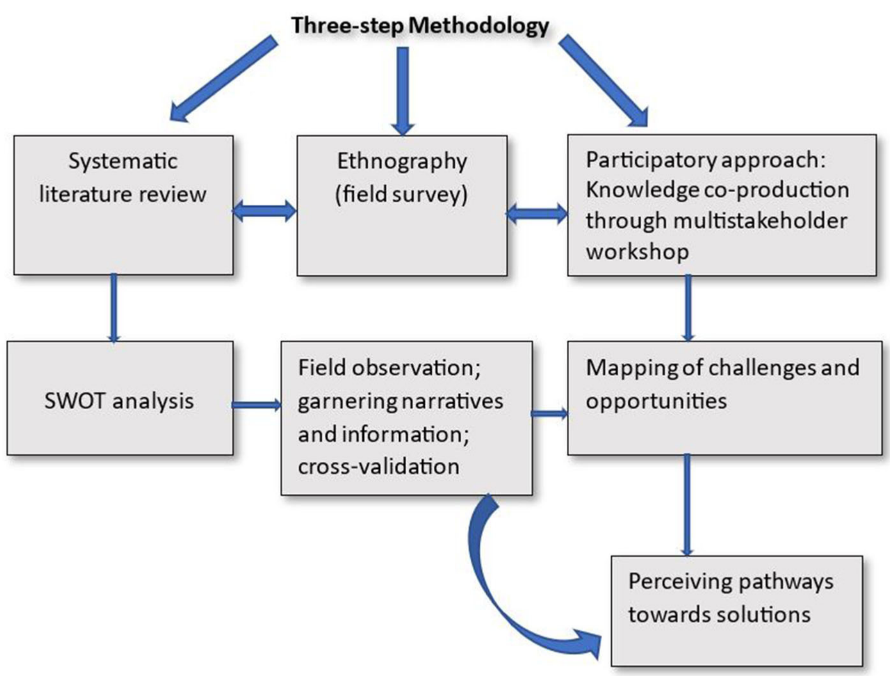


FIGURE 2
The three-step methodology.

TABLE 2 Key terms, phrases, and Zotero tags used for searching the literature.

Review component	Search terms	Search phrases	Zotero tags
SES	Institution, adaptive	Ecological change, resource system, ecological knowledge	Social relations, ecology, governance, gender, labor, culture, and wellbeing
SH	Governance, management	Water-society relations, coastal flooding, water pollution, food production	
Fish/Fishery	economy, organization	Fish processing, dried fish, small-scale fishing, small-scale marine fishing, artisanal fishery, value chain	

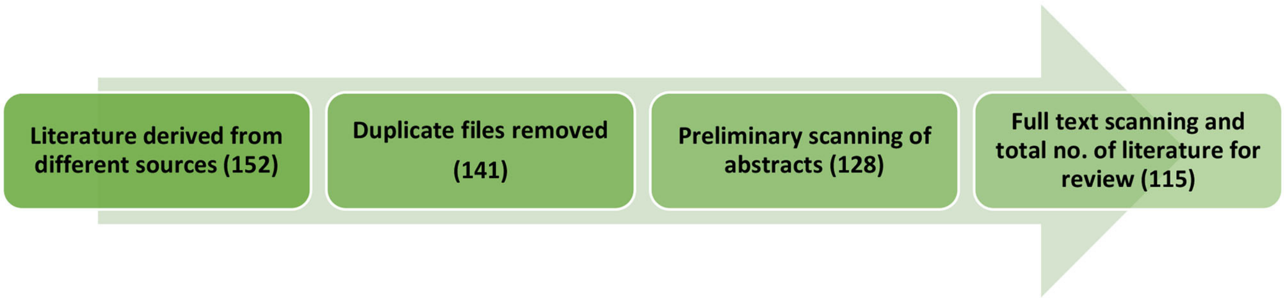


FIGURE 3
Steps followed in the literature selection process.

owners were accompanied by members of the *shabar* committee and the DMF representative whereas *hajira* dry-fishers comprised women from various age-groups ranging between 25 and 60. Each group was formed of 8–10 participants who, in a spontaneous spirit, voiced disquietude, negotiations, and struggles with their lifeways and livelihoods that, seemingly, revolve around these makeshift organizations for four winter months. They reflected on how a multitude of socio-ecological risks are pouring into the dried fish practices and how they are replying to these threats. The FGDs were followed by ten focused interviews of experienced value chain actors including a fisher, a moneylender, a woman dry-fisher, a *khoti* owner, and a local wholesaler, who were asked open-ended questions in a quiet, private setting conducive to contemplating the questions and answers. An alternative to the standardized interview, focused interviews (Merton, 2008) are a form of semi-structured interview which is based upon broad themes chosen in advance, rather than using pre-settled questions (Bailey, 2008). The interviews unwrapped the observed facts, personal accounts, tussles, or consequences of a situation to which the actors are attached. Written notes were maintained throughout the discussions and interviews. Five key informant interviews (KIIs) were conducted with the former president of DMF, a representative of DMF, a principal scientist of CIFRI,[5] a female representative of the local Self-Help Group, and the Associate Director of Fishers (Government of West Bengal), to procure their insights that have been accrued through their distinctive areas of associations. In addition, five semi-structured interviews of the wholesalers were conducted during a survey at Sheoraphuli market, one of the focal dried fish wholesale markets in Bengal. Along the antique alleys of the once-French dominion of Sheoraphuli, we strolled and visited single-room shops of the local wholesalers who either buy dried fish directly from *shabar* owners or restore stocks through an intermediary wholesaler (or moneylender).

For the May 2022 workshop in Kakdwip village, we designed a knowledge co-production template to obtain individual-integrated perspectives on dried fish production in Bengal. The template facilitated cross-learning possibilities among groups (academia, users, NGO) and embraced a plurality of perspectives on risks and opportunities. Trust-building among the groups created an *in-situ* momentum for surpassing the divides between knowledge forms (local, academic, scientific, and practice-oriented) and for thinking about solutions from both individual and sectoral perspectives. By acknowledging the cultural values, concerns, and ideas brought by the stakeholders, the workshop ensured inclusivity in diverse forms of exchanges (Figure 4). The 7-h workshop consisted of two broad sessions and four interconnected sub-sessions, involving 40 participants from different corners of South 24 Parganas and Kolkata. The sub-sessions typically lasted for between 60 and 120 min. Through the literature review, field insights, and improvising on participatory systems mapping (Barbrook-Johnson and Penn, 2021), we outlined thrust areas and adjoining 'lead questions' that guided the facilitator researcher for the sub-session on "close interaction". This sub-session gleaned different views from the same phenomenon from the participants of a group, guaranteeing the richness of the information. Four tables were designated to the stakeholder groups: marine fishers, camp owners (including a DMF representative), women *hajira* workers (including a woman representative of the Self-Help group), and traders. It was followed by an informal conversation in which dried fish actors had open

5 CIFRI stands for Central Inland Fisheries Research Institute.

10.3389/frwa.2023.1043628

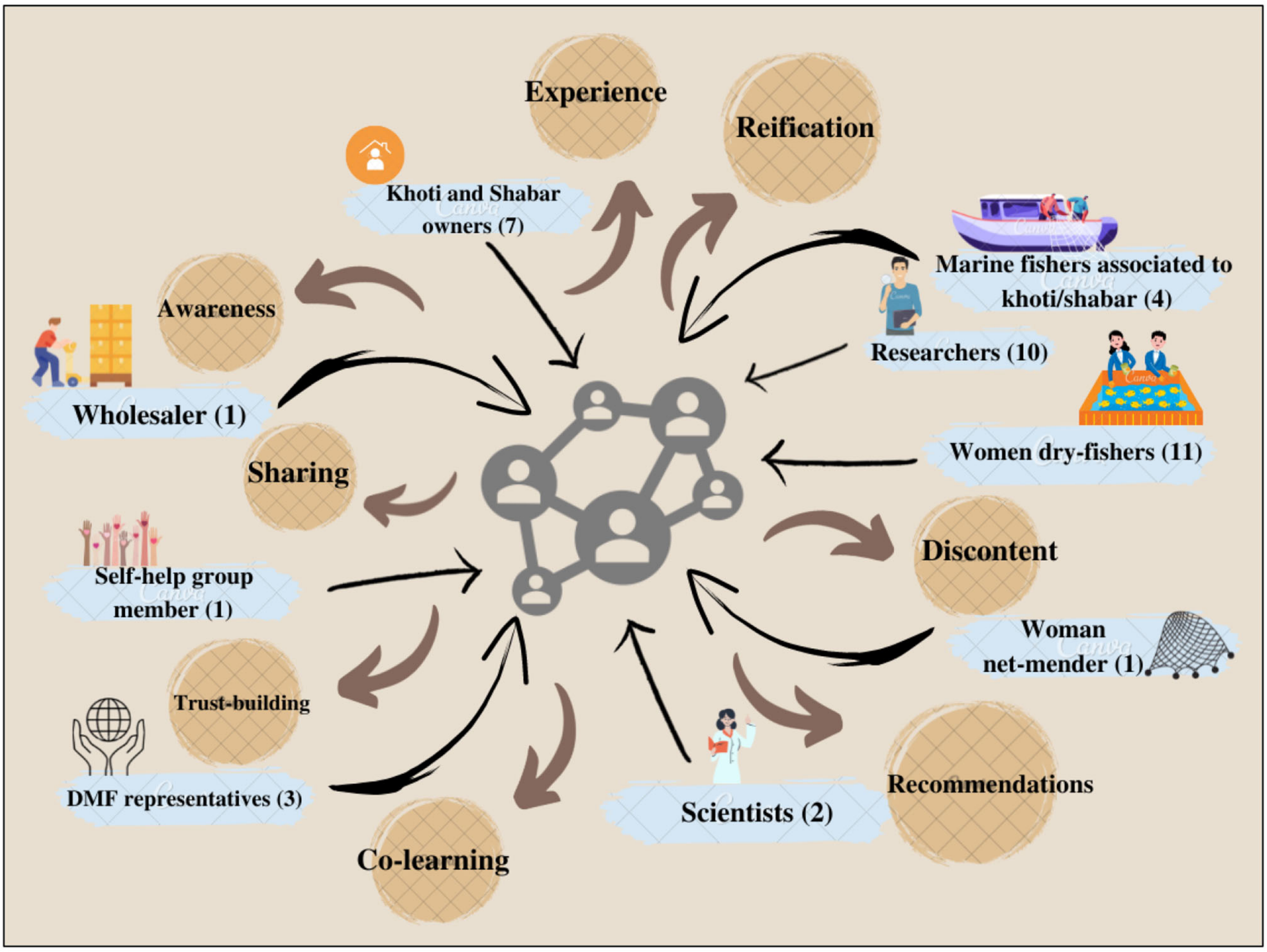


FIGURE 4
Knowledge co-production through dynamic exchanges among multiple stakeholders. Source: Author (Bandyopadhyay).

question-answer rounds with the scientists from Central and State Government institutions. While some researchers took charge of facilitating interactions during sub-sessions, some provided additional participant observation to record varying expressions (excitement, anxiety, anger, joy) of individuals during the sessions. The narratives were transcribed from discussions and sorted thematically to carve out diversity, linkages, and patterns in findings.

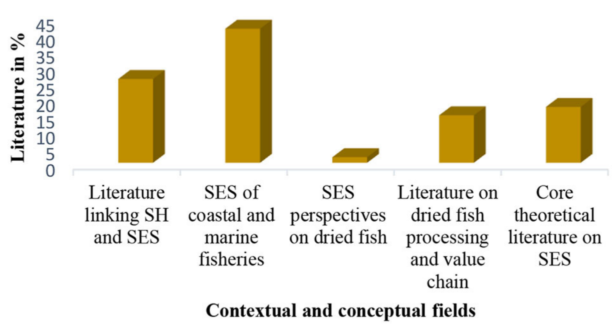


FIGURE 5
Percentage of literature accessed under relevant contextual and conceptual fields.

4. Systematic literature review

A total of 115 pieces of literature were reviewed, of which 68 deal with core and aligned theoretical aspects of SES, 17 relate to dried fish processing and value chains, and the remainder integrate sociohydrology (SH) with SES. Forty-six articles on fisheries appeared among the 68 pieces of SES literature (Figure 5). The bulk of the literature in our sample is geographically oriented to South Asia spanning Bangladesh, India, Sri Lanka, Nepal, while few others focus especially on small-scale fisheries in Cambodia, Vietnam, Thailand, Chile, Mexico, Sweden, Canada, South Africa, Australia, the Solomon Islands, and Tuvalu. While there is a dearth of research exploring SES scenarios in South Asian fisheries, it is even striking to note that only two of the studies provided a SES lens to dried fish. A systematic literature review performed earlier with dried fish literature in hand, submits that dried fish has been viewed from a diverse

TABLE 3 Overview of the places visited, and methods deployed for the survey.

Frasergunj fieldwork			Sheraphuli market survey	
Fish processing sites visited	Methods (Numeric in bracket indicate the number of times conducted)	Stakeholders consulted	Methods	Stakeholders consulted
Baliara	Participant observation, FGD (3), focused interviews (8)	*Shabar* owner, women *hajira* dry-fisher, contractual worker, moneylender, marine fisher, wholesaler, net mender	Focused interviews (6)	Wholesaler and a small trader
Lalgunj	Participant observation, FGD (3), focused interviews (7)	Shabar owner, women *hajira* dry-fisher, member of *shabar* committee, member of local Self-Help Group		
Lakshmipur	Participant observation, FGD (2), focused interviews (4)	Independent wholesaler, member of a local Self-Help Group		

thematic arena including governance, gender, wellbeing, value chain, ecological change, and sustainability, which, according to their immanent conceptual ideals, cannot be studied separately from the assumptions of SES (Ghosh et al., 2022). However, these studies did not follow the fundamental conceptual arguments of SES. Here, a wide range of standard SES literature with core and crisscrossing conceptual frames has been considered for gauging the breadth of SES literature and recognizing feedback that operates at three interlinked institutions including social, market, and governance in coastal fisheries and dried fish. On the other hand, 30 publications were derived from a pool of scholarly works on sociohydrology (SH) whose expanding horizon has entailed SES elements to underscore nested theoretical and applied lenses on human-water systems, flood-risk management, seafood production, adaptive capacities, and ecosystem services. Out of the total SH articles in our sample, seven articles used instances from marine fishing practices.

