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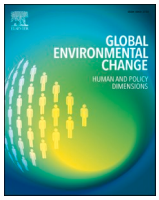

Measuring water insecurity in a changing climate: Rethinking objective and subjective metrics through cross-comparative analysis from Bangladesh and Kenya

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1. Introduction

Climate change is intensifying intra-annual variability in rainfall and temperature, often beyond predictable wet and dry seasons. This shift has significant implications for how water risks are distributed and experienced by households and individuals. Addressing this complexity demands rethinking how water security is conceptualised and assessed – particularly incorporating variability and inequalities across time, space and scale. Global and national monitoring is dominated by objective measures, which emphasise standardisation, aggregation, and comparability, often overlooking contextual nuance. While the scope of objective indicators has expanded from infrastructure-based metrics of access to service delivery indicators – source proximity, faecal contamination, and service reliability - a persistent blind spot remains in capturing seasonality and multiple source use across different purposes. Meanwhile, subjective indicators quantifying lived experiences have gained traction, but their potential to capture intra-annual dynamics and their complementarity with objective metrics across diverse contexts remain underexplored. Advancing conceptual and methodological integration between these approaches is essential to identify who is at risk, when, and why, under conditions of accelerating climatic and social change.

1.1. Intra-annual variability and inequalities in water security

Climate variability - manifested as heatwaves, delayed rainfall onset, or acute hydrological shocks – affects the daily water risks for millions of people living without access to safe and reliable water services. For those reliant on rainfed sources such as seasonal rivers and rainwater harvesting, the onset of rains brings much-needed relief, often reducing the time and money spent on water collection (Hoque and Hope, 2025). Yet decreased reliance on groundwater sources during the wet season can reduce revenues for rural water service providers, jeopardising their financial and operational sustainability (Armstrong et al., 2022; Foster and Hope, 2017). Rainfall also heightens risks of faecal contamination, as surface runoff carries waste into shallow wells and ponds, with higher risks even detected in treated piped water (Dongzagla et al., 2021).

These temporal dynamics manifest differently across space, along the urban-rural continuum. Variations in infrastructure development, economic activity, demographic composition, and cultural norms shape both exposure to intra-annual hydroclimatic changes and the capacity to cope with them. Urban areas may benefit from piped water networks, though supplies can be unreliable, particularly in poorer neighbourhoods. Peri-urban fringes, often neglected by both urban and rural governance, face overlapping risks from rapid urbanisation, ecological degradation, unreliable water access, and weak institutional recognition (Joshi et al., 2022; Ranganathan and Balazs, 2015). With uneven or absent piped coverage, private boreholes and informal water vendors may meet demand, albeit at high costs (Zhao et al., 2025). Rural areas, more attuned to natural cycles of water availability, depend heavily on communal ponds or self-supply wells. Consequently, the water expenditures of rural households closely mirror rainfall patterns (Hoque and Hope, 2025), highlighting their sensitivity to climate variability.

Temporal and spatial heterogeneities are further layered by disparities at the household and individual scales. Young et al. (2022) showed how urbanicity interacts with household wealth - low-income households in city outskirts, suburbs, and small towns experience higher water

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insecurities compared to wealthier households across all urbanicity categories. Higher income enhances coping capacity by enabling households to install private boreholes, expand storage, or purchase bottled water, thereby buffering them against intermittent piped supply and seasonal scarcity. Within the household, women and girls disproportionately bear the burden of water scarcity through responsibilities for collection, treatment, storage, and allocation (Sultana, 2011; Bose et al., 2024). Emerging research shows that outcomes are shaped not only by gender but also by intrahousehold dynamics, where age, social norms, property rights, and infrastructure influence bargaining power and decision-making (Hillesland and Doss, 2024).

1.2. Objective and subjective measures of water security

Objective indicators of water security are commonly reported to quantify progress and identify investment needs in line with global policy discourse. As human well-being and social equity gained prominence in development thinking, global goals evolved from improved infrastructure access under the Millennium Development Goal (MDG) Target 7c to universal and equitable access to safe and affordable drinking water under the Sustainable Development Goal (SDG) Target 6.1. New indicators on source proximity, faecal contamination, and service reliability have altered policy priorities. Monitoring instruments such as the Multiple Indictor Cluster Survey (MICS Round7) now records drinking source for wet and dry seasons and weekly collection frequency and duration for main source by primary collector (UNICEF, 2023). Yet globally and nationally reported statistics are still confined to service classifications based on main source type, distance or collection time and faecal contamination measures, that too, for the main drinking source only. Recent availability of national and sub-national data, particularly in low- and middle-income countries, has improved reporting on inequalities between urban and rural areas and across wealth quintiles (WHO/UNICEF, 2025). While welcome, such disaggregation still conceals pockets of severe crisis, for example, informal settlements within large cities.

Most academic studies are cross-sectional, accommodating seasonality through recall rather than repeated observation. Cronk et al. (2024) analysed source switching across 14 countries where household respondents recalled their primary and secondary water sources. Longitudinal studies are fewer, often limited in scope. For instance, Broyles et al. (2023) used panel data from pre- and post-monsoon seasons in Bangladesh to examine household characteristics, water use, and water insecurity, but only included binary indicators for source type, collection time, payment, storage, and treatment. Hoque and Hope (2025) advanced this field by implementing year-long daily water diaries with 400 households across Ethiopia, Kenya, and Bangladesh to capture intra-annual variability in water sources and expenditures. While offering temporal granularity, the data did not distinguish between drinking and non-drinking uses or identify specific waterpoints, limiting understanding of how households trade-off between quality, distance, and reliability.

Mainstream monitoring tools generally assess water access at the household level, reducing gender analysis to time or distance spent fetching water. While research on water insecurity has largely centred on women's disproportionate physical and emotional burdens shaped by gendered norms and power relations (Ray, 2007, Collins et al., 2019, Sultana, 2011), growing scholarship now examines how masculinities influence water insecurity, with men frequently performing physically demanding or risky tasks and engaging in water labour using transport technologies such as bicycles or trucks (Adams, 2024; Geere and Cortobius, 2017). Gendered differences also extend to children, with girls more commonly responsible for water collection than boys, particularly in rural areas (Graham et al., 2016), though evidence on children remains limited. As climate variability intensifies, understanding how gender and age intersect with culture and context is becoming increasingly vital in explaining the redistribution of water-related responsibilities and burdens (Brewis et al., 2024).

Subjective indicators, grounded in constructivist traditions that emphasise lived experience, local knowledge, and contextual specificity, are gaining traction. The Household Water Insecurity Experiences (HWISE) Scale and the Individual Water Insecurity Experiences (IWISE) Scale use recall-based questions - covering past 4-weeks or 12-months - on how frequently households or individuals encounter water-related problems across multiple dimensions, such as insufficient quantity, access constraints, reliability issues, and psychosocial distress (Jepson et al., 2017, Young et al., 2019).

These scales have been widely applied across more than 55 countries and by over 100 organisations to reveal gendered inequalities (Khalid et al., 2024), inform policy and advocacy, guide emergency and poverty reduction programs, monitor the impact of interventions (Miller et al., 2025), and link water insecurity to food security (Young et al., 2023), disease and treatment adherence (Nutor et al., 2024), and psychosocial well-being (Wutich et al., 2022). They are also being incorporated in nationally representative surveys, such as Mongolia's MICS Plus survey (NSO/UNICEF, 2022) and Mexico's National Health and Nutrition Survey (Connors et al., 2026). The IWISE scales are also recommended by the Joint Monitoring Programme (JMP) as priority gender specific WASH indicators (Caruso et al., 2024). Despite this popularity, their application remains cross-sectional, with limited exploration of their utility in capturing intra-annual variation or socio-spatial inequalities, and of how they complement objective metrics.

1.3. Aim and approach

This study addresses the following research question: What is the relationship between subjective measures and objective metrics of water security, and how does it vary with seasons and urbanicity?

The study employs a methodological design with four core elements: (i) cross-comparative analysis across diverse hydroclimatic and socio-cultural settings in urban, peri-urban, and rural sites in two climate-vulnerable countries – Bangladesh and Kenya; (ii) longitudinal data collection across seasons; (iii) a multi-method approach that integrates objective and subjective measures of water insecurity; and (iv) intra-household analysis to capture gender- and age-specific responsibilities and experiences. The study critically evaluates the strengths and limitation of objective and subjective measures to capture intra-annual variability and to highlight the drivers and distribution of water insecurity.

2. Research design

The study was led by an international research team from the University of Oxford, Bangladesh University of Engineering and Technology, and University of Nairobi. Ethical approval was granted by Oxford's Central University Research Ethics Committee (CUREC) (SOGE-1 A-2021-042). In Kenya, this research was covered by the National Commission for Science, Technology and Innovation (NACOSTI) research permit. The study was conducted in Khulna district of Bangladesh and Turkana county in Kenya, with sites disaggregated as urban, peri-urban and rural within each country.