4.1. Institutional linkages and feedback: *using the SES lens*

SES framework acknowledges the variants of ecosystems, the multiplicity of internal and external drivers, patterns of interactions, and institutional linkages shaping the complex, co-constitutive nature of tightly coupled social and ecological systems (Holling, 1973, 1992; Garcia and Charles, 2008; Rogers et al., 2013; Preiser et al., 2018). At the crux of SES, there are multiple actors, multiple species, and materials—maintaining the properties and behavior of the system through their interactions and change over time (Glaser et al., 2012; Binder et al., 2013; Preiser et al., 2018; Preiser, 2019). Several empirical works in our repository indicate that the framework, as a general tool, is suited to examining the diverse shades of sustainability and adaptive responses in a complex social-ecological landscape that cannot be studied by simplistic, universalized, or deterministic ideas of politics, environment, and culture (Ostrom et al., 1994; Ostrom, 2007; Basurto et al., 2013; McGinnis and Ostrom, 2014; Fischer et al., 2015; Marshall, 2015; Partelow, 2018; Stephenson et al., 2018). Built on the assumption that social actors and ecological resources are co-dependent, SES motifs capture the dynamic interplay between social and ecological processes with an eye to the feedback mechanisms through which they are interlinked (Levin, 1998; Turner et al., 2003; Janssen and Anderies, 2007; Crona et al., 2010; Cinner and Barnes, 2019; Pradhan et al., 2022).

Dried fish production is a coastal resource system in which fish processing integrates marine fishing and land-based practices; a swarm of Bombay Duck (*Harpadon nehereus*) and other fish species form resource units; fishers and fish producers are resource users; and the governance exercises policies and regulations to set legal conditions (Agrawal, 2003; Anderies et al., 2004; Pramanik, 2004; Liu et al., 2007; Ostrom, 2009; Korlagama et al., 2021; Lu et al., 2021; Belton et al., 2022; Ghosh et al., 2022; Hossain et al., 2022). Ostrom (2009, 2011) states that these subsystems can be further defined by some variables (for example, size of the resource system, mobility of resource unit, level of governance, users' values and knowledge, nature's laws) which interact and co-act to produce a variety of responses and outcomes (also see Ostrom, 2005; Leslie and McCabe, 2013). Inside the intersecting physical and normative boundaries (Crona et al., 2015; Pradhan et al., 2022), the dried fish system is visibly contoured by resource sharing (groups of fishing communities converge on one fishing site or same species stock), economic substitutability (coastal and marine fishing as an alternative to fish processing during non-winter seasons), social connectivity (communication, coordination, mediation, negotiation among value chain actors), social-ecological links (access to the processing site, fishing ground, and market) (Shamsuddoha, 2007; Bodin and Crona, 2009; Bodin and Tengö, 2012; Hasan et al., 2016; Shyam et al., 2016; Society for Direct Initiative for Social Health Action, 2016a,b). Given the complex set of mutual links and bundles of interacting processes, whatever socio-economic, and legal drivers effect the fishing activities of communities, by extension, also effect marine ecosystems with which they interdependently interact (Charles, 1998; Ommer et al., 2012; Boonstra, 2016; Arthur et al., 2022).

Most of the case studies in our sample that pivot on coastal fishery and dried fish reported declining catch levels per household or organization, making it difficult to source raw materials for fish processing (Funge-Smith et al., 2005; Dey, 2008; Kehoe, 2011; Hossain et al., 2015; Nadanasabesan, 2015; Lokuge, 2021; Bandyopadhyay et al., 2022; Ghosh et al., 2022). Additionally, extreme weather events including cyclones, capricious rainfall, flood proneness, and water pollution have made for disruptive repercussions on the fisheries sector of maritime countries like

Cambodia, Sri Lanka, India, and Bangladesh (Kunwar and Adhikari, 2016; Galappaththi et al., 2020; Islam et al., 2020; Berenji et al., 2021). Peke (2013) research on Versova and Arnala areas of Maharashtra (India) unpacked how pollution, inadequate water supply, and a premium on coastal zones have pressured women fish processors. Simultaneously, Nayak (2014) presented that the Chilika lagoon on which the artisanal fishers are dependent for their economic and cultural needs showed signs of stress with the commencement of commercial aquaculture activities inducing fluctuation in biophysical processes and alterations of food webs (Nayak and Armitage, 2018). Further, dominant state policies often tend to marginalize social values in fisheries, as sharply reflected by policy incoherence and top-down management measures in various local contexts in India, Bangladesh, and Sri Lanka (Bhatta et al., 2003; Lebel et al., 2006; Shamsuddoha, 2007; Kumar and Mohanta, 2014; Hasan et al., 2016; Shyam et al., 2016; Jeyanthi et al., 2018; Johnson et al., 2018; Islam et al., 2020; Korlagama et al., 2021). Anyhow, institutional practices bear out this narrative of decline.

Everyday practices and social-ecological dynamics of the dried fish sector, are shaped by feedback mechanisms within the core components of three institutions: social (norms, beliefs, conventions), market (network, regulations), and governance (legislations, policies, agencies) (Acheson, 2006; De la Torre-Castro and Lindström, 2009; Crona et al., 2015) (Table 4). Acheson (2006) argues that the global crisis of fisheries resource degradation and sustainability challenges denotes a deep institutional failure. The result is of acute importance in poorer countries of the global South where coastal populations are heavily dependent upon marine resources for livelihoods (Kotchen and Young, 2007; Dey, 2008; Fabinyi et al., 2014). Identifying institutional logics within diverse organizational forms, agencies, and capacities is vital to obtain an accurate understanding of the intricacies of social-ecological changes, vulnerabilities, and management systems of coastal fishery (Westley et al., 2013; Hossain et al., 2015; Moshy et al., 2015; Hoque et al., 2017; Cole et al., 2018). For example, dried fish production is often tied to informal credit systems in which producers establish a connection to markets through a moneylender who provides credit as a means of securing priority access to product (Ghosh et al., 2022). Such unwritten credit sources seem to be attractive to producers in the face of uncertainties in production output and poor availability of financial support from the government. However, it stimulates the entry of new fishers resulting in overfishing. Moreover, it lowers selling prices for the entire stock, and restricts fishers' direct access to the market (Crona et al., 2010, 2015). In fact, the primacy of this credit system is indicative of how the government support (both central and state) has been distanced through projecting the sector as self-sustaining and thus beyond their responsibilities.

Drawing on their empirical studies in South Africa, Herrfahrdt-Pähle and Pahl-Wostl (2012) maintain that institutional resilience is contingent on institutional continuity and change—how they interact, build, or degrade upon institutional processes during crisis situations. In that vein, institutional continuity refers to preserving key institutional contexts in which rules are made in keeping with social memory and relationships, providing transparency to reform processes, etc. (Tidball et al., 2010; Nykvist and Von Heland, 2014). Institutional changes, however, factor in flexible legislation, adaptation after implementation of regulations, regular reviews, etc. Berkes and Folke (1998) underlined trust-building; monitoring environmental feedback; funds for responding to environmental change and remedial actions; a combination of various sources of information and knowledge; sensemaking and collaborative learning as essential features for adaptive, collaborative management of social-ecological systems (Adger, 2000; Olsson, 2003; Olsson et al., 2004; Folke et al., 2005; Andrew et al., 2007; Biggs et al., 2015; Jahan et al., 2017; Whitney et al., 2017; Ward, 2018).

4.2. At the interface of SES and SH: advancing discussions on human-water systems for coastal food production and livelihoods

Growing imperatives to understand the changing patterns of SES have coincided with the emergent trajectories of the SH field (Sivapalan, 2006; Sivapalan et al., 2012, 2014; Pande and Sivapalan, 2017; Konar et al., 2019) which sheds light on how marine water pollution and altered hydrological dynamics in coastal and riverine landscapes have adversely affected food production, ecosystem services, and human health (Sivapalan et al., 2012; Oki, 2016; Yu et al., 2017, 2020; Penny and Goddard, 2018) (Figure 6). Elshafei et al. (2014a; 2014b also see Van Emmerik et al., 2014; Troy et al., 2015; Gunderson et al., 2017) hint at a lack of understanding on how socioeconomic processes are influenced by feedback between human activities and water systems at catchment scales (Schaefli et al., 2011). However, Roobavannan et al. (2018) urge for linking socioecological attributes comprising institutional norms, ecological worldview, social values, and adaptive capacities in the ambit of place-based SH studies for reducing the threat with environmental decision-making (Wescoat, 2013; Yu et al., 2017) (Figure 6). Such ideas may be related to the ongoing debates around Marine Protected Area (MPA) decision-making that often overlooks social contours while implementing MPAs into local ecologies. Penny and Goddard (2018) presented a generic framework combining a range of macro-level contextual parameters from the larger sets of "community sensitivity" (perceived level of threat to a community's quality of life) and "behavioral response". Haeffner et al. (2021) outline a lens of "representation justice" which keeps in view the participation of marginalized and minoritized stakeholders in the decision-making processes for the water sector. They explained how power, gender, and policy aspects can feed into the understanding and application of current SH framings and advocated for meaningful inclusion of diverse social groups, perspectives, and knowledge in the water governance agenda. Kumar et al. (2020 see also Van Emmerik et al., 2014; Mostert, 2018; Sung et al., 2018; Yu et al., 2020) acknowledged that the cumulative impacts of major factors like extreme weather events, flooding, anthropogenic contamination of water, and drinking water issues strike hard the Sundarbans delta-front in both India and Bangladesh where the factors of vulnerability settles in water resources. Exemplifying newly established local institutions based on community organizations for floodplain management in Bangladesh, Sultana and Thompson (2010) recommended more democratic and participatory guidelines that internalize the

TABLE 4 Feedback generating institutional components in fisheries.

Institutions	Components	Feedback/likely effects
Social	• Identity	- Differentiation among social groups and their engagements in fishing based on caste, gender, migration status - Chequered relationships and inequalities determine access to and exclusion from resources
	• Heterogenous involvements	- Some people with access to resources and capital perform managerial activities, seek profits whereas others are concerned with ensuring subsistence
	• Patrilineal taboos	- While financial, ownership, managerial activities are male-dominated, women perform nodal activities in value chain alongside household chores
Market	• Moneylender's existence	- Stimulates continuous entry of new fishers leading to overfishing and plays into social dynamics (values, relations, conflicts) - Fishers are bound to sell the produce at a lower price than the open market - By channelizing different market demands fishing pressure is exerted over seasons and extraction of specific species is targeted - Fishers receive financial support although they are forever indebted with minimum scopes to explore direct trade provisions
	• Globalized export	- Facilitates the functioning of (external) mobile agents looking for an access to local stocks for exploitation - Triggers profit maximization tendencies of middlemen, resulting in typical wage disparities
	• Increased competition	- Cutting down total production expenses that influence wage distribution; product quality is sacrificed in an effort to boost revenues; moral shifts
Governance	• Credit provisions and subsidies	- Poor credit and insurance disbursement system gives rise to informal agreements with local moneylender, an attractive insurance option for producers
	• Relations of power	- Differences in assets and income defining hierarchies and inter- and intra-community power relations create the narrative of contestation, marginalization and exploitation
	• Multiple agencies	- Regulations and interests of many governmental agencies and parastatal bodies converge to often initiate conflicts

reciprocal water, land, and fishery management in flood-prone coastal plains (Oshun et al., 2021; Thaler, 2021; Luu et al., 2022). In their research concentrating on the floodplains of Bangladesh, Di Baldassarre et al. (2015) developed an application-based SH approach, which noted two aspects i.e., adaptation and levee effects (embankment engineering) arising from the interplay of physical and social factors (Di Baldassarre et al., 2013). They observed the crucial role of the former in achieving trade-offs between local economy and flood-risk management through adaptive techniques for fisheries, housing, and agriculture. In a postscript to this article, Gober and Wheater (2015) added the knowledge exchange component into the application insights and called for the dissemination of these outcomes to the floodplain "managers" (also see Loucks, 2015).

4.3. SWOT assessment

The following SWOT matrix (Figure 7) collates crucial strengths, weaknesses, opportunities, and threat factors from the case studies and conceptual interface. For instance, fish spawning grounds are threatened by water pollution and increasing turbidity as a result of microplastic contamination and upstream barrage construction, marking a sociohydrological influence in fisheries. Moreover, the matrix signals the relative influences among SWOT factors, which can often be hard to discern with discrete readings. The mien of fisheries warns that the actors' responses to different circumstances may change the implications of SWOT factors to a considerable extent. If this is so, a strength may also be a weakness, whereas a weakness can indicate opportunities. In the absence of timely recognition and management, an opportunity can mutate into a risk. For example, livelihood diversification (see in "opportunities") results in long-term livelihood sustainability and lessens pressures in the sea, but also erodes cultural values and knowledge (see in "threats") attached to an age-old practice such as fishing.

5. Actors, actions, enactments—ground(ed) narratives

Fish processing entails elaborate arrangements with labor, equipment, and coastal land for drying throughout the winter season (November to February). It is conducted in three types of organizations situated along the shoreline: (i) medium- and large-scale fish drying unit or *shabar* (7–10 and 15–20 *kathas*,[6] respectively), run by a relatively well-off fisher, locally called *bahardar,* who owns both motorized non-mechanical (2-cylinder) and mechanical (4-cylinder and 6-cylinder) fishing boats, (ii) small camp or *khoti* (5–7 *kathas*) run by household members having 2–3 2-cylinder fishing boats and often, a 4-cylinder boat, and

6 1 *katha* is equivalent to 0.0165 acre.

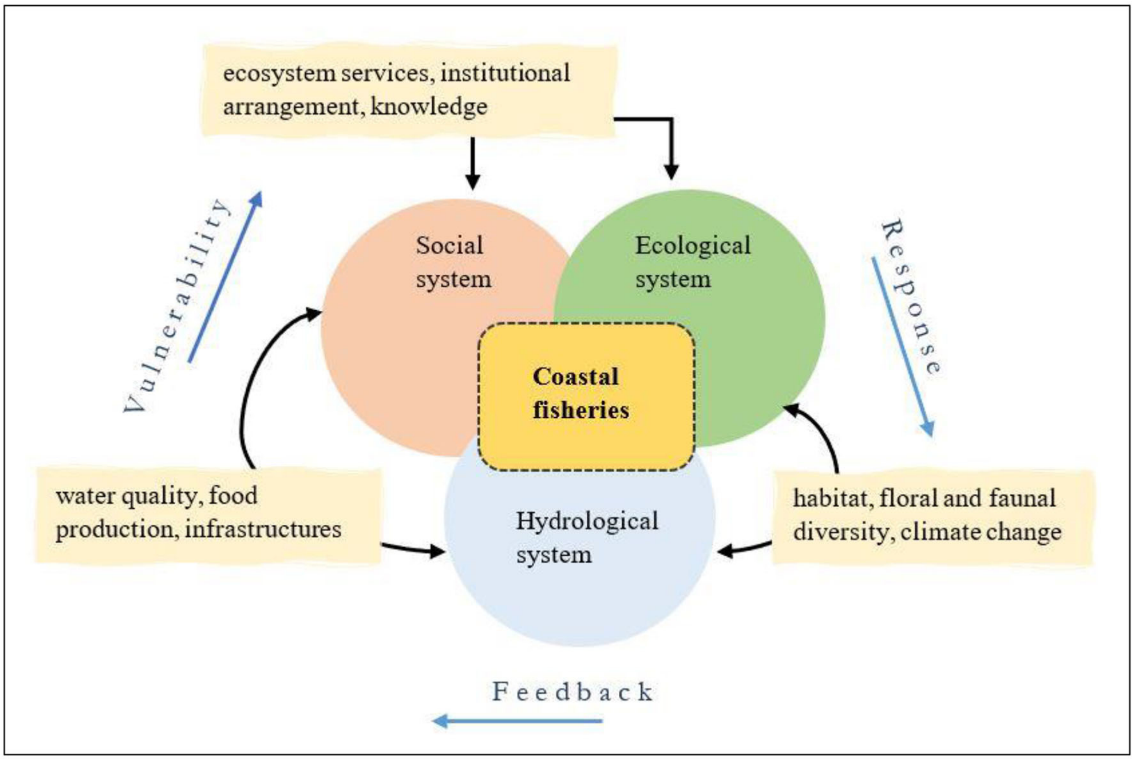


FIGURE 6
Constituents of SES and SH in fisheries: coupled social and hydrological systems are defined by water quality (habitat degradation, resource/fish availability), food production (nutrition, local economy and livelihoods), and infrastructures (dykes, dams, etc.) whereas intersecting SES attributes include ecosystem services (fish as the resource base), institutions (norms, policies, governance) and ecological understandings. Source: Author (Ghosh).

(iii) independent household business operated by family members without any access to fishing boats.

A *shabar* comprises a band of recruited persons who work under the leadership of the *bahardar*, for a common goal i.e., maximum fish production. To put otherwise, these privately operated fish processing units accommodate disproportionate interests and involvements of actors including *bahardar* (camp owners), marine fishers, net menders, fishing crew laborers, boatmen, traders, contractual male laborers, and daily-wage female dry-fishers (sorters and processors) who partake in various activities along the value chain. *Bahardars*, who live in the surrounding villages of Kakdwip, Namkhana, Kalistan, and Pathar Pratima, remain cautious while selecting a campsite. Extensive sandy *char* at the coastal Bay of Bengal is ideally suited for landing and drying fish. Substantial knowledge of topography, the lunar cycle, and tidal patterns is required to make an accurate selection, clearly highlighting the ecological and hydrological connections to the social practices. Three major factors are usually taken into consideration while setting up the camp: (i) proximity of the fishing ground to the camp, (ii) a natural creek where the boats can harbor, (iii) leveled land for a convenient drying and easy landing of fish carrier vessels. The *bahardars* make sure that there is enough space left between the camp-proper's habitation site and the sea line so that the tide level does not reach their temporary shelters even during the high tidal season. Hemmed by an array of shacks that serve as kitchens and storerooms, these camps constitute an open drying courtyard, scaffolds, a shrine to the goddess Ganga, and elevated drying platforms. The racks and posts are made of bamboo sections, whereas tarpaulins and *hogla* grass leaves are used to raise the shacks. Once a spot is fixed by *bahardars*, camps are installed on the same plot for successive years. However, the tenancy right for the *shabar*, is not the same everywhere. *Bahardars* of Baliara reported that a charge between 10,000 and 50,000 INR is paid to a committee for using the land and the committee, formed by locally influential individuals and some *bahardars* with the consent of Panchayat, pays the Panchayat an annual rent. In such cases, the committees are meant to condition the distribution of land for setting up the *shabars* and *khotis*. Some camp owners pay a yearly rent to individuals who claim to inherit the property. However, the land rents vary depending on the size of the camps. In every situation, the agreements are informal and verbal. The *bahardar*'s relationships with fishermen, their impression of individuals' activities, area of the drying ground, and the quantity of fish caught during different periods of the season all play a role in the recruitment of fishers and fish sorters. Contrary to such a specialized arrangement of *shabar*, a *khoti* is more subsistence-based household-run processing camp that is built upon informal relationships within family members and employed fish sorters from the locality. As it seems, many people in groups coordinate and engage with some sets of activities

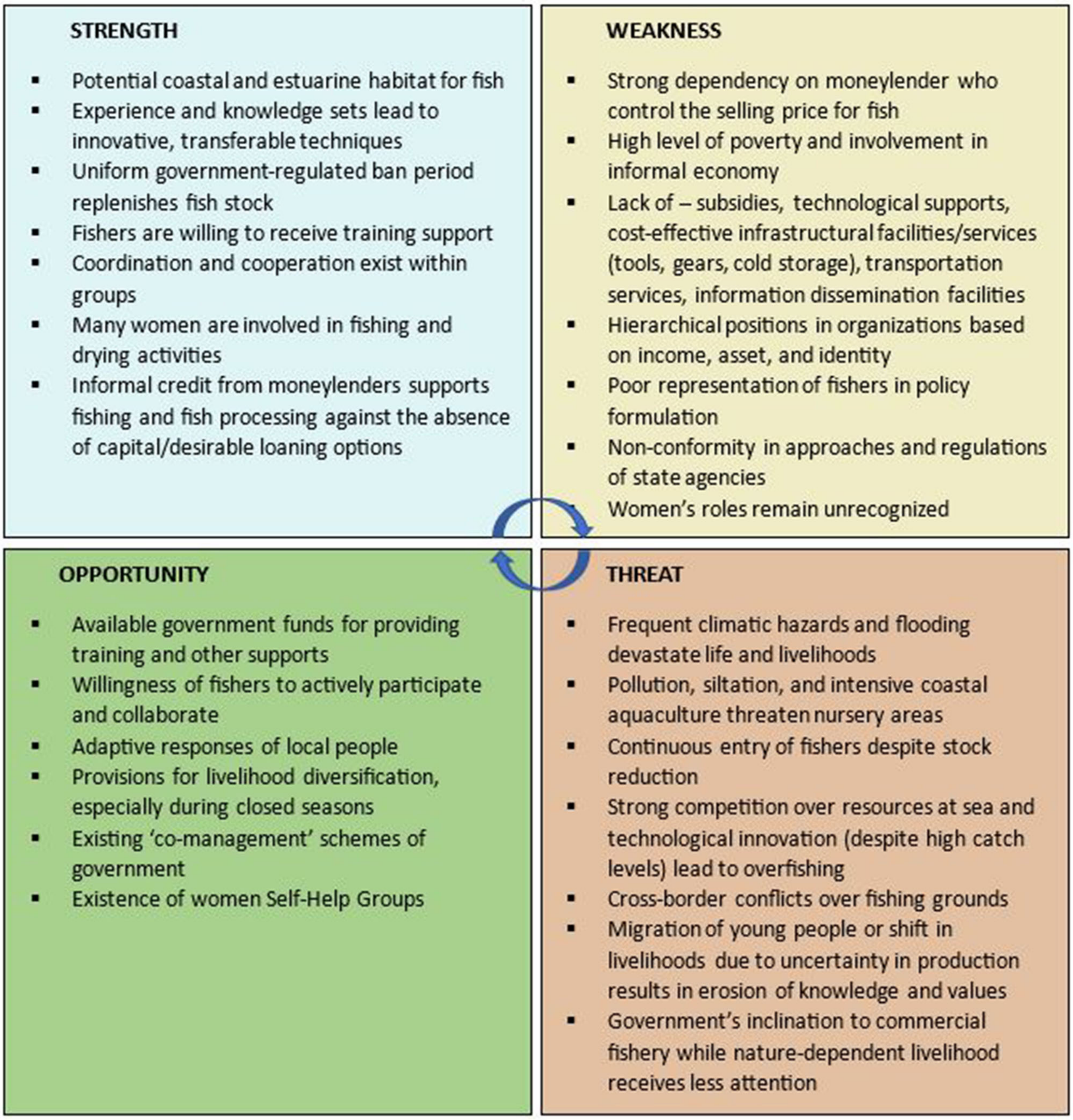


FIGURE 7
SWOT matrix on coastal fishing and fish processing.

in same camp and slowly, the professional relation turn into a physical association and then to, although transitory, a community attachment. A chequered pattern of inter-camp (*shabar* and *khoti*) relations is drawn by differential camp arrangements, resource sharing, affluence of camp owners and networking by the phrase among value chain players. A *shabar* owner's is a large *karbaar* with a higher capital investment, more personal boats, numerous workers in camps, good market connections, and in contrast, *khoti* members are deeply attached to the small family business while having less influence in the locality and fewer assets. Intra-camp relational rhythm shows up along the spectrum of a communal bond to strict hierarchies.

We came to know from conversations that the *khoti* families are natives of the South 24 Parganas and Medinipur districts and acquired their knowledge of fish drying from Bangladeshi *bahardars* who have moved to the Indian Sundarbans following the partition. Throughout the 1950s and 1970s, marine fishers from the Chittagong district of East Pakistan (present Bangladesh) migrated to the southwestern parts of the Sundarbans in India, leaving behind the deep scars of partition[7] on their ancestral soil. The fish drying method in Chittagong district, Bangladesh, was popularly known as *rangabali* practice as the fishers used to travel long distances from their home to reach the *Rangabali char*[8] whose expansive sandy swathe favored fish drying processes. Large-sized *behundi jaal* (a bottom-set bag net, also called *bindi jaal*) have remained historically emblematic of fish drying. During the post-partition period, the knowledge and experiences of offshore fishing, as well as rangabali, were transmitted to non-caste fisher people, shaping the socio-cultural tapestry of the Indian Sundarbans. At the beginning of the drying season, *bahardars* invest substantial capital to cover expenses which include fishing tool (net, boat) repairs, crew employment, fuel, food, transportation, and other essential articles for drying. Those who do not have their own boats, hire them from different sources, mostly from the Rajbanshis[9] and Muslims. There is an agreement between a producer and a middleman who provides producers with capital on credit, locally called *dadan*, insuring his business against all expenditures and uncertainties in production output. The middleman, also known as *dadandar*, is generally a local wholesaler or a wholesaler of both fresh fish and dried fish from the city, lending advance money (*dadan*) ranging between 50,000 INR and 10 lakhs based on the requirements and size of the camp to ensure a steady supply of dried fish at a concessional rate. Taking dadan is a common and compulsory practice that has made fish processing affordable. Personal contact and local networks are the two means by which bahardar connects with dadandar for privately arranged trade exchanges. Dadandar sometimes visits the camp to check out the arrangements and get an idea about the amount of fish captured and fish produced. A monthly or bi-weekly private meeting is held between the producer and dadandar to decide on a payback amount which is negotiated over the cost of arrangement (salaries, maintenance), amount of fish produced, and the running market price. Three important outcomes are associated with such an established trade relationship: firstly, producers are committed to selling the dried fish at a heavily discounted price and, sometimes, they are obligated to supply and excess weight of fish; secondly, by generating market demands, the *dadan* forces the production of the organization—a larger catch; thirdly, if the producer fails to repay his *dadan*, the amount is added to the pile of debt for the following season, which further lowers the price he gets for his catch. However, such an informal trade relationship between producers and *dadandars* is planted on trust and negotiations against the absence of credit support and subsidies from the government. The producer and *dadandar* are both aware of the kind of mutual dependency they have, which partly explains why, notwithstanding occasional grievances of producers, there is no strong or sustained effort to get rid of this otherwise shrewd practice. "There are so many *paikars* (wholesalers) involved in the trade. They will lose business if we do not collaborate with them", expressed a *bahardar* of a Lalgunj *shabar*.

Fishers (*noukar lok*—who work in the sea) and fish processors (*kuler lok*—who work onshore) are appointed by *bahardars* on various short-term contracts from neighboring villages. The fishing crew of a *shabar* consists of 5–6 people, including a boatman (in charge of the boat and crew), fishers, and helpers who set a sail in 30 HP motorized boats (Box 1). With sufficient rations and 10–12 funnel-shaped bag-nets (*behundi jaal*), they travel toward the fishing grounds up to 30 km off the shore. It is important to note here that the high capacity 4- and 6-cylinder motorized boats are deployed to catch deep water fish such as Bombay Duck and Ribbon fish which are available in nearshore waters during September to January. As the months pass, they move into the deeper levels and therefore, small fish (such as Shrimp, Mullet, and Phasa) make up a large portion of the harvest from January onwards. The entire net is likened to a human body, and as such, some of the parts, such as the eye (*chokh*), hand (*hata*), cheilion (*kosa*), ear, and so on, are named in analogy to human body parts. Bag-nets are operated with the coordination of 2–3 4-cylinder trawlers (14–16 meters in length and 2–2.4 meters in depth), and small-sized vessels (about 10 meters in length), locally called *bhutbhuti*. *Bhutbhuti* collects the catch from nets, whereas trawlers with a capacity of 400–500 maunds[10] carry it to the shore. On the other hand, the main asset of a *khoti* is a low-capacity 2-cylinder fishing boat that carries 2–3 fishers and travels for 1 h three times during high tide each day to gather fish from 8 to 10 foot deep seawater. During these short trips, they catch fish with 8 to 10 bag nets, which they set for their next trip as they return. Capturing fish through bottom-set bag nets is less aggressive as fish is not dragged or bottom-chased, rather groups of fish are entrapped in the floating layers of the nets during tides. The fishermen have a clear understanding of the lunar position (locally called *tithi*) which controls the velocity of the water currents according to the tide and ebb. They have learned from their experience and intimate association with the sea that the force of the seawater current gradually increases from the tenth and reaches its optimum either at *amabashya* (the new moon) or *purnima* (the full moon) whichever the case may be. The fishing trip can be a short or broken trip if the storms or cyclones occur in the sea or the trawler, locally understood as the "body", is damaged or ill, or if a bountiful catch is obtained. Crew members earn between 15,000 and 20,000 INR per month during the 4 months of their contract. The *behundi jaal* is handwoven with cotton yarn (often sunn-hemp is also used) by experienced fishers who are either retired or involved in marine fishing as part of the *shabar*. Nowadays, as the *karbaar* allows in more commercial operations with larger amount of fish and many fishing units to be handled, rotproof nylon fibers are used for knitting *behundi jaal*. This arduous exercise would be in vain if the catch is scarce, as it has been lately due to water pollution, siltation, and overfishing.