2.1. Contextual background

2.1.1. Bangladesh

Khulna district lies within the deltaic floodplain of the Ganges–Brahmaputra–Meghna catchment and is shaped by tidal rivers flowing towards the Bay of Bengal. Annual rainfall averages 1800–2000 mm, concentrated in the monsoon months, with temperatures ranging from 12 to 15 °C in winter to 30–35 °C in summer. Tropical cyclones and storm surges frequently breach embankments, inundating settlements and farmland with saline water. Groundwater salinity and fragmented infrastructure development constrain access to safe drinking

water. Around 75% residents rely on tubewells, with smaller proportions using piped water, rainwater, surface water, or bottled water (BBS, 2023). Faecal contamination remains widespread: *E. coli* is present at the point of collection for 37% households and at the point of use for 84% (BBS/UNICEF, 2021). Public investments tend to favour low-salinity areas, leaving high-salinity zones dependent on small donor-supported systems such as reverse osmosis plants, pond sand filters, and local piped schemes (Hoque, 2023).

The district comprises Khulna City Corporation (KCC) and nine upazilas. This study included three KCC wards, including two low-income settlements. Piped water supplied by Khulna Water Supply and Sewerage Authority (KWASA), mostly used for non-drinking used due to salinity, covers part of the city, while private boreholes contribute to falling groundwater levels. Three villages in Dumuria and Batiaghata upazilas served as peri-urban sites, marked by rising land values and livelihood transitions. Six villages in Koyra and Dacope upazilas, reliant on shrimp farming and forest-based work, were selected as rural sites (Fig. 1).

2.1.2. Kenya

Turkana county is Kenya's largest and driest county, with high poverty levels, low literacy, and recurrent drought. Rainfall varies from 900 to 1700 mm annually in upstream areas of the Turkwel basin to around 200 mm near Lodwar (Hirpa et al., 2018), which experiences frequent droughts, including the 2022 event following five consecutive below-average rainy seasons. Thirty-six percent of residents rely on surface water for drinking, followed by piped supplies, boreholes, and vendors (KNBS, 2019). Lodwar, a rapidly expanding town of about 83,000 people, is supplied by the Turkana Urban Water Company through a borehole-fed piped network, though many households still depend on kiosks, neighbours, and wells.

The study included three urban neighbourhoods (California, Napatet, Kawalase), four peri-urban neighbourhoods (Lokaparparei, Ichakun IDP, Natapar Kakono, Natoot), and four rural communities situated 8–40 km from Lodwar (Nayanae Ang'ikalalio, Kakwanyang, Loreng'elup, Kapua) (Fig. 2).

2.2. Methods

2.2.1. Data collection

The study employed a mixed-methods approach, including seasonal intra-household surveys, water infrastructure audits, and individual interviews, with data collection sequenced by season and method in 2023. Study tools were developed iteratively through cross-country workshops involving researchers from both countries, while scoping visits and field reflections were used to identify methodological challenges, refine instruments, and maintain consistency across contexts.

In each country, qualitative data was collected by two researchers, one man and one woman, while quantitative fieldwork was coordinated by a male researcher who trained and supervised enumerators. These

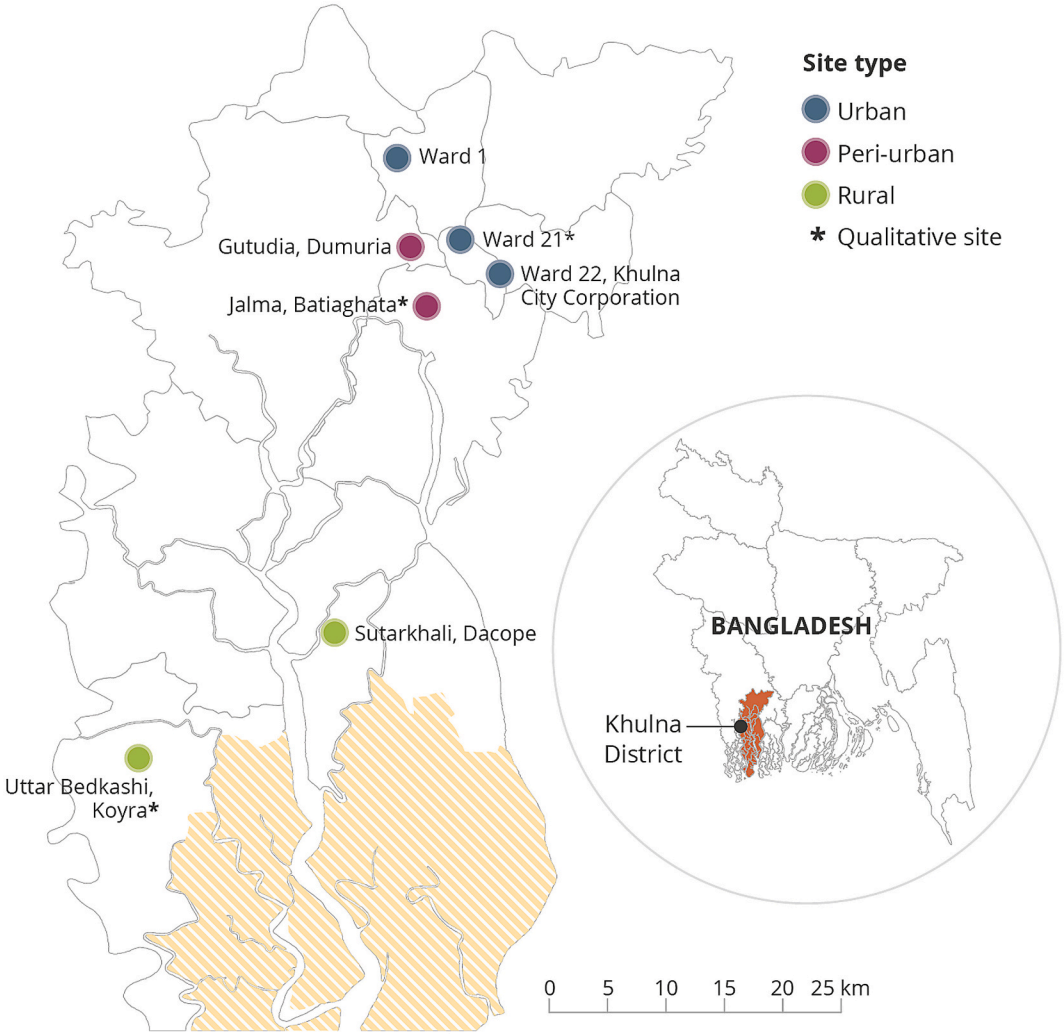

Fig. 1. Map of Khulna district in Bangladesh showing locations of the urban, peri-urban and rural study sites.