Fish processing is carried out from dawn to dusk by men contractual fish sorters and women *hajira fish* sorters who are employed under a 'no work no pay' scenario (Figure 8). Labor demand for fish drying corresponds to the lunar cycle, with two

7 India became independent in 1947 with the painful saga of her partition marking the birth of the Muslim dominions of East Pakistan (later Bangladesh) and West Pakistan. In 1971, Bangladesh was formed as an independent country followed by a historic struggle called Bangladesh Liberation War.

8 Apart from *Rangabali*, the fishers practiced fish drying for six months (October to May) with the *khotis* settled in Sonar *char*, Dhal *char*, *char* Mamtaz, and Andar *char*.

9 A *hindu* fishing caste.

10 1 maund is equivalent to 37.3242 kilograms.

BOX 1 Marine fishing and fish processing methods in the Indian Sundarbans.

FROM FRESH FISH TO DRIED FISH

Fishing

- Fishing crew conduct the trip in the sea for 6–14 days
- The fishers select a suitable place, locally called *phar*, where they can operate bag-nets
- Wooden pole (*khunti*) is planted in the seabed which holds the net during tides
- When the current gets stronger, the net sinks and stretches. Fish drifts in with the current.
- During a subsequent intertidal period, the net comes up to the surface and the catch is emptied
- Bombay duck, Ribbon fish, Honey gourami, various species of phansa, pangas, chhuri, crab, shrimp etc. are captured are transported by the trawler to the shore

Processing

- Sandy courtyard of *shabar* is covered with three layers: tarpaulin at the bottom, thick straw layer at the middle and nylon nets at the top. The layers help to retain warmth for fish during daytime
- Fresh fish is cleaned in bamboo baskets and taken to the *shabar* yard by hand-driven cart
- The fish is laid over the straw bed. Often raised bamboo platforms are constructed for drying
- Natural drying i.e., the combined action of the sun and wind, is adopted. Full-sized fishes are dried without splitting or salting
- Long and soft fishes like Bombay duck are tied together with elastic threads and dried in groups on the bamboo scaffolds surrounding yard. Ribbon fish is fastened in pairs with the drying posts, standing at a height of 1 meter above the ground
- Women workers use locally available balloons to wrap their fingers while tying the mouths of *Bomla* which has sharp teeth. For flipping the fish, they use a knife-like tool called *patta,* made of bamboo. Fish is tended regularly and flipped as needed
- Small, thin fish take 3–4 days to get dehydrated, whereas long, fleshy fish such as Ribbon Fish are sun-dried for 5–7 days until the moisture is eliminated
- Polythene sheets are applied to protect the fish from dewdrops.
- Once the fishes are accurately dried, which is confirmed by their color, texture and odor, they are sorted according to species and stuffed into the gunny bags and kept it in the storeroom

high and two low weeks. The camp starkly manifests a gender divide in labor and wage, revealing hierarchies in the dried fish value chain—while men are assigned to fish cleaning, packaging, applying pesticides to prevent infestation, loading product onto crates or trucks, and weighing the produce, female casual laborers are involved with courtyard cleaning, sorting, scaffolding, and tending fish. These "typical female activities" earn them around 200–250/- INR a day, that too depending on the profit margin of the owner. Only male laborers are offered 4-month contracts for around 60,000–70,000/- INR. *Bahardar* hires *hajira* workers through a local broker who charges 10 INR for each contact. A single drying operation may require the involvement of 8 to as many as 40 workers each day, depending on the size and volume of fish to be processed. At the sites of Lalgunj, Baliara, and Lakshmipur, around 35–40 dry-fishers work in *shabars*, whereas 10–15 dry-fishers including four or five family members, work in *khotis*. Fishing, fish sorting, and drying activities are mostly performed by family members and relatives in a *khoti*. However, these figures drop if there is fewer fish to dry. Depending on workloads or raw fish catches, *khoti* families employ daily-wage fish sorters (four to five) whereas a boatman and fishermen (one or two) are hired at the onset of the drying season. It is customary between *khoti* families to share each other's workload by assisting with various tasks that include carrying bulky fish piles from the coast to the camp, setting up scaffolds, and tending fish. This illustrates how a collective of households practicing the same 'everyday' activities in a same rhythm, slowly transcends into a community with shared values. Landless, poor inhabitants of nearby villages, these women dry-fishers often belong to the same family where the younger generation learns from their mother or grandmother about different fish types, methods of drying, and fishing tools. Their husbands work as fishermen in marine fishing crews, as migrant laborers, or as agricultural laborers in the village or faraway cities. On top of carrying out household duties, women engage in activities (net mending, catching small fish and tiger prawn seed, fish vending, laboring on others' paddy farms) to earn additive income for their families while their husbands are away for work. Although *shabar* owners and *hajira* workers are from a same community or neighborhood, they share a professional, business-centric relationship that often limits them from voicing their concerns and discontents. Moreover, the caste-based identities of participants, particularly among those classified by the government as Scheduled Caste (SC) communities, influence relationships and roles within the organizations. A strong bonding prevails among the actors in the managerial group comprising of *bahardar*, lead fisherman, members working on a shared basis, and sometimes moneylenders, whereas the daily-wage processors work under a stern supervision of the *bahardar* whose aim is to augment profit.

While cyclone hitting the coastal villages of Sundarbans makes a more noteworthy story for frontline media houses, everyday risks and uncertainties of dry-fishers in an informally established social economy like dried fish, are naturalized and neglected. Following the hazardous Bulbul cyclone in November 2019, a media article reported that close to 57 houses and more than 30 *khotis* were razed to the ground by gushing winds and storm surges. In disaster-hit Sundarbans, people do not have a source of livelihood and they barely have food to eat. They keep waiting for the floodwater to go down and start again to struggle from somewhere. A cyclone's impact does not pose the same challenges to men and women, nor it is same for all the members in a camp. Gender-specific social and economic positions of women, as imbricated in the structural relations and practices in the organizations, set conditions for 'common yet differentiated' implications of cyclonic hazards ravaging weak mud houses in the village, household resources (livestock, pond, fields through saltwater intrusion) and entire camp infrastructure at once. A *shabar* owner from Lalgunj mentioned that he had to pay a lot to arrange the camp again after the Bulbul cyclone (9 November, 2019) which caused damages worth INR 6 lakhs. "When cyclone occurs, we stay at the shelter

FIGURE 8
Various activities in a *shabar* of Frasergunj. Source: Fieldwork 2022.

for two-three days only to discover that our homes have been shattered to the ground, all our resources (stored rice, goat, cattle) are gone", lamented Rina *di*, a *hajira* fish sorter of a Lalgunj *shabar*. Cyclonic upshots affect the owner's business and consequently, fall heavily on the shoulders of women *hajira* workers and fishers who must protect both their livelihoods and households. Cyclone ramifications are shaped by the disparate, gendered vulnerabilities of residents who face them in different ways. *Shabar* owners remain concerned about reorganizing the camp and paying off *dadan* while *hajira* workers and fishers strive to get their livelihood back and rebuild mud houses that claims the little that they have saved.

The 'downstream' level (Kaplinsky et al., 2002) of the value chain involves a network of wholesalers, small traders, retailers and fish vendors. From drying camp (*shabar and khoti*), dried fish makes an onward journey to wholesale markets from where it is moved to retail centers. After buying dried fish from bahardars, intermediary traders, *paikers or dadandars* in popular terms, sell a major portion of the stock to wholesale traders of Balighai (in East Medinipur district) and Sheoraphuli (in Hugli district). Most often, *paikers* preserve a part of dried fish in *arats* (stockroom) for selling all year round. From these two export points, dried fish goes to Phuleshwar (in Howrah district), Koley (in Kolkata) and Territi Bazar retail markets. The *paikers* arrange small trucks and boats to transport dried fish from camps to the wholesale markets from where it is transported via trucks and trains to retail centers (see Figure 9). The manager of the *paikers* handle packing and loading of dried fish into trucks or boats. A marginal share of dried fish is sold by *bahardars* directly to local traders and wholesalers of Kolkata and Howrah (see Figure 9). Egra is the largest cooperative-based fish market and Phuleshwar is the largest retail house in Bengal. Over 90% of the wholesalers in Sheoraphuli continue their ancestral businesses, ranging between 25-50 in age (see Figure 10). A slice of dried fish stock consisting of discarded remnants is sent to the Junput market of East Medinipur for distribution to poultry farms. About 20% of dried fish is used by fish meal industries to produce poultry feed. Retailers of Phuleshwar retail market, local small-scale traders, and local vendors, among whom women make up a small but significant segment, are the buyers of dried fish. They purchase 5 to 10 kilograms of dried fish for each variety. From the outlets of Sheoraphuli, dried fish is exported via train to the retail markets of Tripura, Odisha and Assam, whereas a portion is sent to neighboring markets in Barasat, Beldanga, Barrackpore and Katwa. Members of a home-based enterprise producing and selling dried fish in roadside stalls and local markets, stated that they do not depend on *dadan* as it obligates them to trade with *dadandars*. They purchase fresh fish from *bahardars* once the catch arrives onshore and dry them at home (on roofs and yard) for selling at their roadside stores.

6. Collaboration and knowledge co-production through interactive multi-stakeholder workshop

Knowledge co-production is situated within the voluntary commitments and collaborative settings of both academic and non-academic groups, bringing in context-specific knowledge, expertise, and perspectives for collectively exploring major drivers of changes, evaluating scopes for meaningful practices, and crafting avenues

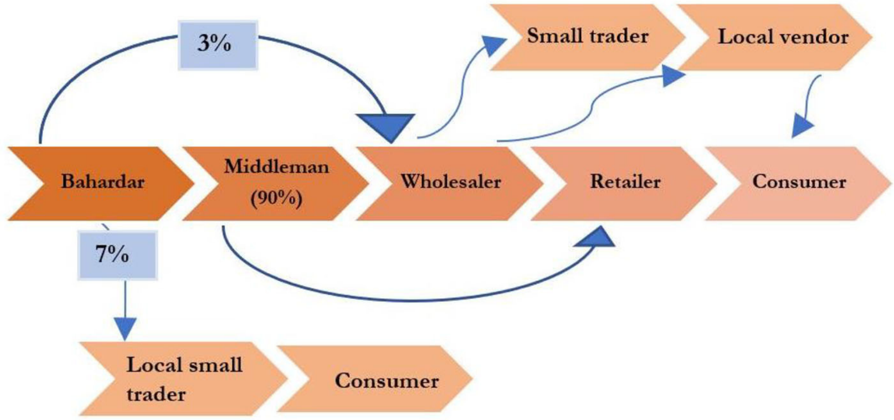


FIGURE 9
Market network within the dried fish value chain. Source: Modified after Society for Direct Initiative for Social Health Action (2016b).

FIGURE 10
Dried fish stores at Sheoraphuli. Source: Fieldwork 2022.

toward solutions (Norström et al., 2020). From a tangible starting point of recognizing stakeholders to asking relevant questions on how a specific challenge has precipitated, how it shapes the lives and livelihoods of people, which factors foster or restrain the activities, and where the policy windows are located the dynamic stages of knowledge co-production are premised on sensible involvements that prioritize trust-building and problem-framing through iterative exchanges.

The two previous sections of the article implied the need to adopt a more social, participatory approach that extends a wider space for interactions, consultations, and collaboration, steering a concerted decision-making process and mapping out solution-oriented trajectories for the dried fish economy in the Sundarbans. We pursued knowledge co-production across a multi-stakeholder partnership framework, prominently accentuating the urgent needs of those whose resources, knowledge, and values are at stake. In essence, the workshop was anchored on the four pillars of knowledge co-production, assumed by Norström et al. (2020)—context-specific, pluralistic, goal-oriented, and interactive (Figure 11). The workshop was context-specific in its focus on the livelihood dependencies, needs, and beliefs of different social groups in *shabar* and *khoti* accompanying various place-based issues (work conditions, flooding, wage distribution, compensation, etc.) whereas the pluralistic workshop strung together a range of views from different backgrounds irrespective of gender, age and ethnicity. A common goal for all participants was to develop a collective understanding of the problems reflecting different inequalities, power hierarchies and the limitations in reaching out to agreed-upon measures of solutions. It paralleled persistent multi-pathway interactions among the participants, enabling a co-learning process through the exchange of experiences, aspirations and values. Most importantly, profound communications put forth individual choices, intimate or distant relationships, and clashes, which cloud the pre-imagined vision of ideal social groups and takes to the real-world conditions for life.

6.1. The workshop: toward climate-resilient fish drying techniques and livelihoods

Our frequent conversations (over two meetings and phone calls) with the representatives of DMF, resulted in a template specifying the stakeholder groups, duration, and location of the one-day workshop which took place on May 23 (see Figures 7, 12). The workshop was scheduled at Kakdwip which is conveniently

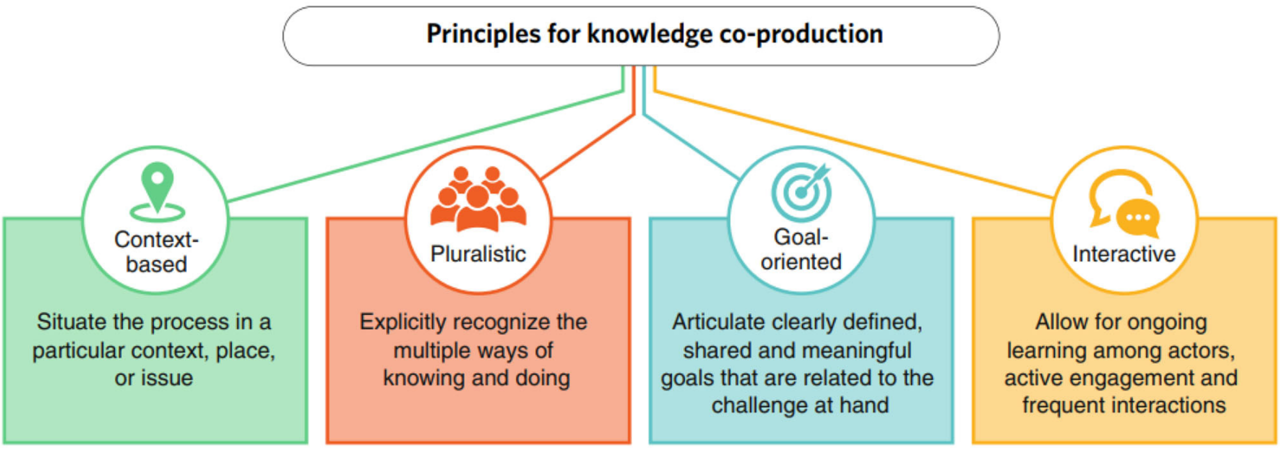


FIGURE 11
Principles of knowledge co-production. Source: Adapted from Norström et al. (2020, p. 184).

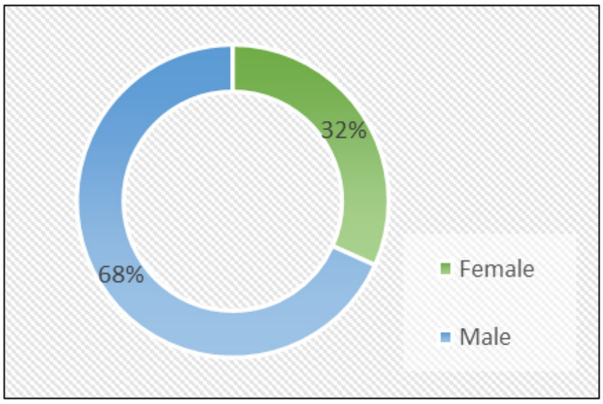


FIGURE 12
Female and male participation at the workshop (excluding researchers and scientists).

accessible by local train and bus from the villages of fish processors. The workshop began with a short video on dried fish processing in Frasergunj village, prepared by the research team (http://toobigtoignore.net/) (see Supplementary material 1). Woven with compelling visuals and narratives on everyday activities in the camps, the video effectively set the tone of the workshop and motivated the dry-fishers whose on-site accounts were depicted on-screen. Four teams were formed in the dynamic group interaction session, each with a discussion moderator and a note-taker: *hajira* workers (total 16 members including four researchers, one SHG representative, and one net mender), small-scale marine fishers (total six participants including two researchers), *shabar-khoti* owners (total nine participants including one researcher and one DMF representative), and trader (total three participants including one researcher and one DMF representative).

6.1.1. Reflections on challenges

"After working for half an hour so as a new recruit the *shabar* owner may tell us to leave empty-handed", stated *Shikha Di* (Figure 13). While more and more work-aspirant dry-fishers intend to join the camp, preferences based on experience, age, and camp requirements dominate their fate. Most often, the contractual male laborers are offered the roles usually assigned to female dry-fishers, further lowering chances of being recruited. Elderly women over 60, who are mostly widows and are losing their eyesight, have even fewer opportunities for employment. They do not have equal access to the state government ventures like pensions for senior citizens, known as *Bardhyokyo Bhata.*[11] The amount of work accomplished hardly varies between men and women workers, rather women's contribution exceeds by time and toil that of the male workers. In reality, the complete processing operation runs seamlessly due to the meticulous effort that they put in every day from 5 AM to 6 PM. However, the wage they receive is lower than that of their male counterparts. It is not only their responsibilities at the camps that continue - during lunchtime they rush home to carry out household 'duties' that include meal preparation, livestock handling, taking care of children and elderly members. The increased pressure that comes with combining household chores with waged work is, clearly, faced by women. Some of them commute quite a distance by feet from the adjacent villages to reach the camp whereas those who had to manage accommodation in tiny shacks of *shabar*, throw themselves into grim living conditions. Low-quality drinking water is another major problem in coastal stretches of Baliara and Lalgunj. All the dry-fishers mentioned that the camps comprise a single bathroom, which too is unhygienic. All the hard toil under the scorching tropical sun brings them

11 The West Bengal government provides a monthly pension to the senior citizens, a pension scheme which comes under the Department of women, child development, social welfare. As per the scheme, anyone aged over 60 is eligible to be enrolled for a pension irrespective of caste, ethnicity, and income.

is a poor diet comprising rice and fish as a reward. While the *hajira* workers from Lalgunj described how they swim across a tidal creek every day to reach the camps, women from Baliara were uneasy about flood risks during cyclones that wipe out the embankments along the rivers. Over 90% of the dry-fishers stated that the *shaba*r yard and the shacks are filled with water during cyclonic storms, further exacerbating the situation. While cyclones and concomitant floods sweep away the entire set-up of the camp, unseasonal rains, and cloudy weather during winter lead to spoilage of dried fish hitting the business hard. During cyclones, they safeguard the dried fish with polythene sheets on raised platforms or in the storerooms. The dry-fishers further told us that the temporary flood relief centers are neither evenly distributed nor adequately equipped. During non-drying seasons, the women eke out a living by working as housemaids in cities, mending nets including *behundi jaal,* and capturing tiger prawn seeds from murky waters, all of which fetch out a low return. Furthermore, collecting tiger prawn seed is an onerous and hazardous activity as women have to partially submerge themselves for a long time into the water that is not only laden with sediments but also contaminated with various toxic pollutants causing acute health problems such as dermatological diseases, digestive issues, and orthopedic pain (see Chowdhury et al., 2017). While the researchers took a closer look at their opinions on the most urgent solutions (see Figure 14), the *shabar* owners, on the other table, pointed out the challenges they run into.

Shabar owners are unable to take loans from the banks which demand assurance upon a permanent business or assets. If the owner fails to repay his *dadan*, the *mahajan* (*dadandar*) allows him one chance to supply the entire amount next year, otherwise the deal is canceled. If an owner fails to pay off the *dadan* (e.g., 10,000/- dry fish is produced at a *dadan* of 2 lakhs), he asks the *dadandar* to withdraw the money so that the owners can take a loan from other sources; however, the *dadandar* does not encourage that as it would reduce his access to low-priced fish supplies from producers. In Frasergunj, there is no active cooperative society for dried fish, unlike the East Medinipur district. "We get a relief [sic] without the consent of *dadan*, but we are helpless as we need money", mentioned a *shabar* owner. The conditions of *dadan* are inflated even further with declining fish quality and shrinking fish stock, which has been affecting the business in the course of the past few decades. Fish producers are concerned about the accumulation of heavy metals in fish and other aquatic resources due to increased water pollution, leading to various fish diseases, early spoilage of fish, reduction in fish diversity, and changes in fish habitat. Most of the metal elements[12] (Cadmium, Chromium, Lead, etc.) that transmit into fish are cumulative poisons causing severe health problems when consumed. The DMF representative, on the other hand, set out how overfishing by industrial trawlers with bottom-chaser trawler nets and fish-finder equipment made inroads into the fish habitat of Bengal's nearshore areas. "Motorized gears triggered the tendency to capture more fish resulting in fish stock depletion – the fishers who invest much time to fish with 1-cylinder or 2-cylinder, are now unable to catch a desired volume of fish at the same site in the sea" [sic], he explained. One of our interlocutors voiced, "diesel price is hiking like never before – we need subsidized diesel".

In order to protect dried fish from infestations by flies, ant and microorganisms, formalin and *doom* (*trichloro organophosphate*) are applied at times by the producers and wholesalers. This lowers the quality of dried fish.[13] It has been found that medicines applied during cloudy weather stiffen dried fish, which does not soften even after boiling for several minutes. "Without hygienic and healthy drying, the dried fish market will start to suffer, as it has already shown some signs of downfall in exports", stated a wholesaler. Transporting dried fish to local or regional market centers is a dire challenge—police patrols and random bribes are commonplace.

Small-scale marine fishers, on the other hand, remain worried about their livelihoods for eight long months when *shabar* remain at closure. "Nobody wants to employ the *boro majhi* during non-drying season, as they have already earned a reputation with being tied to a *shabar* or *khoti.* So, they are replaced by small fishers", reflected an experienced fisher at our discussion table. Large tidal waves caused by a sudden storm cause vessels to capsize, claiming the lives of fishers who stay on-board for days. A member of DMF mentioned that there is no accident benefit for fishers since 2017. "West Bengal once made a group insurance with 20,000 fishers to whom the government provided premium. As per the scheme, by showing *Panchayat*'s certificate or *Matsyajibi* identity card and the dead body (if it is not found, evidence should be provided by any crew members), the family members of the fisher used to receive a compensation of 2 lakhs". However, this insurance plan is not enacted equitably. Such oversight is often the outcome of partisan vote-bank politics bringing about local contestations over funds, and inter-party conflicts on schemes that favor their populist agendas.

6.1.2. Trajectories of solutions

Informal conversations among four stakeholder groups, scientists, and researchers revolved around three broad areas—(i) hygienic and climate-resilient drying, (ii) livelihoods and training potentials, and (iii) everyday dwelling in the delta. Representatives from each ring spontaneously placed their views and ideas on a specific theme that emerged from the discussions themselves. Imperative, in this regard, is that the cross-group exchanges contained, either in hidden or direct articulations, the components of knowledge co-production (Table 5).

i) *Hygienic and climate-resilient drying—technical measures*

The senior scientist started with dried fish quality which, according to him, can be improved by applying an appropriate

12 For the last several years, the aquatic environment of Bengal's nearshore region has been exposed to and harmed by floating microplastics, discharge of contaminated wastewater from commercial shrimp monoculture ponds, and non-point pollution from river-side industrial sites (see Rasul et al., 2020; Ghosh et al., 2022).

13 See Rasul et al. (2020) for details.

FIGURE 13
Snippets of knowledge co-production workshop at Kakdwip. Source: Authors.

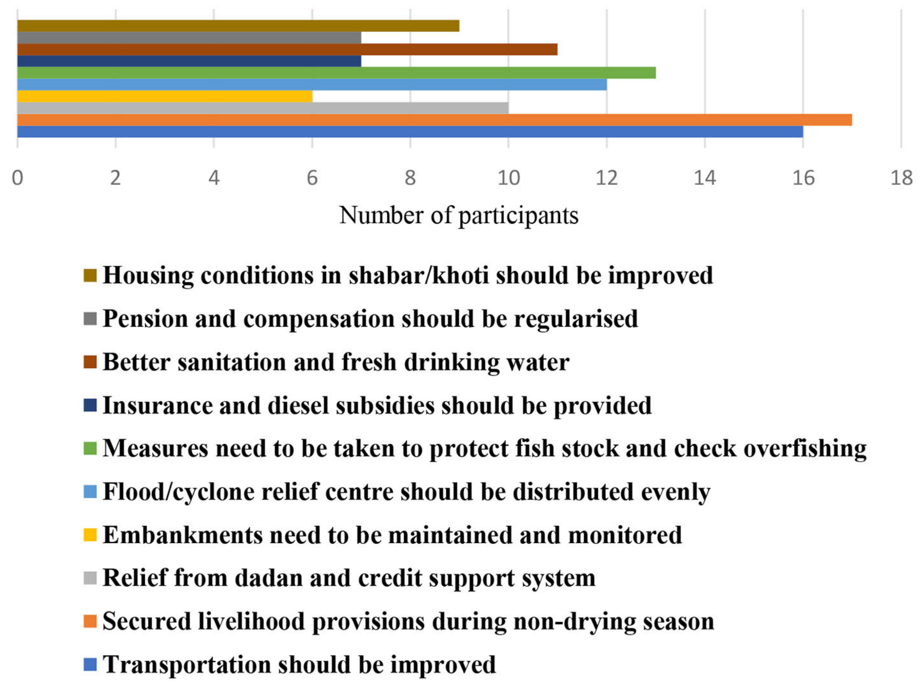


FIGURE 14
Areas in need of attention as indicated by the workshop participants.

amount of coarse common salt (*sodium chloride*). Salting can turn out to be a significant step, as salted fish last for many days without substantial storage and attract less infestation than unsalted ones. High-quality coarse salt accelerates Oxidative stability (lipid oxidation process), an important pre-treatment procedure that reduces drying duration, extends shelf life, and increases product

TABLE 5 Components of knowledge co-production and corresponding examples from the conversations.

Component of knowledge co-production	Examples/quotes
Clarifying	"These days, our major challenge is humidity which remains almost constant throughout the year"
Proposing	"I suggest Solar Tent Dryer for greater uniformity and quality of the output"
Informing	"A similar initiative was once launched on Sagar Island in the Indian Sundarbans, but it failed due to the restricted size and quantity of tents"
Supporting	"It is encouraging to see how the livelihood issues of women dry-fishers are surfacing in these discussions"
Building	"We can take the help of technologies which will play a dual-role role of accelerating the hygienic drying as well as protect fish from rainfall and humidity"
Reifying	"I would think about plant-based propellants that may abate the chances of infestation by keeping ants and flies away without dropping the quality of dried fish"
Reiterating	"Providing proper training will also allow our family members to get involved in these practices for an income"
Collaborating	"Together with DMF, the research team and West Bengal University of Animal and Fishery Sciences (WBUAFS) that organizes training programs on preparation of various fish products, a training workshop for the *hajira* workers can be arranged"

yield. A *shabar* owner with contrary experiences remarked that local markets have less demand for salted fish, while demand for dried fish varies from one market to another across states and depending on the taste, texture, and flavor. According to him, salt gives the cured fish a yellow color and often effects the texture of the fish. The scientist replied, "that being the case, a small proportion of calcium and magnesium salts can be applied". He continued that salted dried fish from Bengal can generate demand in local markets and the Anganwadi centers of Assam and Tripura. On a parallel note, the DMF representative reflected, "air direction and amount are crucial contributors to a good quality dried fish. These days, our major challenge is humidity which remains almost constant throughout the year. Hence, fish takes a long time to dry" (Table 5). Concerning insect infestation in dried fish, the scientist stated, "I would think about plant-based propellants that may abate the chances of infestation by keeping ants and flies away without dropping the quality of dried fish".