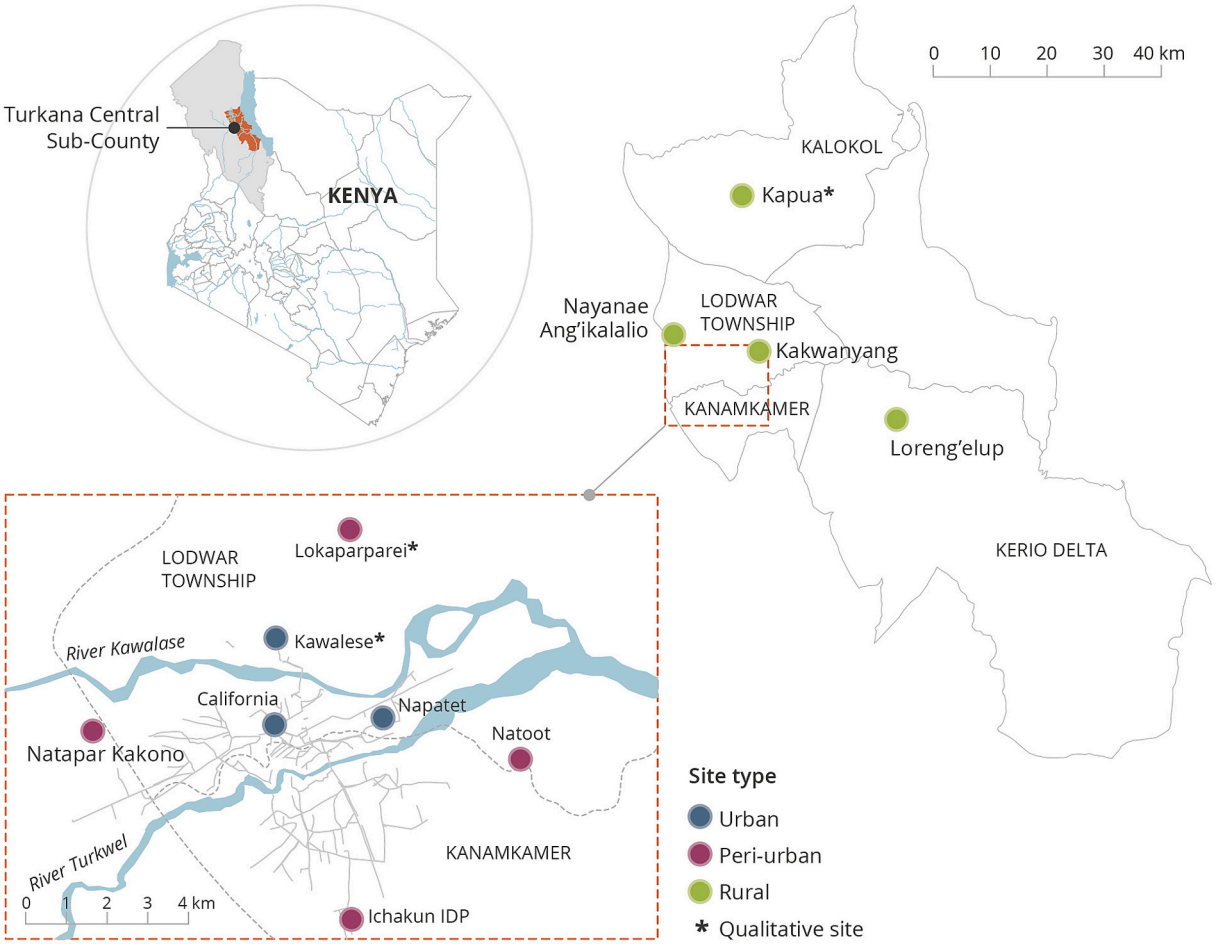

Fig. 2. Map of Turkana Central sub-county of Turkana County in Kenya showing locations of the urban, peri-urban and rural study sites.

researchers underwent training in research methods, ethics, safeguarding, and digital data collection, and were supervised by senior researchers from Oxford, who also participated in pilot data collection. Reflexive discussions on positionality were particularly relevant for qualitative research, recognising how differences in class, education, gender, ethnicity, and urban-rural background could shape researcher-participant interactions and influence data collection and interpretation. Details of data collection are outlined in the Supplementary Materials and summarised in Table 1, with further content on the overall study published in Charles et al. (2025).

Table 1
Data collection methods, with numbers referring to sample sizes.

Description	Site type	Kenya			Bangladesh		
		Hot-wet (May 2023)		Hot-dry (Sep 2023)	Cold-dry (Feb 2023)	Hot-dry (May 2023)	Hot-wet (Sep 2023)
Intra-household survey							
• Three seasons in Bangladesh and two in Kenya	Urban	140		123	100	99	99
• Household survey (~550 households per country): Primary respondent, >18 years, knowledgeable about household assets and water collection	Peri-Urban	160		136	150	149	144
• Individual survey (~1100 individuals per country): Primary and secondary respondent, ideally the spouse or another adult of the opposite sex.	Rural	252		227	305	304	303
	Total	552		486	555	552	546
Semi-structured interviews							
• Men and women selected across HWISE and wealth categories to capture variation in water security and poverty.		Men	Women	HHs	Men	Women	HHs
• Explored gender norms, household dynamics, and decision-making around water management, safety, and adaptive responses during disruption.	Urban	7	9	10	10	10	10
	Peri-Urban	6	9	10	9	11	11
	Rural	8	9	10	10	10	10
	Total	**21**	**27**	30	**29**	**31**	31
Water infrastructure audit							
• Covered all public, community, and commonly used private sources, irrespective of their use for drinking or non-drinking purposes.	Urban	10			155		
• Data collected on source location, technical specifications, ownership, funding, management responsibilities, and usage patterns.	Peri-Urban	27			128		
	Rural	47			342		
	Total	84			625		

2.2.2. Quantitative data analysis

Quantitative data from intra-household surveys and water audit were cleaned, analysed and visualised using Microsoft Excel and R Studio. The analysis of objective indicators covered the household's complete water portfolio, extending beyond the main drinking source to include all water sources used during the four weeks preceding the survey. Each source was linked to the household's roster of waterpoints, including on-dwelling, land-based, and community sources identified through infrastructure audits, to establish their locations and calculate distances using GPS coordinates. For sources requiring water to be carried home, the survey recorded the household members responsible for collection, the daily or weekly collection frequency, mode of transport, and total time spent, including waiting times. These records were matched with household member details to quantify collection responsibilities by gender and age, accounting for multiple trips and multiple sources used.

In Kenya, additional questions about the number and size of jerrycans used the previous day enabled precise calculations of per capita water use, as households typically collected all their water and could recall quantities accurately. In Bangladesh, where diverse container types were used and water usage often occurred directly at sources like rivers or tubewells, estimating total household water use proved challenging. Perception of water quality, reliability, and conflict was based on respondent's subjective evaluation for each source used.

The households'/ individuals' subjective water insecurity experiences were quantified using the 12-item HWISE/IWISE scales. Each item was rated on a 4-point Likert scale reflecting the frequency of challenges encountered in the past four weeks. These challenges included psychosocial distress (worry, anger, shame), limited water quantity for washing (body, clothes, hands), unreliability (source interruptions, plan changes), and extreme scarcity (lack of water, sleeping thirsty, insufficient drinking water). The aggregate HWISE and IWISE scores (out of 36) were treated as continuous variables for descriptive analysis. For the regression model, the HWISE scores were grouped into four ordinal categories - no-to-marginal (0–2), low (3−11), moderate (12−23) and high water insecurity (24–36), following Frongillo et al. (2024).

Mixed-effects ordinal logistic regression models were used to estimate associations between four HWISE severity categories (outcome variable) and multiple dimensions of water service and household characteristics (predicator variables). These included source-use configuration for drinking and domestic purposes, distance to improved and unimproved water sources, collection time categories, perceived reliability, perceived water quality, conflict risk, and whether water sources required payment. Demographic variables included wealth quartile, respondent gender, and the presence of child water collectors. Season and spatial context (urban, peri-urban and rural settlements in Kenya; administrative areas in Bangladesh) were included as contextual variables. For Kenya, the broader site types were used instead of administrative areas, as the some of the latter contained relatively small numbers of households across the four HWISE severity categories, limiting the stability of the ordinal regression model. Household-level random intercepts were incorporated to account for repeated observations from the same households across survey waves (See Supplementary Materials for details).

Gender differences in IWISE scores were analysed using the Wilcoxon signed-rank test, applied to all paired man–woman observations within the same household (Table S3).

2.2.3. Qualitative data analysis

The interview transcripts were translated, with identifier codes linked to the survey data. An iterative thematic analysis, informed by constructivist grounded theory principles (Braun and Clarke, 2006), was conducted using NVivo. Initial codes were developed through repeated review of pilot-stage interviews, field reflections, and early survey findings, allowing themes to emerge inductively from the data while also reflecting the study objectives and interview guides. Preliminary codes were refined through multiple team discussions into a standardised codebook with clearly defined inclusion and exclusion criteria. The codebook was tested through group coding and inter-coder comparison, with discrepancies discussed collectively to improve consistency and refine code definitions. Following agreement, the dataset was divided among researchers for full coding, with iterative refinements made throughout the analysis process. Quotes presented in this study are coded to indicate the country, site type, and gender of the respondent (e.g. BU-W refers to a woman respondent from an urban site in Bangladesh).

3. Results

This section examines how subjective experiences of water insecurity align with objective indicators across seasons and the urban–rural gradient in Kenya and Bangladesh. The analysis first presents the spatial and seasonal variations in water services, comparing objective measures of access, quality, quantity, reliability, and costs across multiple sources (see Table S5–6 for site-wise statistics). It then compares descriptive statistics, regression results, and qualitative findings to assess how these service conditions are reflected in subjective measures, including aggregate HWISE and IWISE scores and item-level responses. Finally, the analysis moves from household to the individual, examining the gendered distribution of water collection responsibilities and differences in IWISE scores.

3.1. Intra-annual dynamics of water services across urban-rural continuum

3.1.1. Urban

Urban water access is shaped less by seasonal source switching than by neighbourhood-level inequalities in infrastructure coverage, reliability and water quality, which drive widespread use of multiple supplementary sources.

In Kenya's Lodwar town, centrally located neighbourhoods benefit from the utility's piped water supply, with 95% households in California having a private or shared connection, paying between KSh 100 and 2000 (average: KSh 580 or USD 4.2) monthly. Though the piped water is generally of good quality, the supply is unreliable, leading residents to supplement with water from community handpumps and motorised boreholes. Due to on-premises availability, California records the highest water consumption, averaging 17 l per capita daily (lpcd) in the hot-wet season and 11.9 lpcd in the hot-dry season. In comparison, in peripheral neighbourhoods like Napatet, only 40% households have piped connections and many depend on community handpumps that provide relatively saline water, costing KSh 10 per 20-l jerrycan (USD 3.6/m^3). Water access is precarious outside the utility's service area, with Kawalase depending on water vended from the utility's boreholes (KSh 10/jerrycan) or surface water from the River Kawalase. The river water, likely to be contaminated with faecal waste, becomes more saline as the dry season progresses. *"If you are the first one to collect, you'd need to scoop out the top layer to remove visible dirt"* (KU-M).