The junior scientist pointed out, "we can take the help of technologies that would play a dual-role role of accelerating the hygienic drying as well as protect fish from rainfall and humidity. I suggest Solar Tent Dryer for greater uniformity and quality of the output". When drying fish artificially, some factors can ensure optimum drying conditions, especially during humid winters, such as the initial drying temperature (25–45°C) in tropical regions, relative humidity (initially 50–65%) that controls the drying rate and texture (hard or soft) of the dried fish, and faster air flows.

Different from a conventional solar dryer which contains solar cells, the tent dryer (Figure 15) is structured as a tent made with wooden or bamboo frames that are covered with transparent polythene, allowing sunlight to get in. Solar tent dryers assure fish drying in any weather condition and a clean environment; it also preserves the nutritional quality of fish. The scientist also acknowledged that solar tent dryers will not be able to produce more dried fish in large-scale arrangements which extend to many *kathas* of land.

"Would it facilitate equal drying at every side?" asked a *shabar* owner. The scientist stressed tending the fish properly while drying. On this front, the *shabar* owner cautioned, "we cannot over-dry the fish so that the smell is gone. In Tripura, people often soak the fish in water to add smell as they prefer a pungent odor". Drawing evidence from experimentation conducted by the Bangladesh Fisheries Research Institute (BFRI), the DMF representative reminded the group that the solar tent dryer can stand out as a successful low-cost fish dryer made up of locally available materials, but the model would not function in the absence of sun. He maintained that a similar initiative was once launched on Sagar Island in the Indian Sundarbans, but it failed due to the restricted size and quantity of tents. He further described a transparent version of a solar tent dryer called a BFRI model which is constructed by using two layers of thin (0.20 mm) celluloid allowing for better insulation and effective utilization of heat energy. The model has been successful in capturing sensory qualities, nutritional properties, and water absorption capacity in dry fish.

ii) *Livelihood and training*

The junior scientist emphasized livelihood diversification, especially for the 8-months non-drying period. Some dried fish (such as dried shrimp) could be further processed to prepare different fish products, such as dried fish pickles, sauces, and *papad*. Dry-fishers could produce shrimp pickles as a collective business during the non-drying season—local Self-Help Groups (SHG) of which they are part, could be mobilized to that end. She continued, "together with DMF, the research team, and West Bengal University of Animal and Fishery Sciences (WBUAFS) that organizes training programs on preparation of various fish products, a training workshop for the *hajira* workers can be arranged". She added that packaging should be considered important for product safety

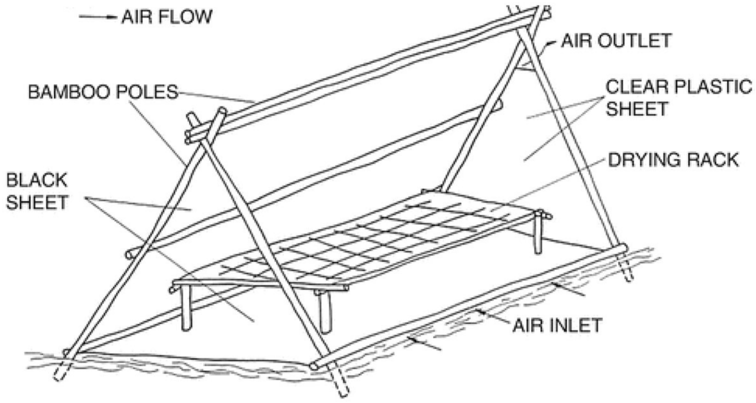


FIGURE 15
Model of small solar tent dryer. The tent's top must have a circular vent for air circulation. Inside the tent, a bamboo platform covered in dark polythene sheets lies for drying the fish. The temperature can be controlled by opening air vents permitting free air circulation while tarpaulin sheets protect the fish from dewdrops and sporadic rains (Source: Banout, 2017).

and successful sales. "I would request the senior scientist to think about how the market connection could be established for these products, which have potentials to be directly sold to urban retail stores". The senior scientist replied that a scientist team of CIFRI will initiate a conversation with NFDB (National Fisheries Development Board) and NABARD about the market connections, low-interest loans, and implementation of two FPOs (Farmers Producers Organization) at Sagar and Frasergunj. Also, as a nodal loaning agency, NABARD guarantees an interest subvention of up to 3% per annum to the SHGs which can be mobilized for the training program.

iii) *Everyday dwelling in the delta*

Chandana Das, a woman *hajira* dry-fisher from Lalgunj, expressed "it is encouraging to see how the livelihood issues of women dry-fishers are surfacing in these discussions. Considering the risk involved in crossing a tidal channel, I urge everyone to pay adequate attention to the transport of women from their villages to processing centers. Insufficient access to safe drinking water is another significant issue, especially for the *hajira* workers of Kalistan and Lalgunj. A tube well near the *shabar* would resolve the water-related problems". A fish sorter from Lakshmipur added, "trainings on duck and goat farming are often provided by the government jointly with NGOs; however, the results are not achieved due to the lack of monitoring and disconnected efforts. Providing proper training will allow our family members to get engaged in these practices for an income." "We need to convey these issues more formally to the fisheries department. Sanitation infrastructure and cyclone relief centers should be prioritized", said the DMF representative. In foregrounding the consequences of repeated cyclones and attendant flooding of the camp areas, the senior scientist said, "I have already placed a proposal in my network at IMD,[14] Alipore regarding the installation of a cyclone forecasting station at the eastern side of Sundarbans—it will be beneficial for people living in the western islands too".

From audio-visual presentations (short-term dissemination) to a concrete policy brief (intermediate plan), from co-organizing training programs (intermediate plan) to mobilizing SHGs (long-term intervention)—this collaborative pursuit, characterized by what Norström et al. (2020) describe as "open, deliberative, and reflexive" attributes, pledges to promulgate the calibrated results for cross-departmental attention and seeks to create space for voices that have remained inaudible so far. Our experiences of the workshop underlined four aspects: firstly, there are intersecting spaces of discontent and community ethos differently influencing the perspectives of the stakeholders—tracking and sensitizing these overlaps is essential for designing future plans; second, women's contributions, living conditions, and accessibilities (to markets, credit, and other resources) did not find room for discussion to date, whereas a major focus has been channeled to fish production processes and nutritional aspects of the product; third, the sector strives for "right-based" conversations placing priorities upon "multiple rights", insurance, and tenurial rights issues; fourth, it is necessary to build awareness through policies, trainings and support about safe drying conditions with regard to hygienic sanitation practices, improved packaging and adoption of organic pest prevention measures; fifth, sustained communication among actors might allow a trustful monitoring of change, and keep open the possibilities for more inter-sectoral engagements.

7. Conclusions

The "three-step" methodology, used in the article, reveals the granular complexities and potentialities in the dried fish sector. The following points summarize what makes up the article:

14 IMD stands for Indian Meteorological Department.

- By drawing in the sociohydrological features of coastal environments and livelihoods, we note an indelible influence of water dynamics on food production in general and fisheries in specific. SES provides a fuller understanding about the institutional effects on social-ecological setting of fisheries in the Southern countries by underlining the operational principles of local economic organizations, management approaches to coastal fisheries, unequal access to market and resources and so on. Relatedly, it looks into how institutional processes respond to evolving social-ecological scenarios and crises situations while both SES and SH lenses stress upon the significance of collaborative learning about and management of vulnerable coastal resource systems.
- We applied various ethnographic methods to grasp the complex nature of dried fish 'social economy' in terms of differential relationships, practices, everyday struggles and emergent risks that characterize dried fish organizations. The study also draws in locally tuned understanding about the increased biophysical threats, slow-onset social and economic shifts, and adaptive 'tactics' in the delta. Our observations make visible how the political economic forces coupled with social dynamics in organizations have shaped collective involvement in local economies through instilling competition and undermining claims over resources and benefits.
- Grounded on the assumption that relationships, policies, and practices are multi-way and complex, our take of knowledge co-production was to incorporate inputs from local people in order to perceive opportunities for co-interventions (training, SHG mobilization, knowledge dissemination) through which knowledges may transfer into solution-oriented practices. Here, 'knowledge' derived from 'pluri-voice', transcends an established, theory-driven, scholarly idea to take into account perspectives, concerns and experiences arising from lived realities of local people in shifting social, ecological and economic circumstances.

We further believe that the buzzing policy discussions on some popularized connotations such as 'welfare', 'wellbeing', and 'resilience' only legitimize the capitalist interests by appropriating the very notion of 'sustainability' and thereby, remaining fallaciously lop-sided, myopic, and redundant. This essay on dried fish sector of the Indian Sundarbans indicates the potential of participatory-transdisciplinary approach in reinforming 'sustainability' through blurring west-borne dichotomies between social and ecological, vulnerability and resilience, normative and real, and finally, theory and practice.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

RG designed the research, conducted field surveys, performed data analysis, developed the article structure, and led the writing and revisions. JM supervised the research and field surveys, provided advice on the conceptualization of the research and article design, and contributed to the writing and revised the manuscript. PG transcribed a part of the write up. AB, AC, PG, SP, AS, and PS contributed to the fieldwork and workshop. The manuscript is the outcome of the collaborative efforts of all authors. All authors contributed to the article and approved the submitted version.

Funding

Field trips in Frasergunj have been funded by the Social Sciences and Humanities Research Council (SSHRC, Canada) sponsored The Dried Fish Matters Project (https://driedfishmatters.org/), hosted at the University of Manitoba and the EU-ICSSR sponsored EqUIP Project. Fieldwork has also been partially funded by the EU-ICSSR sponsored EqUIP Project entitled Toward a fluid governance: Hydrosocial analysis of flood paradigms and management practices in Rhone and Ganges basins (India, France, Switzerland).

Acknowledgments

We are sincerely grateful to the dried fish workers, fishermen, and owners of the Baliara, Lalgunj, and Lakshmipur dried fish camps for generously spending time with us and remaining patient with our continuous probing during the field investigations and workshop. We are grateful to Dr. Archan Kanti Das (CIFRI) and Dr. Swarnadyuti Nath (WBUAFS) for being a crucial part of the Kakdwip workshop and enriching the discussions with valuable insights. We are thankful to Mr. Narayan Das, Mr. Milan Mondal, and Mr. Pradip Chatterjee of Dakshinbanga Matsyajibi Forum (DMF), our NGO partner in this project. We are also thankful toward Swissnex Cluster of Collaboration in South Asia for funding a small-scale project in Indian Sundarbans.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.youtube.com/watch?v=aR6tC_aLPgQ&t=87s.

References

Acheson, J. M. (2006). Institutional failure in resource management. *Annu. Rev. Anthropol.* 35, 117–134. doi: 10.1146/annurev.anthro.35.081705.123238

Adger, W. N. (2000). Social and ecological resilience: are they related?. *Prog. Hum. Geogr.* 24, 347–364. doi: 10.1191/030913200701540465

Agrawal, A. (2003). Sustainable governance of common-pool resources: context, methods, and politics. *Annu. Rev. Anthropol.* 32, 243–262. doi: 10.1146/annurev.anthro.32.061002.093112

Anderies, J. M., Janssen, M. A., and Ostrom, E. (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecol. Soc.* 9, 18. doi: 10.5751/es-00610-090118

Andrew, N. L., Béné, C., Hall, S. J., Allison, E. H., Heck, S., Ratner, B. D., et al. (2007). Diagnosis and management of small-scale fisheries in developing countries. *Fish Fish.* 8, 227–240. doi: 10.1111/j.1467-2679.2007.00252.x

Arthur, R. I., Skerritt, D. J., Schuhbauer, A., Ebrahim, N., Friend, R. M., Sumaila, U. R., et al. (2022). Small-scale fisheries and local food systems: Transformations, threats and opportunities. *Fish Fish.* 23, 109–124. doi: 10.1111/faf.12602

Bailey, K. (2008). *Methods of Social Research.* New York, NY: Simon and Schuster. The Free Press, A division of Macmillan, Inc.

Bandyopadhyay, A., Ghosh, R., Mukherjee, J., and Pathak, S. (2022). From the shabars of the Indian Sundarbans: everyday empirics through photography. *Coast. Stud. Soc.* 1–17. doi: 10.1177/26349817221107301

Banout, J. (2017). "Solar drying systems," in *Solar Drying Technology*, eds O. Prakash and A. Kumar (Singapore: Springer), 39–67.

Barbrook-Johnson, P., and Penn, A. (2021). Participatory systems mapping for complex energy policy evaluation. *Evaluation* 27, 57–79. doi: 10.1177/1356389020976153

Basurto, X., Gelcich, S., and Ostrom, E. (2013). The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environ. Change* 23, 1366–1380. doi: 10.1016/j.gloenvcha.2013.08.001

Belton, B., Johnson, D. S., Thrift, E., Olsen, J., Hossain, M. A., Thilsted, S. H., et al. (2022). Dried fish at the intersection of food science, economy, and culture: a global survey. *Fish Fish.* 23, 941–962. doi: 10.1111/faf.12664

Berenji, S., Nayak, P. K., and Shukla, A. (2021). exploring values and beliefs in a complex coastal social-ecological system: a case of small-scale fishery and dried fish production in Sagar Island, Indian Sundarbans. *Front. Mar. Sc.* 8, 795973. doi: 10.3389/fmars.2021.795973

Berkes, F., and Folke, C. (1998). Linking social and ecological systems for resilience and sustainability. *Link. Soc. Ecol. Syst.* 1, 4. doi: 10.1017/S1355770X992 20165

Bhatta, R., Rao, K. A., and Nayak, S. K. (2003). Marine fish production in Karnataka: trends and composition. *Econ. Polit. Wkly.* 46, 85–93.

Biggs, R., Rhode, C., Archibald, S., Kunene, L. M., Mutanga, S. S., Nkuna, N., et al. (2015). Strategies for managing complex social-ecological systems in the face of uncertainty: examples from South Africa and beyond. *Ecol. Soc.* 20. doi: 10.5751/ES-07380-200152

Binder, C. R., Hinkel, J., Bots, P. W., and Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecol. Soc.* 18. doi: 10.5751/ES-05551-180426

Bodin, Ö., and Crona, B. I. (2009). The role of social networks in natural resource governance: What relational patterns make a difference? *Global Environ. Change* 19, 366–374. doi: 10.1016/j.gloenvcha.2009.05.002

Bodin, Ö., and Tengö, M. (2012). Disentangling intangible social–ecological systems. *Global Environ. Change* 22, 430–439. doi: 10.1016/j.gloenvcha.2012.01.005

Boonstra, W. J. (2016). Conceptualizing power to study social-ecological interactions. *Ecol. Soc.* 21, 12. doi: 10.5751/ES-07966-210121

Carter, L., Cosijn, M., Williams, L. J., Chakraborty, A., and Kar, S. (2022). Including marginalised voices in agricultural development processes using an ethical community engagement framework in West Bengal, India. *Sustain Sci.* 17, 485–496. doi: 10.1007/s11625-021-01055-1

Chacraverti, S. (2014). The Sundarbans fishers coping in an overly stressed mangrove estuary. *Int. Collect. Support Fishwork.* 136. Available online at: http://hdl.handle.net/1834/32692

Chandra, G., and Sagar, R. (2003). *Fisheries in Sundarbans: Problems and Prospects*, 1–6.

Charles, A. T. (1998). Living with uncertainty in fisheries: analytical methods, management priorities and the Canadian groundfishery experience. *Fish. Res.* 37, 37–50. doi: 10.1016/S0165-7836(98)00125-8

Chowdhury, A., Aliya, N., and Subodh, M. K. (2017). Health risk assessment of 'tiger prawn seed' collectors exposed to heavy metal pollution in the conserved mangrove forest of Indian Sundarbans: a socio-environmental perspective. *Hum. Ecol. Risk Assess.* 2, 203–224. doi: 10.1080/10807039.2016.1238300

Cinner, J. E., and Barnes, M. L. (2019). Social dimensions of resilience in social-ecological systems. *One Earth* 1, 51–56. doi: 10.1016/j.oneear.2019.08.003

Cole, S. M., McDougall, C., Kaminski, A. M., Kefi, A. S., Chilala, A., Chisule, G., et al. (2018). Postharvest fish losses and unequal gender relations: drivers of the social-ecological trap in the Barotse Floodplain fishery, Zambia. *Ecol. Soc.* 23, 1–13. doi: 10.5751/ES-09950-230218

Crona, B., Nyström, M., Folke, C., and Jiddawi, N. (2010). Middlemen, a critical social-ecological link in coastal communities of Kenya and Zanzibar. *Mar. Policy* 34, 761–771. doi: 10.1016/j.marpol.2010.01.023

Crona, B. I., Van Holt, T., Petersson, M., Daw, T. M., and Buchary, E. (2015). Using social–ecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Global Environ. Change* 35, 162–175. doi: 10.1016/j.gloenvcha.2015.07.006

Danda, A. A., Sriskanthan, G., Ghosh, A., Bandyopadhyay, J., and Hazra, S. (2011). *Indian Sundarbans Delta: A Vision*. New Delhi: World Wide Fund for Nature-India, 40.

De la Torre-Castro, M., and Lindström, L. (2009). Fishing institutions: addressing regulative, normative and cultural-cognitive elements to enhance fisheries management. *Mar. Policy* 34, 77–84. doi: 10.1016/j.marpol.2009.04.012

Dey, M. M. (2008). *Strategies and Options for Increasing and Sustaining Fisheries and Aquaculture Production to Benefit Poorer Households in Asia.* WorldFish. Available online at: https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/1569/WF_1798-Letter.pdf?sequence=1&isAllowed=y (accessed June 25, 2022).

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., and Blöschl, G. (2013). Socio-hydrology: conceptualising human-flood interactions. *Hydrol. Earth Syst. Sci.* 17, 3295–3303. doi: 10.5194/hess-17-3295-2013

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., et al. (2015). Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resour. Res.* 51, 4770–4781. doi: 10.1002/2014WR016416

Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R. A. (2014a). prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydro. Earth Syst. Sci.* 18, 2141–2166. doi: 10.5194/hess-18-2141-2014

Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R. A. (2014b). prototype framework for models of socio-hydrology: identification of key feedback loops with application to two Australian case-studies. *Hydrol. Earth Syst. Sci.* 11, 629–689. doi: 10.5194/hessd-11-629-2014

Fabinyi, M., Evans, L., and Foale, S. J. (2014). Social-ecological systems, social diversity, and power: insights from anthropology and political ecology. *Ecol. Soc.* 19. doi: 10.5751/ES-07029-190428

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., et al. (2015). Advancing sustainability through mainstreaming a social–ecological systems perspective. *Curr. Opin. Environ. Sustain.* 14, 144–149. doi: 10.1016/j.cosust.2015.06.002

Folke, C., Hahn, T., Olsson, P., and Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* 30, 441–473. doi: 10.1146/annurev.energy.30.050504.144511

Funge-Smith, S., Lindebo, E., and Staples, D. (2005). *Asian Fisheries Today: The Production and Use of Low Value/Trash Fish From Marine Fisheries in the Asia-Pacific Region*. FAO RAP Publication. Available online at: https://www.fao.org/publications/card/en/c/d9cfc265-9c49-5161-8138-08a88b379a15/ (accessed July 13, 2022).

Galappaththi, E. K., Ford, J. D., and Bennett, E. M. (2020). Climate change and adaptation to social-ecological change: the case of indigenous people and culture-based fisheries in Sri Lanka. *Clim. Change* 162, 279–300. doi: 10.1007/s10584-020-02716-3

Garcia, S. M., and Charles, A. T. (2008). Fishery systems and linkages: implications for science and governance. *Ocean Coast. Manag.* 51, 505–527. doi: 10.1016/j.ocecoaman.2008.05.001

Ghosh, R., Mukherjee, J., Pathak, S., Choudry, A., and Bhattacharya, S. (2022). *Dried Fish in West Bengal, India: Scoping report. DFM Working Paper*. Available online at: https://driedfishmatters.org/pub/dried-fish-in-west-bengal-india-scoping-report.html (accessed August 05, 2022).

Glaser, M., Krause, G., Ratter, B. M., and Welp, M. (2012). *Human Nature Interactions in the Anthropocene: Potentials of Social-Ecological Systems Analysis*. New York, NY: Routledge

Gober, P., and Wheater, H. S. (2015). Debates—Perspectives on socio-hydrology: Modeling flood risk as a public policy problem. *Water Resour. Res.* 51, 4782–4788. doi: 10.1002/2015WR016945

Gunderson, L., Cosens, B. A., Chaffin, B. C., Arnold, C. A., Fremier, A. K., Garmestani, A. S., et al. (2017). Regime shifts and panarchies in regional scale social-ecological water systems. *Ecol. Soc.* 22, 1. doi: 10.5751/ES-08879-220131

Haeffner, M., Hellman, D., Cantor, A., Ajibade, I., Oyanedel-Craver, V., Kelly, M., et al. (2021). Representation justice as a research agenda for socio-hydrology and water governance. *Hydrol. Sci. J.* 66, 1611–1624. doi: 10.1080/02626667.2021.1945609

Handbook on Fisheries Statistics (2020). *Department of Fisheries, Ministry of Fisheries, Animal Husbandry & Dairying*. New Delhi: Government of India.

Hasan, M. M., Rasul, M. G., Ferdausi, H. J., Hossain, M. M., Shah, A. K., Bapary, M. A., et al. (2016). Present status of dried fish markets in Sylhet of Bangladesh. *Progress. Agric.* 27, 235–241. doi: 10.3329/pa.v27i2.29336

Herrfahrdt-Pähle, E., and Pahl-Wostl, C. (2012). Continuity and change in social-ecological systems: the role of institutional resilience. *Ecol. Soc.* 17. doi: 10.5751/ES-04565-170208

Holling, C. S. (1973). Resilience and stability of ecological systems. *Ann. Rev. Ecol. Syst.* 4, 1–23 doi: 10.1146/annurev.es.04.110173.000245

Holling, C. S. (1992). Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecol. Monogr.* 62, 447–502. doi: 10.2307/2937313

Hoque, S. F., Quinn, C. H., and Sallu, S. M. (2017). Resilience, political ecology, and well-being: an interdisciplinary approach to understanding social-ecological change in coastal Bangladesh. *Ecol. Soc.* 22. doi: 10.5751/ES-09422-220245

Hossain, M. A., Belton, B., and Thilsted, S. H. (2015). *Dried Fish Value Chain in Bangladesh*. Draft of World Fish. Dhaka.

Hossain, M. A., Sultana, M. T., Ferdous, S., Alam, S., Akhtar, R., Rahman, S., et al. (2022). *Key Locations: Dry Fish Processing and Trading in Bangladesh. DFM Working Paper*. Available online at: https://driedfishmatters.org/pub/key-locations-dry-fish-processing-and-trading-in-bangladesh.html (accessed July 17, 2022).

Islam, M. M., Pal, S., Hossain, M. M., Mozumder, M. M., and Schneider, P. (2020). Coastal ecosystem services, social equity, and blue growth: a case study from south-eastern Bangladesh. *J. Mar. Sci. Eng.* 8, 815. doi: 10.3390/jmse8100815

Jahan, I., Ahsan, D., and Farque, M. H. (2017). Fishers' local knowledge on impact of climate change and anthropogenic interferences on Hilsa fishery in South Asia: evidence from Bangladesh. *Environ. Dev. Sustain.* 19, 461–478. doi: 10.1007/s10668-015-9740-0

Janssen, M. A., and Anderies, J. M. (2007). Robustness trade-offs in social-ecological systems. *Int. J. Commons* 1, 43–65. doi: 10.18352/ijc.12

Jeyanthi, P., Chandrasekar, V., Ashok, A., Nair, V. R., Thomas, J., Jos, K. D., et al. (2018). Institutional development and efficiency of fishermen cooperatives in marine fisheries: a case study from Kerala. *Fish. Technol.* 55, 79-85. Available online at: http://krishi.icar.gov.in/PDF/ICAR_Data_Use_Licence.pdf

Johnson, D. S., Acott, T. G., Stacey, N., and Urquhart, J. (2018). *Social Wellbeing and the Values of Small-Scale Fisheries*. Cham: Springer International Publishing. doi: 10.1007/978-3-319-60750-4

Kaplinsky, R., Morris, M., and Readman, J. (2002). *Understanding Upgrading Using Value Chain Analysis*.

Kehoe, C. (2011). *Understanding Small-Scale Fisheries in Thailand: Ecological Change and Local Governance Systems* (Dissertation). Ottawa, CA: University of Ottawa.

Konar, M., Garcia, M., Sanderson, M. R., Yu, D. J., and Sivapalan, M. (2019). Expanding the scope and foundation of sociohydrology as the science of coupled human-water systems. *Water Resour. Res.* 55, 874–887. doi: 10.1029/2018WR024088

Korlagama, D., Wickrama, S., and Adikari, A. A. (2021). *Preliminary Analysis of the Social Economy of Dried Fish in Sri Lanka. DFM Working Paper*. Available online at: https://api.zotero.org/groups/2183860/items/Z5KCPQ4W/file/view (accessed June 16, 2022).

Kotchen, M. J., and Young, O. R. (2007). Meeting the challenges of the anthropocene: towards a science of coupled human–biophysical systems. *Global Environ. Change* 17, 149–151. doi: 10.1016/j.gloenvcha.2007.01.001

Kumar, B. S., and Mohanta, R. A. (2014). preliminary study on community based traditional fish drying activities of important marine fishes: Ganjam coast, Odisha and Improved scenario using modern technique. *Int. J. Res and Innov. Earth. Sci.* 1, 2394–1375.

Kumar, P., Avtar, R., Dasgupta, R., Johnson, B. A., Mukherjee, A., Ahsan, M. N., et al. (2020). Socio-hydrology: A key approach for adaptation to water scarcity and achieving human well-being in large riverine islands. *Prog. Dis. Sci.* 8, 100134. doi: 10.1016/j.pdisas.2020.100134

Kunwar, P. S., and Adhikari, B. (2016). Status and development trend of aquaculture and fisheries in Nepal. *Nepal. J. Aquac. Fish.* 3, 1–1.

Lebel, L., Anderies, J. M., Campbell, B., Folke, C., Hatfield-Dodds, S., Hughes, T. P., et al. (2006). Governance and the capacity to manage resilience in regional social-ecological systems. *Ecol. Soc.* 11. doi: 10.5751/ES-01606-110119

Lemos, M. C., and Morehouse, B. J. (2005). The co-production of science and policy in integrated climate assessments. *Glob. Environ. Change* 15, 57–68. doi: 10.1016/j.gloenvcha.2004.09.004

Leslie, P., and McCabe, J. T. (2013). Response diversity and resilience in social-ecological systems. *Curr. Anthropol.* 54, 114–144. doi: 10.1086/669563

Levin, S. A. (1998). Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1, 431–436. doi: 10.1007/s100219900037

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., et al. (2007). Complexity of coupled human and natural systems. *Science* 317, 1513–1516. doi: 10.1126/science.1144004

Lokuge, G. (2021). *Dried fish in Cambodia: Literature Review. DFM Working Paper*. Available online at: https://driedfishmatters.org/pub/dried-fish-in-cambodia-literature-review.html (accessed June 20, 2022).

Loucks, D. P. (2015). Debates—Perspectives on socio-hydrology: simulating hydrologic-human interactions. *Water Resour. Res.* 51, 4789–4794. doi: 10.1002/2015WR017002

Lu, N., Liu, L., Yu, D., and Fu, B. (2021). Navigating trade-offs in the social-ecological systems. *Curr. Opin. Environ. Sustain.* 48, 77–84. doi: 10.1016/j.cosust.2020.10.014

Luu, T., Verhallen, M., Tran, D. D., Sea, W. B., Nguyen, T. B., Nguyen, H. Q., et al. (2022). Statistically examining the connection between dike development and human perceptions in the floodplains' socio-hydrology system of Vietnamese Mekong Delta. *Sci. Total Environ.* 810, 152207. doi: 10.1016/j.scitotenv.2021.152207

Marshall, G. A. (2015). Social-ecological systems framework for food systems research: accommodating transformation systems and their products. *Int J Commons* 9, 881–908. doi: 10.18352/ijc.587

McGinnis, M. D., and Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecol. Soc.* (2014) 19, 30. doi: 10.5751/ES-06387-190230

Merton, R. K. (2008). *Focused Interview*. London: Simon and Schuster. Collier Macmillan Publishers.