Similar to urban sites in Kenya, half of households in Bangladesh's Khulna city have an improved source on premises, either a piped connection from KWASA or a private borehole. However, KWASA's piped water is saline. In Ward 1, 60–70% households use this water for non-drinking purposes, while only 2–7% use it for drinking, relying instead on neighbours' deep tubewells. Ward 21 lacks piped connections due to its informal settlement status, and motorised boreholes installed by NGOs serve as the primary water sources. *"This year, a deep tubewell was installed nearby [2 minutes walking distance], which we helped fund. Even with slow flow, it was for the first time, we didn't have to go to the new market [20 minutes away] for water in the dry season"* (BU-W).

Ward 22 faces the most severe water challenges, with most households relying on only two handpumps within a wood mill's premises for drinking, while the river and piped water are used for washing and

bathing. Although the mill's tubewells generally provide good quality water the *"water doesn't rise properly"* during low tides, particularly in hot-dry season, leading to long waiting times (BU-W). The route to the water source becomes hazardous in the monsoon due to slippery conditions. Water stress is intensified during Ramadan, which has coincided with the driest months in recent years and is exacerbated by frequent tubewell breakdowns due to high demand. The piped water has an unpleasant odour, described as smelling like *"bleach"* or *"drain water,"* and reportedly causes stomach problems. Ward 22 exhibits the lowest water quality satisfaction in urban Khulna. Compared to urban Kenya, where distances to non-dwelling sources average between 2.1 and 2.5 km, waterpoints are relatively nearby, within 0.6 km.

3.1.2. Peri-urban

Peri-urban water security depends strongly on proximity to formal service networks, with households outside these systems facing greater distances, higher costs and unreliable alternatives, although access is comparatively better where usable groundwater is locally available.In Kenya's peri-urban areas, being outside LOWASCO's service area means access is hindered by long distances (>3 km) and limited on-premises sources. Natoot experiences the most reliable access, with free water from a school borehole and nearby tap connections. The Internally Displaced Population in Ichakun benefit from several prepaid kiosks charging KSh 5–10/jerrycan (USD 1.8–3.6/m^3), offering consistent access to improved sources. The challenge is greatest in Lokaparparei, where local sources include a private water tank costing KSh 30/jerrycan (USD 10.7/m^3), and a county-managed free tank, both being filled by tanker trucks from LOWASCO's boreholes. However, the county tank is only filled occasionally, while the private one is unaffordable for many. *"Today I might have some money, but tomorrow I might not. Another day I may even have KSh 200, but I may need to buy food with that."* (KP-M). Affordability constraints also extend to purchasing firewood or chemicals for water treatment and replacing damaged jerrycans. *"The road to the river is full of stones. If you roll the jerrycans, they will break in a few weeks"* (KP-W). The alternatives are a recently installed school borehole and River Kawalase, both of which are salty and make it *"difficult to urinate"* when drunk and *"eats away the clothes"* when washed. Collection time surges from 0.5 to 1.7 h between hot-wet and hot-dry seasons, with increasing male involvement (ratio shift from 2.8 to 1.7), while per capita consumption falls (9.2 to 8.7 lpcd).

Peri-urban sites in Bangladesh reported less water-related problems due to availability of low-saline groundwater. Drinking water comes from deep tubewells (hand-pumped or motorised), with 23% households having their own tubewell on premises, while the rest rely on neighbours or public waterpoints. *"We get water from our neighbour's tubewell. We have good relations with him, but I worry what if he refuses to give water one day"* (BP-M). There are also two piped schemes from private boreholes. *"The water comes 15 days a month. The operator may be away sometimes or wants to save electricity bill. But he will start calling for money at the start of each month. We can't even talk harshly as he might cut the line"*.

3.1.3. Rural

Rural water security is highly seasonal and precarious, with dependence on surface water, rainwater and limited storage increasing collection burdens and water quality risks in dry periods, while infrastructure, donor support and household affordability strongly shape access to safer alternatives.

Compared to urban and peri-urban sites, the quantity of water consumed is lowest in rural Kenya averaging 9.7 lpcd in the hot-wet season and 8.7 lpcd in the hot-dry season. In Kapua, 95% residents depend on rivers, with boreholes or wells supplementing household needs. The river water in Kapua is *"fresh and sieved by the sand"* compared to the saline boreholes at the foot of the hills which *"makes your stomach full, but heart dry"* (KR-W). While source type remains relatively unchanged across seasons, collection distances increased from 2.6 km to 3.5 km (Table S6) as people needed to walk downstream to find water. Dependence on rainwater and ponds also leads to significant seasonal variations in water quality in rural Bangladesh, with only 39% households reporting good quality in the hot-dry season rising to 72% in the hot-wet season (Table S5). *"The pond water remains good only during the rainy season,"* but as rainfall decreases, *"the quality starts to degrade"* due to contamination from *"leaves, fish, and duck waste,"* rendering it unusable for cooking and even dishwashing (BR-M). Rainwater is the preferred source, with one woman stating *"Cooking with rainwater gives the meat such a beautiful colour! When people ask the secret of my tasty food, I say it's rainwater."* (BR-W).

However, lack of storage capacity is the biggest barrier, with localised differences between villages in Dacope (Fig. S2). Only 21% households in Sutarkhali possess large storage tanks, compared to 65–68% in Nalian and Kalabogi villages. This difference is due to long-term donor interventions in cyclone affected villages, where households received storage tanks. The piped scheme installation in Dacope brought short-term relief, but the need to clean the source pond in the hot-dry season and frequent functionality challenges makes the supply unreliable. The rise of desalination plants provides an alternative in the hot-dry season, but *"each 30-litre container costs BDT 30 (USD 0.29), which can rise to BDT 40 during high-demand periods"* (BR-M). This is a significant cost for families with irregular income, mostly reliant on seasonal fishing or forest-based livelihoods.

3.2. Alignment and divergence between subjective and objective water insecurities

There are significant spatial and seasonal in households' HWISE scores, as illustrated in Fig. 3. and Table 2, with regression models showing the extent to which the observed differences are explained by objective indicators of water services, seasons and household characteristics (Fig. 4).

In Bangladesh, households surveyed during the hot-dry season had almost four times higher odds of belonging to a more severe HWISE category (OR = 3.94, CI:3.04–5.11) compared to the cold-dry season, while there was no significant difference between the cold-dry and hot-wet seasons. Although Ward 22 and Dacope recorded the highest mean HWISE scores during the hot-dry season, Ward 22 was not significantly different from the reference site (Ward 1) once water service and household characteristics were controlled for. In contrast, households in Dacope had three times higher odds of experiencing greater water insecurity (OR = 2.98, CI:1.74–5.09), while households in Ward 21 had substantially lower odds (OR = 0.28, CI:0.15–0.53). This suggests that the water insecurity observed in Ward 22 is largely explained by differences in water services, whereas Sutarkhali exhibits additional place-specific vulnerabilities not fully captured by the model.

Compared to those with improved drinking water available on premises, households not using an improved source (OR = 3.04, CI:1.76–5.23) or travelling up to 2 km to access one (OR = 1.70, CI:1.27–2.26) had higher odds of severe water insecurity. Perceived conflict risk, reliability, water quality and collection burden emerged as strong predictors. Risk of conflicts with neighbours or community more than doubled the odds of severe water insecurity (OR = 2.55, CI:1.95–3.32). Households reporting that 'all sources were always available' (OR = 0.61, CI:0.48–0.79) and that their drinking water was 'always of good quality' (OR = 0.28, CI:0.22–0.35) had considerably lower odds of severe water insecurity. Collection burden remained important, with cumulative collection time of more than two hours per day doubling the odds of severe water insecurity (OR = 2.32, CI:1.59–3.38) compared to those having all sources on premises or delivered.

In Kenya, despite objective indicators and qualitative data showing increased hardships in hot-dry season, households on average reported lower HWISE scores in the hot-dry season - 60% lower odds of belonging to a more severe HWISE category than the hot-wet season (OR = 0.39, CI:0.29–0.52). This mismatch is intriguing, with some plausible

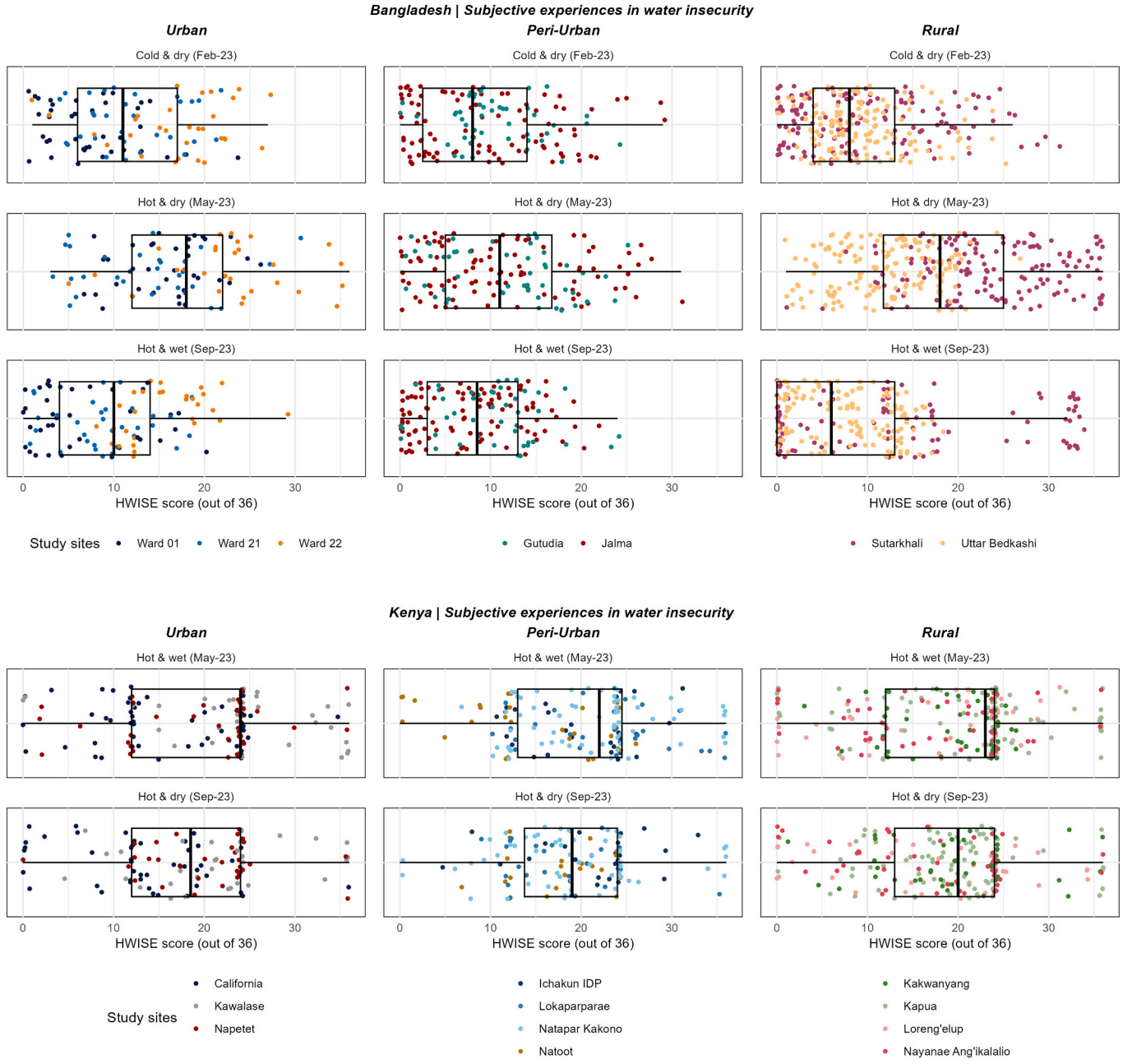

Fig. 3. Seasonal and spatial variations in household experiences of water insecurities in Bangladesh and Kenya.

explanations. Kenya endured five consecutive below-average rainy seasons, leading to its most severe drought in recent history. However, above-average Mar-May 2023 rains brought significant recovery in forage and water resources, alongside flash floods in some areas. This improvement likely influenced subjective experiences, as people compared the dry season to harsher previous years. A woman in Kapua reported very low water insecurity (HWISE = 10) in the dry season, while fetching three jerrycans of water daily with her two children from a river 4 km away. She mentioned, *"This place is good now; people can dig wells wherever there is grass nearby. When there was no grass [referring to the drought], we had to cross two rivers and go to the other side of the hill to get water"* (KR-W). Unexpected rains before and during the September survey may also have introduced a 'recency bias' in participants' reporting.

In Kenya, both peri-urban (OR = 0.55, 95% CI:0.35–0.89) and rural households (OR = 0.38, 95% CI:0.23–0.63) had significantly lower odds of belonging to a more severe HWISE category than urban households. At first glance, this appears inconsistent with the high HWISE scores observed in locations such as Lokaparparei. However, the regression indicates that these spatial differences are largely explained by underlying service conditions included in the model, rather than an independent effect of settlement type itself. Households without an improved drinking source had four times higher odds (OR = 4.28, CI:2.22–8.25), while households travelling up to 2 km (OR = 2.40, CI:1.42–4.07) or > 2 km (OR = 3.40, CI:1.77–6.54) to access improved sources also faced greater insecurity than those with on-premises access. Reliance on unimproved water sources was associated with substantially higher odds of severe water insecurity, particularly where sources were distant. Reliability was again a major predictive factor; households whose entire water portfolio consisted of always-available sources had half the odds of severe water insecurity (OR = 0.49, CI:0.35–0.68). Collection burden also remained important, with daily collection times

Table 2
Distribution of households across different indicators of water access, perceptions of service levels, collection burden, and subjective experience of water insecurity by season.

Variable	Category	Bangladesh			Kenya	
		Hot-wet	Hot-dry	Cold-dry	Hot-wet	Hot-dry
HWISE severity	No-to-marginal (0–2)	32.6%	4.9%	18.6%	6.2%	6.0%
	Low (3–11)	32.8%	26.7%	47.7%	9.0%	11.5%
	Moderate (12–23)	29.7%	47.5%	30.1%	36.5%	51.0%
	High (24–36)	4.9%	20.9%	3.6%	48.3%	31.6%
Respondent gender	Female	78.4%	78.4%	78.7%	47.2%	48.1%
	Male	21.6%	21.6%	21.3%	52.8%	51.9%
Wealth quartile	Poorest	24.7%	24.9%	25.1%	24.6%	25.1%
	Lower-middle	24.9%	24.9%	24.9%	25.3%	25.8%
	Upper-middle	25.3%	25.2%	24.9%	24.8%	23.4%
	Wealthiest	25.1%	25.0%	25.1%	25.3%	25.6%
Use of improved drinking water source	No improved drinking source	5.1%	4.4%	4.9%	22.8%	31.3%
	Improved on premises	50.5%	39.0%	43.7%	17.6%	13.9%
	Within 2 km	43.4%	54.4%	49.8%	48.1%	40.7%
	Beyond 2 km	0.9%	2.2%	1.6%	11.6%	14.1%
Use of unimproved source for any purpose	No unimproved source	34.6%	34.1%	21.8%	55.2%	58.1%
	Unimproved source on premises	52.0%	47.5%	57.2%	2.2%	1.0%
	Within 2 km	11.9%	17.2%	18.4%	25.1%	14.8%
	Beyond 2 km	1.5%	1.1%	2.5%	17.4%	26.1%
Reliability	All sources are always available	31.1%	15.4%	25.3%	33.9%	34.0%
	At least one unreliable source	68.9%	84.6%	74.7%	66.1%	66.0%
Perceived conflict risk at shared sources	No	76.0%	60.4%	61.9%	51.0%	43.5%
	Yes	24.0%	39.6%	38.1%	49.0%	56.5%
Cost	Free	81.1%	63.5%	55.2%	46.8%	48.8%
	Paid source	18.9%	36.5%	44.8%	53.2%	51.2%
Perceived water quality	Always good quality	31.1%	15.4%	25.3%	33.9%	34.0%
	Not always good quality	68.9%	84.6%	74.7%	66.1%	66.0%
Source-use configuration	Different drinking and domestic sources	76.0%	60.4%	61.9%	51.0%	43.5%
	Domestic-only source	24.0%	39.6%	38.1%	49.0%	56.5%
	Drinking-only source	81.1%	63.5%	55.2%	46.8%	48.8%
	Same drinking and domestic source	18.9%	36.5%	44.8%	53.2%	51.2%
Child collectors (<18 yr) present	No	92.9%	87.8%	96.8%	60.0%	52.9%
	Yes	7.1%	12.2%	3.2%	40.0%	47.1%
Cumulative time across all collectors and sources	On premises/delivered	39.4%	17.4%	42.6%	19.3%	9.1%
	≤30 min/day	31.0%	24.5%	19.1%	15.4%	6.5%
	31–60 min/day	11.5%	20.0%	12.1%	11.2%	10.3%
	61–120 min/day	11.5%	14.3%	14.6%	17.4%	16.3%
	>120 min/day	6.6%	23.8%	11.6%	36.7%	57.9%
Gender composition of collectors (Ratio of female: male collectors)	No collectors (Only on-premises sources)	39.9%	17.2%	42.1%	19.1%	5.7%
	Balanced (=1)	12.5%	29.4%	9.9%	23.3%	21.3%
	Female only	41.9%	43.7%	34.3%	49.7%	64.6%
	Male only	5.7%	8.7%	13.7%	6.1%	5.0%
	Mostly female (>1)		0.9%		1.1%	2.4%
	Mostly male (<1)				0.7%	1.0%

exceeding 30 min increasing the likelihood of severe water insecurity.

Across both countries, households using the same set of sources for drinking and domestic purposes generally reported lower HWISE scores than those relying on mixed or unimproved source combinations. However, after controlling for water service characteristics, source-use configuration was not independently associated with water insecurity in most cases, with only weak evidence that households reporting drinking-only sources experienced greater insecurity in Bangladesh. Wealth, respondent gender, the presence of child collectors, and the gender composition of water collectors were not independently associated with HWISE severity after adjustment.

Household-level random effects were larger in Kenya (variance = 0.78) than in Bangladesh (0.26), indicating greater unexplained heterogeneity between Kenyan households after accounting for observed predictors. This is expected given the mismatch between the HWISE scores and objective indicators in the hot-dry season.

Comparisons of HWISE item scores reinforce these contextual insights (Fig. 5). In Bangladesh, regardless of season or site, psychosocial distress indicators - worry (average - 1.66 out of 3), anger (1.33), and shame (1.10) - were consistently higher than indicators related to hygiene (e.g., handwashing (0.43), body washing (0.66)). These patterns might be indicative of water insecurities driven by quality concerns (mostly salinity) rather than quantity – as availability of source on-premises, albeit of poor quality, eases high volume uses like washing and bathing. In contrast, Kenya exhibited uniformly high scores across all domains, including hygiene (e.g., handwashing (1.55), body washing (1.72)) and severe deprivation indicators like no usable water (1.54) and insufficient drinking water (1.71), indicating a broader, more acute water crisis driven by quantity constraints and unreliable infrastructure.

3.3. Gendered burdens and individual subjective experiences

Gender differences in water collection responsibilities are evident in the objective indicators, and the qualitative accounts. Cultural norms are stricter in rural Kenya, where a man is deemed to be *"belittled and controlled by his wife"* if he is seen fetching household water, as his responsibility is looking after the livestock. The woman is the *"one who feels the pain"* (KR-W) of water stress and allocates it for different uses and people within the household. Dry periods bring increased hardship for women, with one recounting that *"You cannot travel anywhere. You cannot sleep thinking about where to get water the next day. Managing the little water you get causes quarrels at home"*. Collection becomes time consuming, with women needing to wake up early and go to the river. *"The water level goes so low that you need to wait for two hours for the well to replenish after someone has collected water"* (KR-W). By the time the mother returns, there is no time to boil, and the thirsty children often

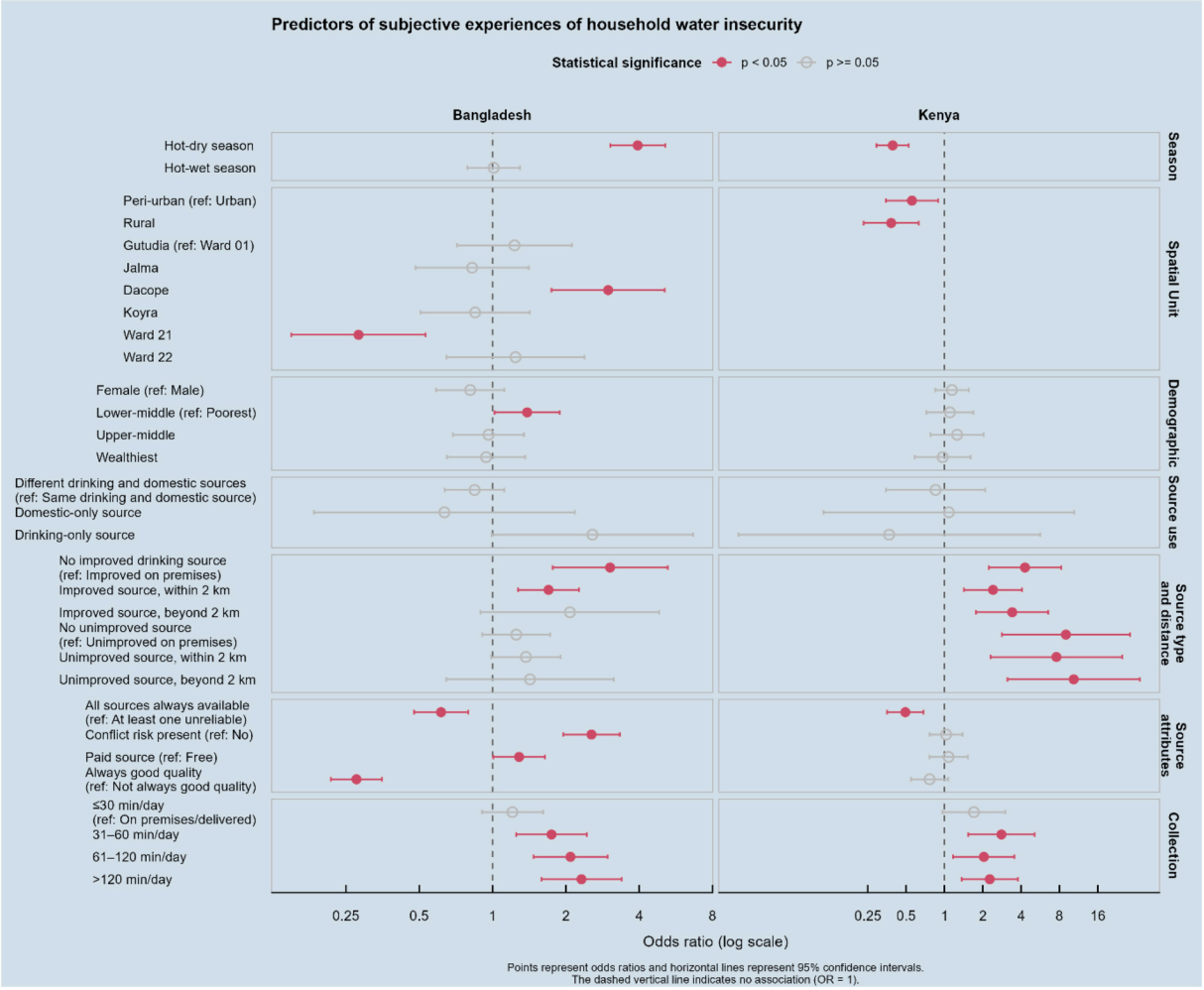

Fig. 4. Forest plot showing the odds ratio and confidence intervals of the predicator variables in Kenya and Bangladesh.

drink the untreated water. Men may be involved when more water is needed for construction work, the wells need to be dug deeper in the dry months, or if he has a motorbike. *"A man can offer to help when his wife is sick or gone to visit her family, but if he is respected amongst his neighbours, they can go to fetch on his behalf"* (KR-M). Gendered roles are more fluid in urban areas, where *"there are men who cook while a woman is seated"* (KR-W).

In Bangladesh, while views were less conservative, men's engagement in water collection was limited due to their income generating responsibilities. *"It is not a problem if men fetch water. In fact, if there is one man and ten women in the queue, the women let the man go first... The motor is turned on only at a fixed time – around Asr prayers (late afternoon) and last till Maghrib prayers (after sunset), after which it is locked. Men are not usually home at that time"* (BU-W). Like Kenya, men got involved during periods of acute crisis. A fisherman in Dacope recalled, *"Last year, I had to bring water from [another district]... my boat got damaged, and several of my containers broke."* The journey took a full day, and missing work affected his income, *"I was not able to work and earn...the indirect cost of water was high"* (BR-M). Unlike Kenya, involvement of children under 12 years in water collection is limited.

The IWISE scores of men and women within the same household do not show a consistent pattern across seasons or sites. In Bangladesh, while men and women's IWISE scores show higher variation in the hot-dry season (Fig. 6), no directionality is observed. Statistically significant gender differences were observed only in peri-urban locations during the cold-dry and hot-wet seasons, with women reporting marginally higher insecurity than men. These small differences may reflect the effects of rain and seasonal waterlogging, which make access routes more difficult to navigate, as noted in the interviews. In Kenya, significant differences were limited to specific sites: women reported higher insecurity than men in rural Kakwanyang during the hot-wet season, whereas in urban California during the hot-dry season men reported slightly higher insecurity than women.

Children and adolescents play a vital role in water collection in Kenya (Table 2). *"When the water table is high, children can go to the river by themselves but when the wells need to be dug deeper, as in the drier months, there is risk of young children falling into the well"* (KR-M). Among children below 12 years, gender differences in water collection are minimal, ranging between 13 and 22% across both seasons. When older children go to boarding school, the mothers are often left with caring responsibilities for younger ones making it difficult to fetch water. Girls' participation increases with age, rising from 36 to 52% for adolescent girls to 52–79% for adult women, while male involvement drops significantly with age.

4. Discussion

Intra-annual hydro-climatic variability produces different patterns and experiences of water insecurity across the urban–rural continuum, mediated by environmental, infrastructural, financial and institutional conditions. Although increasingly recognised in the literature, these dynamics remain poorly represented in global and national monitoring, masking local vulnerabilities and potentially misdirecting policy and programmes.

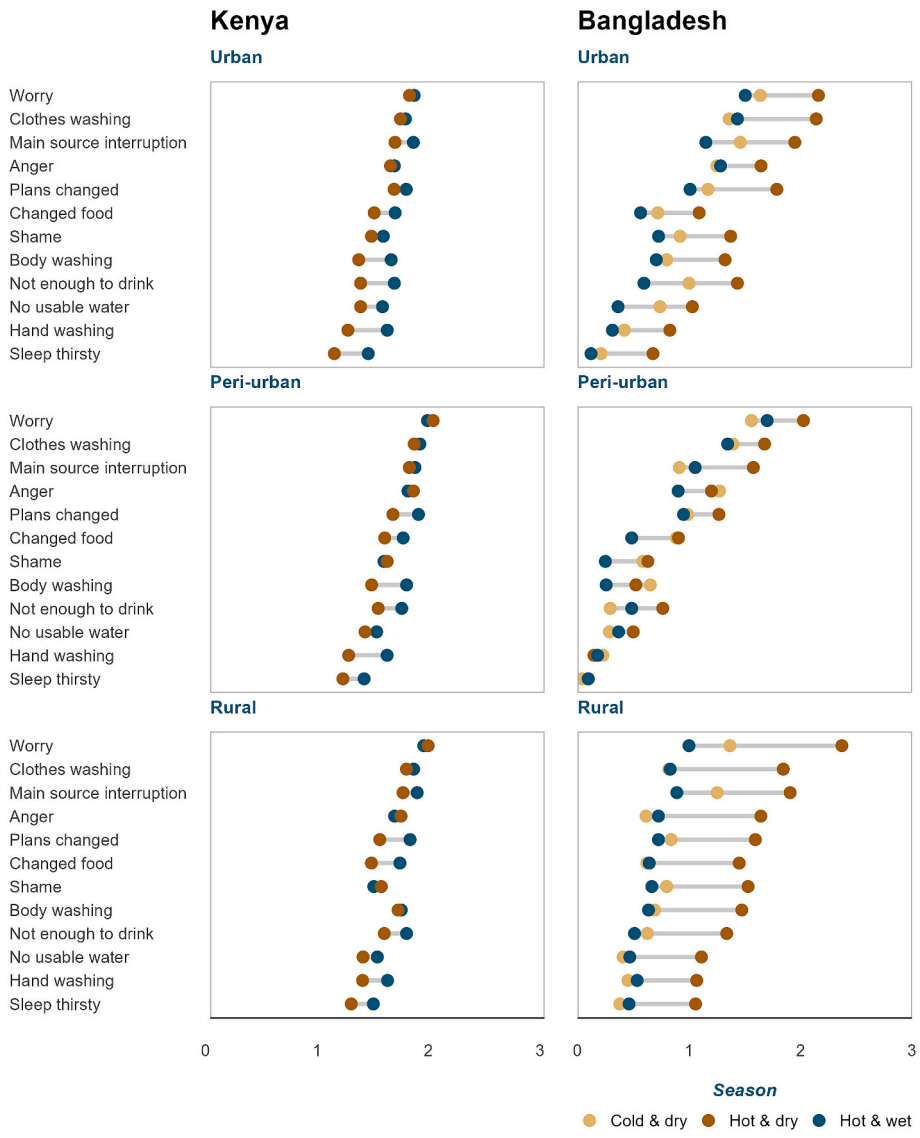

Fig. 5. Mean scores of the 12 HWISE items across different sites and seasons in Bangladesh and Kenya.

To our knowledge, this is the first longitudinal study to follow the same households across seasons while examining wider water-use portfolios, comparing objective and experiential measures and integrating qualitative evidence. This rich cross-country evidence allows us to examine not only variability, but what evidence is needed, how different forms of evidence should be interpreted together, and how they can inform monitoring, policy and services under increasing climate variability.

4.1. Broadening objective indicators to capture water insecurity's blind spots

Hydro-climatic variability affects households differently across the urban–rural continuum because infrastructure mediate seasonal changes in availability. Urban households experience the least source switching, as piped networks and boreholes buffer hydrological variability. Yet stable source use does not ensure water security: quality, reliability and collection effort vary seasonally, with piped water becoming foul-smelling or undrinkable in urban Bangladesh and boreholes producing saline or discoloured water. Overcrowding, intermittent supply and unequal network coverage further undermine security.

Peri-urban households outside formal networks combine boreholes, kiosks, tankers, vendors and surface water, making affordability, reliability and collection conditions particularly important. Seasonal crisis is greatest where alternatives are scarce. Distance alone therefore inadequately captures access, as difficult terrain, carrying or dragging containers and unsafe travel increase labour, cost and risk.

Rural households are most exposed because of greater reliance on rainfall, surface water and shallow groundwater sensitive to environmental conditions. In Kenya, digging in dry riverbeds involve labour and risks invisible to source classifications and distance measures. In Dacope and Kapua, surface water is often preferred to saline groundwater, demonstrating that an ‘improved’ source is not necessarily the most usable. Rainwater storage and alternative sources strongly shape resilience.

These findings challenge ‘access’ measures centred on source type, particularly the improved–unimproved distinction. Water security depends on quantity, quality, reliability, and affordability of available alternatives. A focus on drinking water overlooks cooking, washing and bathing, for which households often use different sources. Nearby lower-quality water may reduce collection burdens for non-drinking uses, while better water is reserved for drinking or cooking. Monitoring only the main source therefore misses broader water portfolios and how seasonal change redistributes costs, risks and labour.

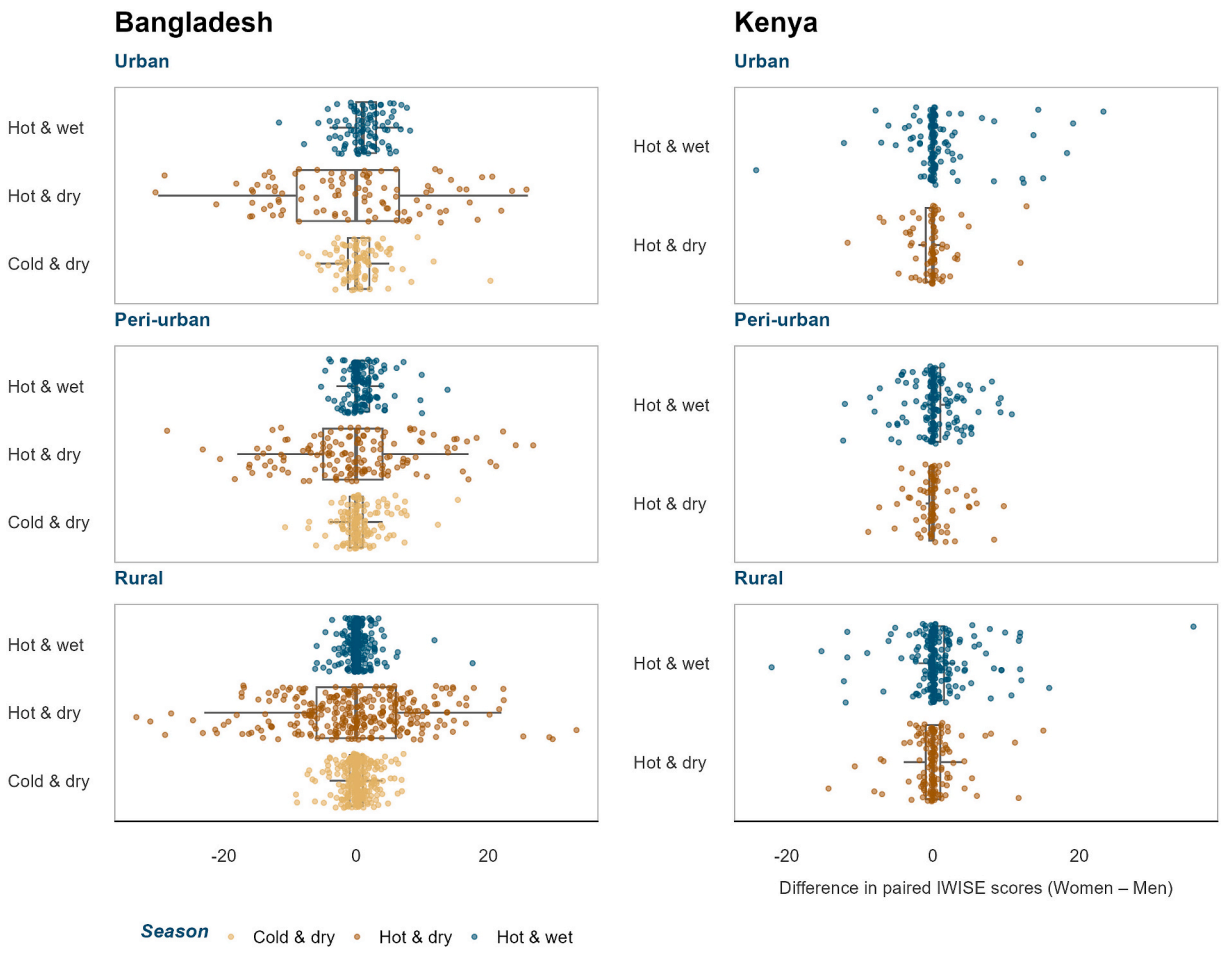

Fig. 6. Gender differences in individual experiences of water insecurities in Bangladesh and Kenya by season and site type.

Multiple-source use, source switching and decentralised supply should not themselves be interpreted as water insecurity. Debates on modular, adaptive and decentralised (MAD) systems suggest their significance depends on whether they expand household choice or impose additional financial, time, water-quality and management burdens (Wutich et al., 2023; Stoler et al., 2022). Monitoring should therefore capture both household water portfolios and the service characteristics of each source across seasons. This can distinguish adaptive diversification from constrained coping and assess whether MAD configurations strengthen resilience or shift responsibility, costs and risks from public providers to households, communities and private actors.

Infrastructure audits can complement household surveys by providing supply-side evidence. In our study, they helped calculate and verify collection distances and waiting times, assess source dominance and potential overcrowding, and cross-validate household-reported service characteristics. Data on functionality, yield, reliability, water quality, operating schedules, ownership and seasonal performance can identify where infrastructure buffers or amplifies hydro-climatic variability and whether households diversify by choice or because services are failing.

JMP already demonstrates this approach in urban areas by combining utility and regulatory data with household surveys and censuses. Comparable data are much scarcer outside utility coverage. In Bangladesh, government records of public infrastructure are often outdated or incomplete, and exclude donor-funded or private systems. Strengthening water infrastructure inventories could improve cross-validation while reducing repeated household survey requirements. Where infrastructure characteristics, service areas and water quality are routinely monitored, household surveys could focus more selectively on source portfolios, burdens and lived experiences. Combined with water quality assessments, infrastructure audits could therefore make monitoring more efficient without relying on improved–unimproved classifications.

Quality, quantity, affordability and collection effort interact with household resources and divisions of labour to determine who bears deteriorating access. Changes in distance or reliability can alter both the amount and distribution of labour. Children's involvement varied markedly by context, gender and age. In Bangladesh, washing and bathing frequently occur at ponds or tubewells, water carried home and, together with short distances and communal supervision, limiting children's participation in collection. In Kenya, younger children commonly fetch water independently or with adults. Men's participation in water chores rises where heavy labour or vehicle transport is required, aligning with previous literature (Adams, 2024; Brewis et al., 2024). Monitoring both drinking and non-drinking sources, alongside different household members' time allocation, can reveal the fluidity, seasonality and risks of water responsibilities.

4.2. *Promises and pitfalls of subjective indicators*

HWISE represents an important advance in measuring lived water insecurity beyond infrastructure-focused metrics. In this study, scores captured spatial and seasonal variation: they were highest in arid and peri-urban Kenyan settlements reliant on contaminated or vended sources and lowest in Bangladeshi locations with stable, largely self-supplied groundwater. Large wet–dry differences in Dacope also demonstrate their capacity to detect temporal changes overlooked by static infrastructure classifications.

However, aggregate HWISE scores do not identify the underlying drivers of insecurity. As Stoler et al. (2023) note, unidimensional scales offer simplicity and comparability but do not pinpoint subdimensions such as quality, affordability or collection time needed to target interventions. In Bangladesh, where quantity is rarely constrained, but salinity and contamination are persistent, the scale's emphasis on scarcity weakens its contextual validity. in Kenya, intermittent access and high variability mean HWISE captures general distress without distinguishing infrastructural from environmental causes. Several quantity-based items therefore reflect an implicit scarcity-oriented, and potentially urban, framing.

Adaptations of HWISE illustrate the tension between contextual relevance and standardisation. Broyles et al. (2023), for example, combined questions on handwashing, shame and thirst and added water-quality questions, revealing quality as a greater threat than quantity in some contexts. Such adaptations improve contextual relevance but reduce cross-context comparability (Stoler et al., 2023). This matters when comparing contrasting hydro-social settings such as Kenya and Bangladesh. Mean dry-season HWISE scores in Dacope and Ward 22 were similar to those in Lokaparparei and Kawalase across seasons, despite substantially different service conditions.

Item-level analysis can strengthen interpretation of aggregate scores. Tesfaye et al. (2020) show that frequently reported experiences are not necessarily perceived as most severe. Concern about unsafe drinking water, for example, may be both common and highly distressing. Item-level analysis can reveal whether aggregate changes reflect worry, interruptions, insufficient or unsafe water, each requiring different responses.

Qualitative evidence is equally important. Many households reported low HWISE scores despite poor objective service levels and accounts of insecurity in qualitative interviews. This divergence is consistent with ethnographic work showing that people may perceive limited water as sufficient where scarcity is normalised or social norms redefine adequacy (Hadley and Wutich, 2009; Tsai et al., 2016). It also aligns with 'response shift' in quality-of-life (Sprangers and Schwartz, 1999) and food-security research (Maes et al., 2010), whereby people recalibrate standards, reprioritise needs and adjust social comparisons under prolonged hardship.

Qualitative evidence also identifies dimensions missed by standardised scales. Although IWISE scores showed few gender differences, objective and qualitative evidence revealed gendered consequences. Reduced water use during Kenya's hot-dry season may have differentiated effects on hygiene because needs and practices vary by gender. In coastal Bangladesh, Sen (2023) documented women using coconut oil to mitigate itching from saline water, while Khanam et al. (2023) describe early marriage linked to skin discolouration and hair loss associated with saline bathing water. Women in our study similarly described poor food taste and hair damage. Such embodied consequences are tangible expressions of insecurity but fall outside existing quantitative scales.

Previous studies have commonly treated HWISE/IWISE either as outcomes for identifying predictors or exposures linked to consequences such as water borrowing and psychosocial stress (Ford et al., 2023; Rosinger et al., 2020). Our regression analysis likewise identified factors associated with HWISE severity. Yet literal interpretation could imply, for example, greater water security during the hot-dry season or greater insecurity among urban than peri-urban households. This warrants caution as HWISE/IWISE scores are increasingly translated into prevalence or severity categories and used as direct indicators of water insecurity, including in JMP gender-specific priority indicators (Caruso et al., 2024).

Experiential measures are therefore most informative when combined with objective and qualitative evidence. Aggregate scores identify where and when insecurity changes; item-level data identify the experiences driving change; infrastructure and water-quality data reveal underlying service conditions; and qualitative research explains how households interpret and manage them. Together, these approaches distinguish chronic from seasonal insecurity, adaptive from compelled diversification, and population-level patterns from inequalities within communities and households, providing a stronger basis for targeted policy and service responses.

5. Conclusion

Hydro-climatic variability, likely to become increasingly important under climate change, interacts with spatial and social inequalities to produce substantial intra-annual variation in water insecurity. Monitoring frameworks based largely on static infrastructure indicators and single-source reporting inadequately capture these dynamics. We propose five ways to strengthen the complementarity of objective and subjective indicators and better reflect the temporal, spatial and social dimensions of water insecurity.

First, national and global monitoring should capture seasonal variation more systematically, distinguishing chronic, seasonal and episodic water insecurity. This would help identify where long-term infrastructure investment is needed and where predictable deterioration could be addressed through seasonal preparedness, supplementary supply or targeted service improvements.

Second, monitoring should capture the multiple sources households use for drinking and non-drinking purposes. This can inform context-specific combinations of networked and decentralised provision, storage, distribution and treatment, while distinguishing adaptive diversification from reliance on additional sources because existing services are unreliable, unaffordable or unsafe.

Third, household surveys should be linked with infrastructure and water-quality monitoring. Updated inventories of public, donor-funded and private systems, including their functionality, yield, reliability and quality, could identify seasonal vulnerabilities, support preventive maintenance and target investment where infrastructure inadequately buffers climatic variability.

Fourth, monitoring should identify all household members involved in water collection, disaggregated by sex, age and water use. This would reveal who bears changing burdens and inform waterpoint location, operating hours, storage, delivery and seasonal planning.

Finally, HWISE/IWISE should be interpreted alongside individual scale items, objective service indicators and qualitative evidence. Item-level analysis can identify the experiences driving insecurity and distinguish frequency from perceived severity, while qualitative research can explain these patterns and reveal experiences that standardised indicators overlook.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in order to improve writing efficiency, and generate or check codes for data visualisation and regression analysis in R. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Sonia Ferdous Hoque: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Md Rajibul Islam:** Project administration, Investigation, Formal analysis, Data curation. **Marina Korzenevica:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saskia Nowicki:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cheruiyot Buses:** Project administration, Methodology, Formal analysis, Data curation. **Fahreen Hossain:** Methodology, Investigation, Formal analysis, Data curation. **Khonker Taskin Anmol:**

Methodology, Investigation, Formal analysis, Data curation. **Daniel Esukuku Ekai:** Methodology, Investigation, Formal analysis, Data curation. **Mercy Musyoka:** Methodology, Investigation, Formal analysis, Data curation. **Katrina Charles:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103262.

Data availability

Data will be made available on request.

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