Moshy, V. H., Bryceson, I., and Mwaipopo, R. (2015). Social-ecological changes, livelihoods and resilience among fishing communities in Mafia Island Marine Park, Tanzania. *Forum Dev. Stud.* 42, 529–553. doi: 10.1080/08039410.2015.1065906

Mostert, E. (2018). An alternative approach for socio-hydrology: case study research. *Hydrol. Earth Syst. Sci.* 22, 317–329. doi: 10.5194/hess-22-317-201810.5194/hess-22-317-2018

Nadanasabesan, N. (2015). *The need for sustainable development of the small-scale fisheries. A case study from the Northern Province, Sri Lanka (Doctoral dissertation, Master's thesis in international fisheries management)*. Faculty of Biosciences, Fisheries and Economics, The Arctic University of Norway (UIT), Tromsø, Norway.

Nayak, P. K. (2014). The Chilika Lagoon social-ecological system: an historical analysis. *Ecol. Soc.* (2014) 19. doi: 10.5751/ES-05978-190101

Nayak, P. K., and Armitage, D. (2018). Social-ecological regime shifts (SERS) in coastal systems. *Ocean Coast. Manag.* 161, 84–95. doi: 10.1016/j.ocecoaman.2018.04.020

Nishat, B. (2019). *Landscape Narrative of the Sundarban: Towards Collaborative Management by Bangladesh and India.* Washington, DC: The World Bank. 1–207.

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., et al. (2020). Principles for knowledge co-production in sustainability research. *Nat. Sustain.* 3, 182–190. doi: 10.1038/s41893-019-0448-2

Nykvist, B., and Von Heland, J. (2014). Social-ecological memory as a source of general and specified resilience. *Ecol. Soc.* (2014) 19. doi: 10.5751/ES-06167-190247

Oki, T. (2016). *Socio-Hydrology on the Global Scale in the Anthropocene. Japan Geoscience Union Meeting 2016.* Tokyo: Institute of industrial Science, University of Tokyo. Available online at: https://www2.jpgu.org/meeting/2016/PDF2016/H-SC02_all_e.pdf (accessed July 02, 2022).

Olsson, P. (2003). *Building Capacity for Resilience in Social-Ecological Systems* (dissertation). Stockholm: Stockholm University.

Olsson, P., Folke, C., and Berkes, F. (2004). Adaptive comanagement for building resilience in social–ecological systems. *Environ. Manage.* 34, 75–90. doi: 10.1007/s00267-003-0101-7

Ommer, R. E., Perry, R. I., Murray, G., and Neis, B. (2012). Social–ecological dynamism, knowledge, and sustainable coastal marine fisheries. *Curr. Opin. Environ. Sustain.* 4, 316–322. doi: 10.1016/j.cosust.2012.05.010

Oshun, J., Keating, K., Lang, M., and Miraya Oscco, Y. (2021). Interdisciplinary water development in the Peruvian Highlands: the case for including the coproduction of Knowledge in socio-hydrology. *Hydrology* 8, 112. doi: 10.3390/hydrology8030112

Ostrom, E. (2011). Background on the institutional analysis and development framework. *Policy Stud. J.* 39, 7–27. doi: 10.1111/j.1541-0072.2010.00394.x

Ostrom, E. (2005). "Policies that crowd out reciprocity and collective action," in *Moral Sentiments and Material Interests: The Foundations of Cooperation in Economic Life*, eds H. Gintis, S. Bowles, R. Boyd, and E. Fehr (MIT Press), 253–275.

Ostrom, E., Gardner, R., and Walker, J. (1994). *Rules, Games, and Common-Pool Resources.* University of Michigan Press.

Ostrom, E. A. (2007). diagnostic approach for going beyond panaceas. *Proc. Nat. Acad. Sci. U. S. A.* 104, 15181–15187. doi: 10.1073/pnas.0702288104

Ostrom, E. A. (2009). general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Pande, S., and Sivapalan, M. (2017). Progress in socio-hydrology: a meta-analysis of challenges and opportunities. *Wiley Interdiscip. Rev. Water* 4, e1193. doi: 10.1002/wat2.1193

Partelow, S. A. (2018). Review of the social-ecological systems framework. *Ecol. Soc.* 23. doi: 10.5751/ES-10594-230436

Peke, S. (2013). *Women Fish Vendors in Mumbai: A Study Report.* International Collective in Support of Fishworkers.

Penny, G., and Goddard, J. J. (2018). Resilience principles in socio-hydrology: a case-study review. *Water Sec.* 4, 37–43. doi: 10.1016/j.wasec.2018.11.003

Pradhan, S. K., Nayak, P. K., and Armitage, D. A. (2022). social-ecological systems perspective on dried fish value chains. *Curr. Res. Environ. Sustainab.* 4, 100128. doi: 10.1016/j.crsust.2022.100128

Pramanik, S. K. (2004). *Dry Fish Production Profile of Indian Sundarban.* New Delhi: Classical Publishing Company.

Preiser, R. (2019). Identifying general trends and patterns in complex systems research: an overview of theoretical and practical implications. *Syst. Res. Behav. Sci.* 36, 706–714. doi: 10.1002/sres.2619

Preiser, R., Biggs, R., De Vos, A., and Folke, C. (2018). Social-ecological systems as complex adaptive systems. *Ecol. Soc.* 23. doi: 10.5751/ES-10558-230446

Rasul, M. G., Chunhong, Y., and Shah, A. A. (2020). Chemical and microbiological hazards of dried fishes in Bangladesh: a food safety concern. *Food Nutr. Sci.* 11, 523–539. doi: 10.4236/fns.2020.116037

Rogers, K. H., Luton, R., Biggs, H., Biggs, R., Blignaut, S., Choles, A. G., et al. (2013). Fostering complexity thinking in action research for change in social–ecological systems. *Ecol. Soc.* 18. doi: 10.5751/ES-05330-180231

Roobavannan, M., Van Emmerik, T. H., Elshafei, Y., Kandasamy, J., Sanderson, M. R., Vigneswaran, S., et al. (2018). Norms and values in sociohydrological models. *Hydrol. Earth Syst. Sci.* 22, 1337–1349. doi: 10.5194/hess-22-1337-2018

Schaefli, B., Harman, C. J., Sivapalan, M., and Schymanski, S. J. (2011). HESS Opinions: Hydrologic predictions in a changing environment: behavioral modeling. *Hydrol. Earth Syst. Sci.* 15, 635–646. doi: 10.5194/hess-15-635-2011

Shamsuddoha, M. (2007). "Supply and value chain analysis in the marketing of marine dried fish in Bangladesh and non tariff measures (NTMs) in international trading," in *Presentation at the 106th Seminar of the EAAE Pro-poor Development in Low Income Countries.* Montpellier: Food, Agriculture, Trade and Environment.

Shyam, S. S., Rahman, M. R., and Nashad, M. (2016). Economic analysis of fish drying units in Kozhikode, Kerala. *Discov. Nat.* 10, 1–8. Available online at: http://discoveryjournals.com/nature/current_issue/v10/n25/

Sivapalan, M. (2006). "Pattern, process and function: elements of a unified theory of hydrology at the catchment scale," in *Encyclopedia of Hydrological Sciences, Vol. 1,* ed M. G. Anderson (London: John Wiley and Sons), 193–220.

Sivapalan, M., Murugesu, M., Konar, V., Srinivasan, A., Chhatre, A., Wutich, C. A., et al. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future.* 2, 225–230. doi: 10.1002/2013EF000164

Sivapalan, M., Savenije, H. H., and Blöschl, G. (2012). Socio-hydrology: a new science of people and water. *Hydrol. Process.* 26, 1270–1276. doi: 10.1002/hyp.8426

Society for Direct Initiative for Social and Health Action (2016a). *2016 Report on 'the Study on Business Prospects of Cooperatives of Small-Scale Marine Fishers in West Bengal, India.* Society for Direct Initiative for Social and Health Action (DISHA). Available online at: https://www.dishaearth.org/SSF%20Business%20prospects_a_study.pdf (accessed March 14, 2022).

Society for Direct Initiative for Social and Health Action (2016b). *2016 Report on 'Asserting Rights, Defining Responsibilities: Small-Scale Fishing Communities and Coastal Fisheries Management Perspectives in East Medinipur Coast in West Bengal, India'.* Society for Direct Initiative for Social and Health Action (DISHA). Available online at: https://dishaearth.org/Fishworkers'%20Rights%20Study%20E.%20Medinipur%20with%20Annexures.pdf (accessed March 14, 2022).

Stange, K. (2017). *Knowledge Production at Boundaries: An Inquiry Into Collaborations to Make Management Plans for European Fisheries (doctoral dissertation).* Wageningen University and Research. Wageningen, Netherlands.

Stephenson, R. L., Paul, S., Wiber, M., Angel, E., Benson, A. J., Charles, A., et al. (2018). Evaluating and implementing social–ecological systems: a comprehensive approach to sustainable fisheries. *Fish Fish.* 19, 853–873. doi: 10.1111/faf.12296

Sultana, P., and Thompson, P. (2010). Local institutions for floodplain management in Bangladesh and the influence of the Flood Action Plan. *Environ. Hazards* 9, 26–42. doi: 10.3763/ehaz.2010.SI05

Sung, K., Jeong, H., Sangwang, N., and Yu, D. J. (2018). Effects of flood control strategies on flood resilience under sociohydrological disturbance. *Water Resour. Res.* 54, 2661–2680. doi: 10.1002/2017wr021440

Thaler, T. (2021). Social justice in socio-hydrology—how we can integrate the two different perspectives. *Hydrol. Scie. J.* 66, 1503–1512. doi: 10.1080/02626667.2021.1950916

Tidball, K. G., Krasny, M. E., Svendsen, E., Campbell, L., and Helphand, K. (2010). Stewardship, learning, and memory in disaster resilience. *Environ. Educ. Res.* 16, 591–609. doi: 10.1080/13504622.2010.505437

Troy, T. J., Konar, M., Srinivasan, V., and Thompson, S. (2015). Moving sociohydrology forward: a synthesis across studies. *Hydrol. Earth Syst. Sci.* 19, 3667–3679. doi: 10.5194/hess-19-3667-2015

Turner, B. L., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., et al. (2003). Illustrating the coupled human–environment system for vulnerability analysis: three case studies. *Proc. Nat. Acad. Sci. U. S. A.* 100, 8080–8085. doi: 10.1073/pnas.1231334100

Van Emmerik, T. H. M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H. H. G., et al. (2014). Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. *Hydrol. Earth Syst. Sci.* 18, 4239–4259. doi: 10.5194/hess-18-4239-2014

Ward, C. D. (2018). *Climate Variability in Social-Ecological Systems of the Southern Cape: Integrating Farming and Fishing Perspectives* (dissertation). Faculty of Science, Department of Environmental and Geographical Science, University of Cape Town, Cape Town, South Africa.

Wescoat, J. L. Jr. (2013). Reconstructing the duty of water: a study of emergent norms in socio-hydrology. *Hydrol. Earth Syst. Sci.* 17, 4759–4768. doi: 10.5194/hess-17-4759-2013

Westley, F. R., Tjornbo, O., Schultz, L., Olsson, P., Folke, C., Crona, B., et al. (2013). Theory of transformative agency in linked social-ecological systems. *Ecol. Soc.* 18, 3. doi: 10.5751/ES-05072-180327

Whitney, C. K., Bennett, N. J., Ban, N. C., Allison, E. H., Armitage, D., Blythe, J. L., et al. (2017). Adaptive capacity: from assessment to action in coastal social-ecological systems. *Ecol. Soc.* 22. doi: 10.5751/ES-09325-220222

Wyborn, C., and Bixler, R. P. (2013). Collaboration and nested environmental governance: scale dependency, scale framing, and cross-scale interactions in collaborative conservation. *J. Environ. Manage.* 123, 58–67. doi: 10.1016/j.jenvman.2013.03.014

Yu, D. J., Chang, H., Davis, T. T., Hillis, V., Marston, L. T., Oh, W. S., et al. (2020). Socio-hydrology: an interplay of design and self-organization in a multilevel world. *Ecol. Soc.* 25. doi: 10.5751/ES-11887-250422

Yu, D. J., Sangwan, N., Sung, K., Chen, X., and Merwade, V. (2017). Incorporating institutions and collective action into a sociohydrological model of flood resilience. *Water Resour. Res.* 53, 1336–1353. doi: 10.1002/2016WR019746

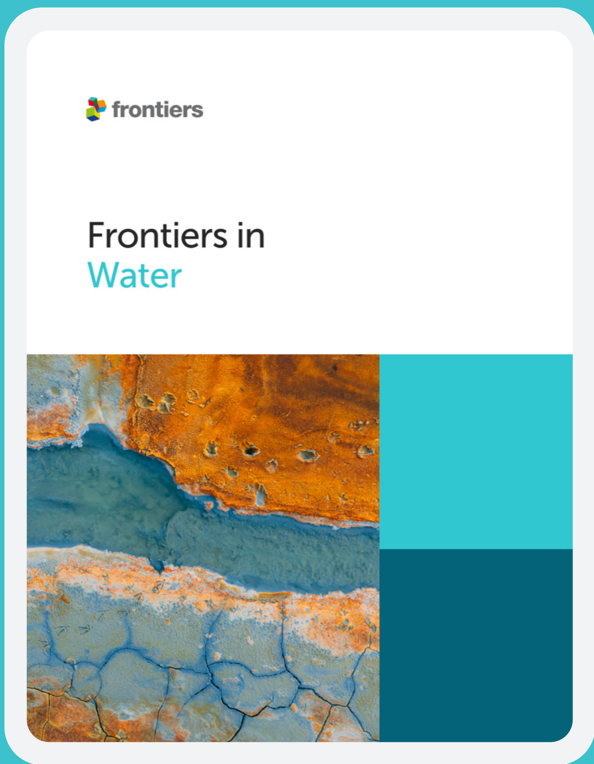
Frontiers in Water

Transforming our approach to water research and its applications

A journal dedicated to exploring challenges facing freshwater systems, including demand and supply of water resources, extreme weather events and climate change.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact