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RESEARCH ARTICLE

Spatial heterogeneity of household water insecurity in rural Uganda: implications for development

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ABSTRACT

Little is known about the micro-scale spatial patterns of household water insecurity and their implications for community water interventions. This cross-sectional study analyses the location data of 250 households surveyed in Arua, Uganda, in August–September 2017 to evaluate correlates and geospatial clustering of household water insecurity, that is, geographical patterns in how water insecurity is experienced. The spatial cluster analysis identified clusters or outliers in every community, though with different spatial patterns. Household water insecurity was positively associated with food insecurity, round-trip fetching time, and water-related conflict within households and with neighbours. The observed spatial heterogeneity provides a new view of how household water insecurity experiences may vary in space and time, and can help practitioners understand the heterogeneity of impact that is often observed in water interventions.

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KEYWORDS
Water insecurity; food insecurity; conflict; geographical information system (GIS); spatial analysis; Sub-Saharan Africa; Uganda

Introduction

The world spends billions of dollars annually on water, sanitation and hygiene (WASH) projects, yet progress towards the global targets for Sustainable Development Goal 6 for universal safe water and sanitation is behind schedule (WHO/UNICEF, 2021) and slowed further by the COVID-19 pandemic (Howard et al., 2020). Understanding communities' precise and diverse conditions, needs, and attitudes is crucial to the success of WASH interventions in improving the physical and mental health of those experiencing water insecurity (Workman et al., 2021a). In practice, the underappreciation of these dynamics may help explain why up to half of WASH interventions fail after two to five years (UNDP Water Governance Facility/UNICEF, 2015).

Many water interventions test the effectiveness of a discrete water solution in a community, often a particular kind of well, or new filtration or disinfection media (Clasen et al., 2007). These types of interventions, and many municipal water service expansion projects, carry an implicit presumption of homogeneity in how community members experience water insecurity. But the complex set of socio-behavioural factors

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that shape water decision-making (Smiley & Stoler, 2020) can result in heterogeneous water insecurity experiences, at both the community and household levels, that are in turn associated with other forms of resource stress and psychosocial phenomena (Workman et al., 2021b; Wutich & Brewis, 2014). The literature on WASH programme failure has examined the role of structural issues such as rigid research designs (Burton et al., 2021), ineffective cross-sector collaboration (Cronin & Pond, 2008; Weekly, 2021), and narrow monitoring and evaluation criteria (Stoler et al., 2023). Inadequate prioritization of socio-behavioural factors is also an important consideration for why WASH programmes underperform, and is often attributed to insufficient community engagement in WASH project design, implementation and maintenance (Barrington et al., 2021; Nelson et al., 2021; Worsham et al., 2021).

Household water insecurity, broadly defined, has been associated with food insecurity (Brewis et al., 2020); worry, stress and shame (Brewis et al., 2021; Wutich et al., 2020); physical injuries (Venkataramanan et al., 2020b); and interpersonal conflict and violence (Cooper et al., 2021; Pearson et al., 2021). Women typically bear the emotional and physical brunt of water insecurity because they are usually responsible for obtaining household water and performing domestic chores such as cooking, cleaning and child-rearing (Bukachi et al., 2021). Households cope with water insecurity in similarly heterogeneous ways (Venkataramanan et al., 2020aa), for example, social networks can provide support in times of need through gifting and sharing of water (Rosinger et al., 2020; Wutich et al., 2018) and households may switch water sources (Pearson et al., 2016) or relocate their household (Pearson et al., 2015).

Increased attention to differential experiences of household water insecurity around the world has led to several new metrics to measure it (Octavianti & Staddon, 2021). One increasingly common metric is the cross-culturally validated Household Water Insecurity Experiences (HWISE) scale, which measures how frequently households experience various dimensions of water insecurity. The HWISE scale is a useful monitoring and evaluation tool for assessing the impact of household water interventions around the world (Slaymaker et al., 2020). Different versions of the HWISE scale have been used to demonstrate relationships with a range of social, demographic, economic and political factors (Brewis et al., 2020; Jepson et al., 2021; Pearson et al., 2021; Stoler et al., 2020; Venkataramanan et al., 2020b), but none of these studies explicitly accounted for household water insecurity as a spatial phenomenon or focused on the heterogeneity of water insecurity experiences. Previous applications of spatial analysis have primarily focused on analysing groundwater quality, household water sources or seasonality (e.g., Ferdous Hoque, 2023 Kulinkina et al., 2016; Stoler et al., 2012).

This study presents an exploratory analysis of the spatial patterns of household water insecurity and related phenomena in five rural communities of Arua, north-western Uganda. We focused on identifying the similarities and differences within and between communities to explore the spatial heterogeneity of household water insecurity in communities whose needs are typically portrayed as spatially and temporally homogenous by macro-level global development indicators (Price et al., 2021). This study evaluated two overarching research questions: To what extent do indicators of household water and food insecurity; perceived stress; and water-related worry, inadequate hygiene and conflict exhibit geospatial clustering? How might this inform development efforts? The spatial analysis explicitly tested the hypothesis that these household-level experiences exhibit spatial patterns. We discuss how the observed spatial properties of these indicators may have important implications for the deployment of WASH interventions in different contexts.

Methods

Study site and sample

This study leveraged the geographical coordinates of 250 households surveyed in Arua, Uganda, as part of a larger Household Water Insecurity Experiences (HWISE) parent study (Young et al., 2019b). Arua was selected as a site representative of high-growth towns in rural Uganda given its role as a regional commercial corridor. About 80% of water sources are communally managed in Arua. An estimated 57% of Arua residents were reported to rely on boreholes, though over 10% of boreholes are reported to be non-functional (Ministry of Water & Environment, 2022). In addition, due to increasing numbers of refugees from South Sudan and the Democratic Republic of Congo in the Arua area (Andreasi Bassi et al., 2018), the number of non-functional boreholes has increased due to pressure from excessive usage, which often led to residents relying on surface water sources (Associazione Centro Aiuti Volontari [ACAV], 2020). Although refugee status was not asked in the HWISE interviews for the safety of the respondents, the refugee population makes Arua a study site of particular interest in the context of ongoing political conflict and anticipated increases in climate migration in the region.

We conducted household surveys with individuals aged 16 years and older who were knowledgeable about their household's water use. Interviews were conducted in August and September 2017, during Arua's rainy season, by trained enumerators who were fluent in Lugbara, familiar with the area and context, and experienced in conducting survey research.

Households were selected using a multi-step cluster sample design which first involved obtaining a list of all villages in Arua district's four rural counties, sorted by sub-county, as our sampling frame. One village was randomly selected from each sub-county using a random number generator, until there were five selected villages (population range = 326–930, mean = 562). Next, we randomly selected 50 households from each of the five villages, this time by applying a random number generator to a household listing at the village level, yielding a sample size of 250 households. The target sample size was predetermined by a power calculation from the parent study that was designed to validate the original HWISE scale (Young et al., 2019b). An extra list of randomized households was retained for each village to replace households where the field team could not locate a qualifying adult to participate, and 128 of the final 250 households were selected from this back-up list. We obtained informed consent from all participants and encountered no refusals to participate.

This study was approved by the institutional review board (IRB) at the University of Miami (protocol number 20210117), with original data collection approved and supervised by the Michigan State University IRB (protocol number 17-604). The authors have no competing interests to declare.

Measures

This study geographically visualized and analysed household scores across several scales computed from the parent HWISE survey. The primary outcome of interest, the 11-item HWISE scale (HWISE-11), is computed from survey items that reported the frequency of various water insecurity experiences in the four weeks before the survey. Likert-type responses were individually scored from 0 to 3, with 0 = never, 1 = rarely (one to two times in the previous four weeks), 2 = sometimes (three to 10 times), 3 = often (11–20 times) or always (more than 20 times; Young et al., 2019a, 2019b). We generated a score for each household by summing values across the 11 items, resulting in a range from zero to 33, with higher scores indicating greater water insecurity. HWISE-11 scores have been shown to correlate highly with the original 12-item HWISE scale (Stoler et al., 2020; Venkataramanan et al., 2020b). We also calculated the Household Food Insecurity Access Scale (HFIAS; Coates et al., 2007) as a measure of food insecurity, and the four-item Perceived Stress Scale (PSS-4; Cohen et al., 1983). In a comparison of 27 HWISE study sites, Arua had the sixth-highest site-level mean HWISE score – and highest among sites surveyed in the rainy season – and the third-highest HFIAS score (Stoler et al., 2021). We categorized households' primary drinking water sources into five types: piped water, surface water (unprotected dug well, protected and unprotected springs, surface water), groundwater (borehole, tube well, protected dug well), rainwater, and other. The survey also collected demographic information, such as respondent age, number of household members, and self-reported income and wealth measures, as well as household water characteristics such as the number of minutes (round trip) required to fetch water, amount of drinking water storage and monthly financial expenditures on water.

Following an approach used by another HWISE study site in Torreón, Mexico (Jepson et al., 2021), we also measured the water insecurity subdomains of water worry, inadequate hygiene and water-related conflict using subscores derived from related survey items.

A water worry subscore was constructed by adding the scores from two items, Worry and Angry, with a range of 0–6:

- In the last four weeks, how frequently did you or anyone in your household worry you would not have enough water for all of your household needs?
- In the last four weeks, how frequently did you or anyone in your household feel angry about your water situation?

A hygiene subscore was constructed from three items, Body, Hands and Children, with a range of 0–9:

- In the last four weeks, how frequently have you or anyone in your household had to go without washing their body because of problems with water (e.g., not enough water, dirty, unsafe)?
- In the last four weeks, how frequently have you or anyone in your household had to go without washing hands after dirty activities (e.g., defaecating or changing diapers, cleaning animal dung) because of problems with water?

- In the last four weeks, how frequently have you or anyone in your household not had enough water to wash the faces and hands of children in your household?

The water-related conflict subscore was constructed by adding the values from items about the frequency of conflict with neighbours and within the household over water:

- In the last four weeks, how frequently did you or anyone in your household have problems with water that caused difficulties with neighbours or others in the community?
- In the last four weeks, how frequently did you or anyone in your household have problems with water that caused difficulties within your household?

The two questions that comprise the conflict subscore were also analysed separately to evaluate the potential difference in spatial patterning between these two types of water-related conflict, as they have been shown to be distinct, yet associated, phenomena (Pearson et al., 2021).

Spatial analysis

Household locations of all 250 participants were geocoded from their respective latitude and longitude coordinates using ArcGIS Pro 2.8.1 (Esri, Redlands, CA, USA). We began by computing frequency statistics for all measures and visualizing the household values of HWISE-11, HFIAS, PSS-4 and the water worry, hygiene and conflict subscores to qualitatively assess the presence of any spatial patterns. We computed mean centres and directional distributions to better understand the compactness and orientation of these spatial distributions. Each of the five communities was evaluated separately to account for their geographically disparate locations, and to facilitate spatial analysis within and between clusters.

We began our spatial statistical analysis by computing the global Moran's I statistic to understand the overall (global) degree of spatial autocorrelation (i.e., statistically significant spatial patterning) for each community using an inverse distance spatial weights matrix. We then tested each community for the presence of spatial clusters for each scale and subscore by computing the local indicators of spatial association (LISA) and Getis–Ord G_i^* statistics using an inverse distance-squared or $K = 6$ nearest-neighbours spatial weights matrix. As a robustness check, we tested a variety of spatial weights matrices that applied various distance decay models, distance thresholds or fixed numbers of neighbours. The inverse distance-squared matrix was most consistent with our expectations that water insecurity experiences are most likely to be shared by households separated by short distances. The theoretical basis for this expectation is twofold: (1) household-level experiences of water insecurity, food insecurity and water-related stress have been shown to be correlated in prior studies (Brewis et al., 2020; Stoler et al., 2020); and (2) water is physically heavy and inconvenient for households to move across longer distances. This spatial weights matrix was also the best compromise between the varying distributions of the households in each sample cluster.

All the maps presented in this study were produced using a jitter function that randomly displaces each household's longitude and latitude. We used donut-method geomasking which relocates each coordinate by at least a minimum distance, up to a maximum distance (Hampton et al., 2023), and has been shown to protect against positive and false identification of households (Seidl et al., 2018). We used this procedure to protect the privacy of participants and to ensure that all households are visible in each map, as some households share coordinates because they live in compound housing that shares the same roof. We deliberately do not report the donut-distance thresholds to reduce the precision of any attempt to reverse-geocode respondent locations. Note that we implemented the geomasking in our maps after conducting the spatial statistical analysis on the actual locations; this caveat is important for interpreting patterns of spatial clusters or outliers in the maps.

The spatial analysis of each measure (water insecurity, food insecurity, etc.) is presented as a figure containing five pairs of maps corresponding to the five study communities. The pairs are arranged in rows for comparison of the spatial distribution of scores (top row) and the spatial cluster analysis results (bottom row) across the five sites. Our focus is understanding the 'pattern of patterns', so to speak, or the degree of spatial heterogeneity observed across the 250 sampled households in the five study communities and across outcome measures, rather than the results from any single community.

Regression analysis

Finally, we fit multivariable ordinary least squares regression models of the HWISE scale scores to assess whether any associations with household characteristics in Arua were consistent with those found in previous household water insecurity studies. The purpose of this step was to confirm whether the water security experiences observed in Arua were typical of those observed elsewhere in the region and world. Specifically, we regressed HWISE scale scores on household socio-demographic characteristics, HFIAS scores, PSS scores and the two conflict items. The household socio-demographic characteristics were commonly used control measures known to influence household water use: age, household size, number of children under 16 years of age, round-trip minutes fetching water, amount of drinking water storage (litres), money spent on water (US$), monthly income (US$) and self-reported relative wealth using the McArthur Scale of Subjective Social Status. To avoid endogeneity problems, we did not model the water worry or hygiene subscores because most of the items in these subscores are already included in the HWISE scale.

We used Pearson's and Spearman's correlation matrices to assess all independent variables for potential collinearity a priori, and we monitored variance inflation factors (VIFs) for collinearity while building our multivariable models, removing any factor with VIF > 5. We began building our multivariable model by introducing all items which demonstrated significant bivariate associations with the HWISE scale. We then iteratively added the remaining covariates and checked collinearity diagnostics until all independent variables were included in the final multivariable model. All correlation and regression analyses were performed using IBM SPSS Statistics v26.

Table 1. Mean (SD) of household demographics and resource insecurity measures in five communities of Arua, Uganda.

	Community					
Measure	1	2	3	4	5	All
Age	35.0 (13.24)	38.1 (15.50)	34.6 (12.60)	38.3 (17.16)	36.9 (15.43)	36.5 (14.76)
Household size	6.3 (2.94)	5.6 (3.18)	6.7 (2.88)	6.0 (2.78)	5.7 (2.87)	6.1 (2.87)
Number of children under 16	3.6 (2.28)	3.2 (2.18)	3.7 (2.26)	3.0 (1.98)	3.3 (2.11)	3.4 (2.16)
Minutes fetching water, round trip	65.6 (40.52)	63.7 (48.61)	41.0 (32.11)	43.1 (35.85)	39.3 (33.80)	50.6 (40.06)
Amount of drinking water storage (l)	21.8 (11.50)	22.6 (12.96)	23.3 (11.63)	31.0 (31.52)	23.3 (14.68)	24.4 (18.25)
Money spent on water (US$)	0.35 (0.31)	0.23 (0.10)	0.12 (0.14)	0.62 (1.03)	0.22 (0.84)	0.31 (0.63)
Monthly income (US$)	8.4 (10.83)	11.6 (22.64)	38.6 (104.01)	12.9 (16.97)	15.5 (18.26)	17.5 (50.20)
Self-reported relative wealth (ladder)	8.4 (2.19)	8.0 (2.58)	6.6 (3.16)	7.7 (2.21)	7.9 (2.15)	7.7 (2.54)
Water insecurity (HWISE-11)	16.5 (5.77)	15.1 (7.79)	10.0 (7.52)	7.9 (7.52)	9.8 (7.96)	11.9 (8.02)
Food insecurity (HFIAS)	13.2 (3.73)	15.7 (4.13)	11.4 (5.56)	8.7 (5.33)	10.7 (6.34)	11.9 (5.58)
Perceived stress (PSS-4)	9.5 (1.89)	9.0 (1.96)	9.0 (1.37)	8.2 (1.65)	9.1 (2.00)	8.9 (1.83)
Water worry subscore	3.9 (1.54)	3.2 (1.66)	2.4 (2.02)	1.7 (1.69)	2.2 (1.75)	2.7 (1.90)
Hygiene subscore	3.7 (1.87)	3.5 (2.65)	2.1 (2.03)	1.8 (2.04)	2.5 (2.62)	2.7 (2.37)
Conflict subscore	2.1 (1.45)	2.0 (1.78)	0.8 (1.15)	0.9 (1.40)	1.4 (1.44)	1.5 (1.55)
Intrahousehold conflict	1.0 (0.92)	0.8 (0.92)	0.4 (0.67)	0.4 (0.70)	0.6 (0.84)	0.7 (0.84)
Conflict with neighbours	1.1 (0.79)	1.2 (1.11)	0.4 (0.66)	0.5 (0.89)	0.8 (0.81)	0.8 (0.92)

Results

Household characteristics

The demographic and household characteristics of our study participants are summarized in Table 1. Most respondents were women (85.6%), of whom the majority (89.7%) were responsible for acquiring water for their household. Most households had children less than 16 years old (88.4%), with a mean of 3.37 children (range = 0–10). Among 221 households with children under 16 years, over half (55.2%) reported that their children had missed school at least once during the past four weeks to help fetch water. The mean reported round-trip time to fetch water was 51 min (SD = 40.1 min; range = 0–240 min). Most households relied on groundwater as their primary drinking water source (70%), and surface water as their primary non-drinking water source used for domestic purposes (55%).

Monthly household incomes ranged from 0 to 2 million Uganda shillings (UGX) (= US$564.19 as of August 2017), with a mean of UGX64,702.45 (US$18.25). Using the MacArthur Scale of Subjective Social Status (range = 1–10, 1 being the highest), participants self-reported a mean score of 7.7 (SD = 2.5), with a median of 9. The average amount spent on water in the past four weeks was UGX1129.86 (US$0.32), although three households reported spending UGX20,000 (US$5.64).

Water insecurity

HWISE-11 scores (n = 227) ranged from 0 to 30 with a mean of 11.9 (SD = 8.0). Communities 1 and 2 had mean scores of 16.5 and 15.1, respectively, while the other three communities had mean scores less than 11. In the top row of maps in Figure 1, community 4 appears to have the lowest HWISE-11 scores, while higher HWISE-11

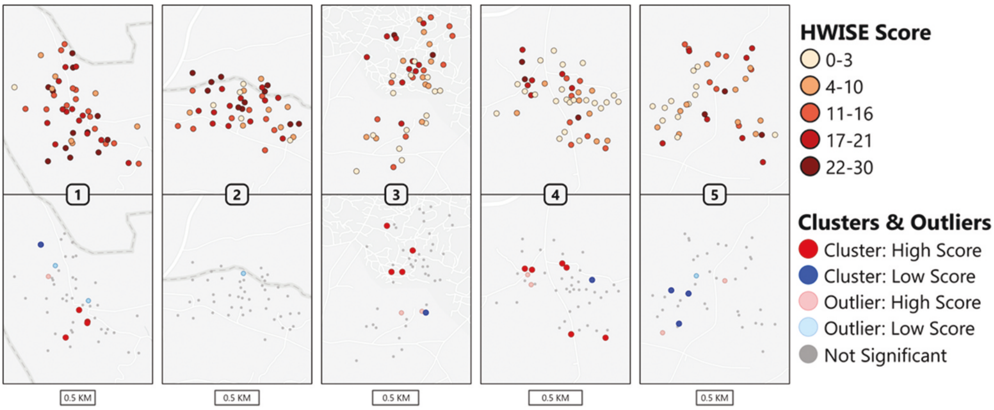

Figure 1. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of Household Water Insecurity Experiences (HWISE-11) scale scores by community (1–5).

Table 2. Global Moran's *I* tests of spatial autocorrelation for five communities by measure in Arua, Uganda (presented as *I*-statistic, *Z*-statistic).

	Community				
Measure	1	2	3	4	5
Water insecurity (HWISE-11)	0.05, 0.58	0.05, 0.53	0.2, 1.88	0.32, 2.27*	0.18, 1.17
Food insecurity (HFIAS)	0.17, 1.59	0.11, 0.93	0.03, 0.37	0.36, 2.67**	−0.13, −0.7
Perceived stress (PSS-4)	0.17, 1.57	−0.22, −1.48	−0.12, −0.71	−0.13, −0.83	0.21, 1.56
Water worry subscore	0.09, 0.90	−0.15, 0.91	0.26, 2.08*	0.21, 1.58	0.14, 1.04
Hygiene subscore	0.15, 1.39	0.15, 1.22	0.06, 0.57	0.27, 2.02*	0.28, 1.89
Conflict subscore	−0.03, −0.66	−0.08, −0.43	0.09, 0.84	0.10, 0.84	−0.26, −1.60
Intrahousehold conflict	0.00, 0.20	−0.04, −0.17	0.06, 0.62	−0.06, −0.31	−0.16, −0.97
Conflict with neighbours	−0.02, −0.04	−0.05, −0.21	0.03, 0.36	0.14, 1.16	−0.12, −0.65

Note: $^*p < .05$; $^{**}p < .01$.

scores are scattered throughout communities 1, 2 and the northern area of community 3. The Moran's *I* global test for spatial autocorrelation (Table 2) only revealed statistically significant clustering of HWISE-11 scores in community 4 ($I = 0.32$, $Z = 2.27$, $p = 0.02$), though community 3 trended towards significant clustering ($I = 0.24$, $Z = 1.88$, $p = 0.06$). The LISA statistic detected clusters of high HWISE-11 scores in the southern area of community 1, the north-west of community 3, along one of the roads in community 4, and a cluster of low scores in community 5 (Figure 1, bottom row). The LISA statistic identified at least one spatial outlier, which is either a high score surrounded by low scores or vice versa, in all communities.

Food insecurity

The mean HFIAS score among all households ($n = 239$) was 11.9, and much like the HWISE scores, the first two communities had higher mean HFIAS scores than the other communities. The highest mean, 15.7 (SD = 4.1), was in community 2, and the lowest mean, 8.7 (SD = 5.3), was in community 4. The top row of Figure 2 presents the distribution of HFIAS scores; community 2 appears to have the highest levels of food insecurity, while community 4 appears to have the least severe food insecurity. The LISA

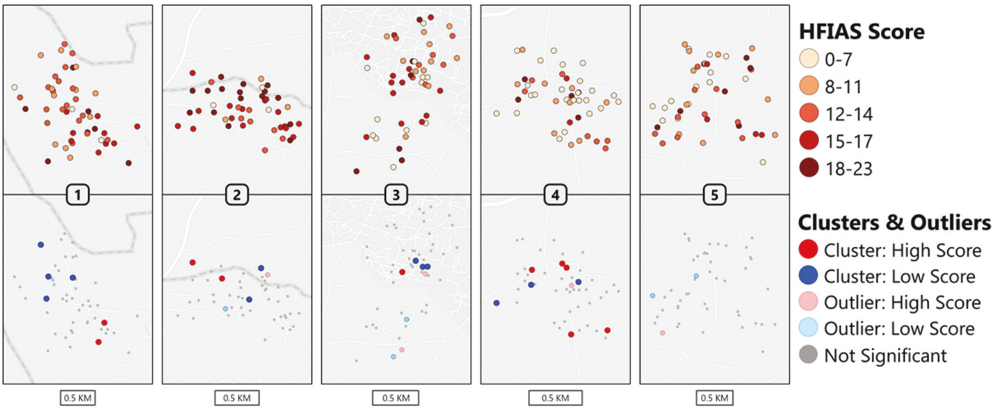

Figure 2. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of Household Food Insecurity Access Scale (HFIAS) scores by community (1–5).

statistic (Figure 2, bottom row) identified spatial clusters or outliers in each of the five communities, with multiple clusters of both low and high HFIAS scores in communities 2 and 4, despite these communities having the lowest and highest overall mean HFIAS scores respectively. The Moran's I test only detected statistically significant patterning of HFIAS scores in community 4 ($I = 0.36$, $Z = 2.67$, $p = 0.008$).

Perceived stress

Community-level mean PSS-4 scores ranged from 8.2 to 9.5, and the mean of all households ($n = 250$) was 8.9 (SD = 1.8). While PSS scores appeared to be heterogeneously spread throughout the communities (top row of Figure 3), community 4 had the lowest overall scores. The Global Moran's I statistic did not identify statistically significant clustering of PSS scores in any of the five communities. The LISA statistic identified the highest number of clusters and outliers in community 4, with many low-high outliers

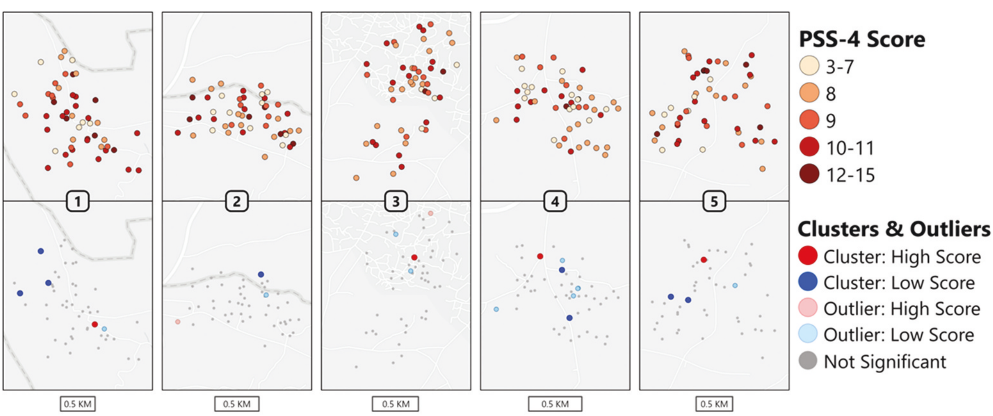

Figure 3. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of Perceived Stress Scale (PSS-4) scores by community (1–5).

along the edge of the sample, and clusters of both low and high scores in the centre of the community (bottom row of Figure 3). The LISA statistic generally identified fewer clusters and outliers of PSS scores than for the other measures assessed, but still identified clusters and outliers in each community.

Water worry

The mean water worry subscore for all households (n = 243) was 2.7 (SD = 1.9). Community-level mean water worry subscores ranged from 1.7 in community 4 to 3.9 in community 1. The distributions of water worry scores in the top row of Figure 4 suggest patterns in communities 3 and 4. The Moran's I statistic identified statistically significant patterning of water worry scores in community 3 ($I = 0.26$, $Z = 2.08$, $p = 0.04$). The LISA statistic detected clusters of high subscores in the north of community 3 and in the centre and south-eastern edge of community 4 (Figure 4, bottom row), which, as expected, generally concurred with the spatial patterns of the HWISE score. Community 2 was the only one to not have any clusters or outliers detected during spatial analysis.

Hygiene

The mean subscore for water-related hygiene issues among all households (n = 245) was 2.7 (SD = 2.4), and community-level mean scores ranged from 1.8 in community 4 to 3.7 in community 1. The distribution of hygiene subscores in the top row of Figure 5 was visually similar to the distribution of water worry subscores, yet Moran's I was only statistically significant for community 4 ($I = 0.27$, $Z = 2.02$, $p = 0.04$). The LISA statistic identified clusters of high subscores in all five communities, and clusters of low subscores in communities 1, 2 and 4 (Figure 5, bottom row). As with water worry, high hygiene subscores tended to occur in the same regions as the clusters of high HWISE scores.

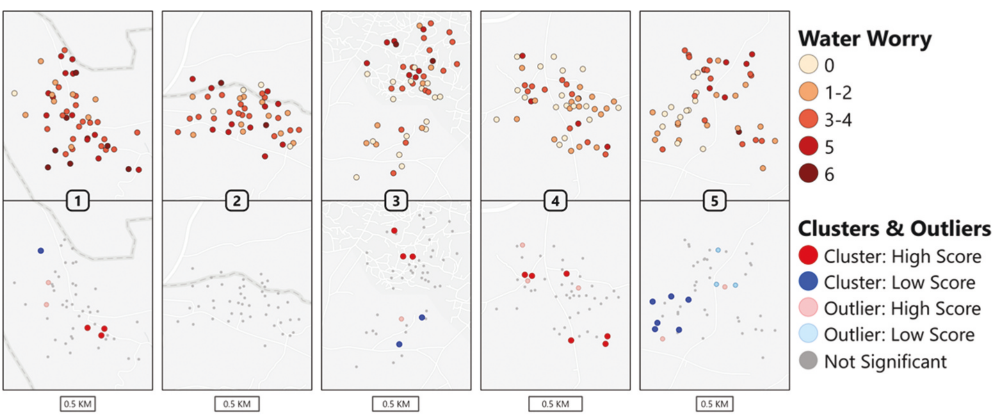

Figure 4. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of water-related worry subscores by community (1–5).

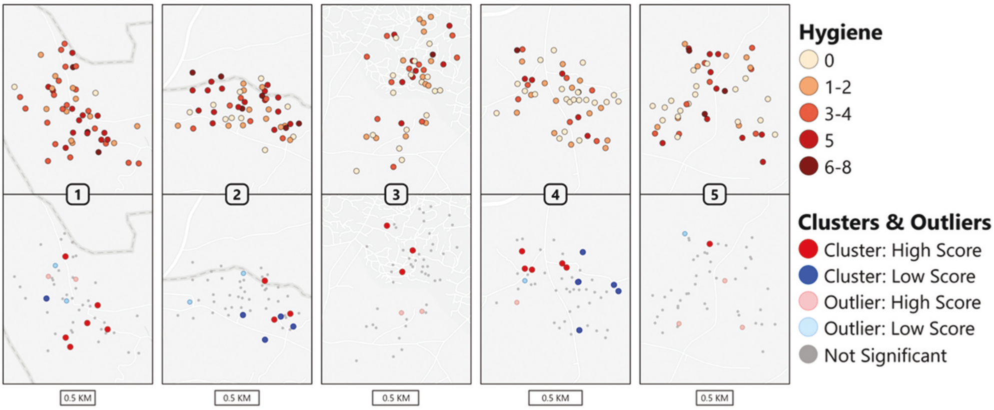

Figure 5. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of hygiene subscores by community (1–5).

Conflict

The mean conflict subscore (n = 245) was 1.5 (SD = 1.6), and communities 1 and 2 again had higher mean subscores than the other three communities. Moran's I did not detect any global spatial patterns for the water-related conflict subscore or for either of its two component items: conflict within the household and conflict with neighbours. The LISA statistic identified clusters of high conflict subscores in communities 1, 3 and 4, and clusters of low conflict subscores in communities 1 and 2 (Figure 6, bottom row). These clusters tended to include different households from those identified as clusters of HWISE scores. Figures 7 and 8 present intrahousehold conflict and conflict with neighbours separately; the overall patterns and presence of clusters were similar in communities 1 and 5, but diverged in communities 2, 3 and 4.

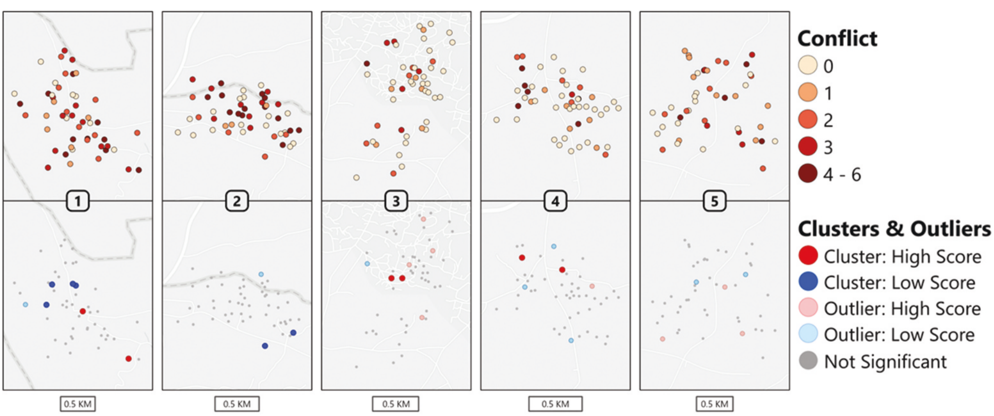

Figure 6. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of water-related conflict subscores (including intrahousehold conflict and conflict with neighbours) by community (1–5).

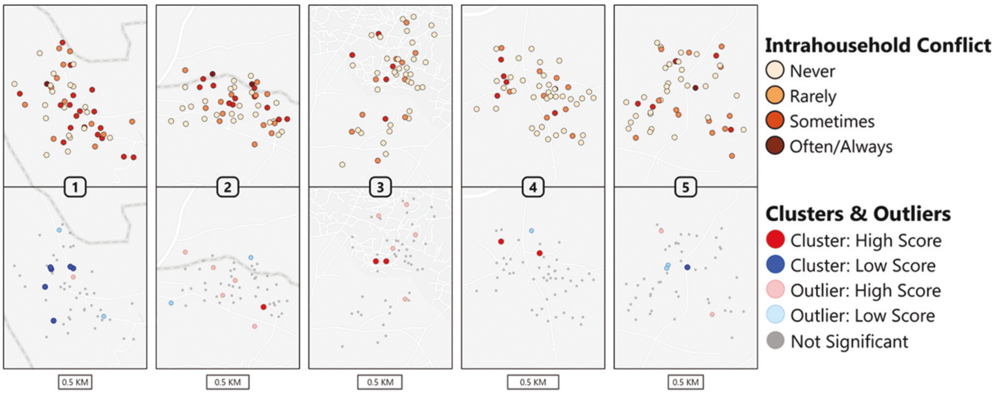

Figure 7. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of water-related intrahousehold conflict scores by community (1–5).

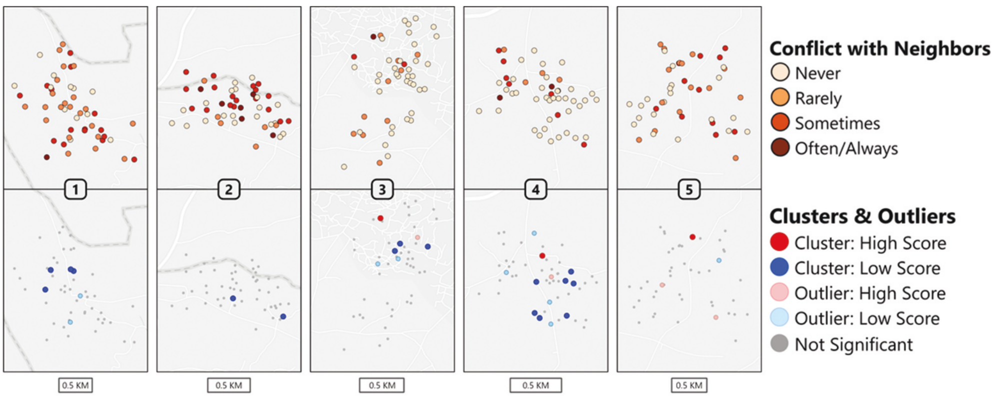

Figure 8. Spatial distribution by quintile (top row) and spatial cluster map (bottom row) of water-related conflict with neighbours by community (1–5).

Regression analysis

Our regression model assessed the association between the HWISE scale and age, gender, household size, time spent fetching water, HFIAS scores, PSS-4 scores, MacArthur ladder scores (a measure of perceived social standing), monthly income, intra-household conflict and conflict with neighbours (Table 3). We modelled 197 households with complete information across all measures. The VIFs of all variables included in the model were less than 1.6. We observed statistically significant positive associations between the HWISE scale and food insecurity ($B = 0.17$, standard error (SE) = 0.07, $p = 0.021$), fetching time ($B = 0.04$, SE = 0.01, $p \leq 0.001$), intra-household conflict ($B = 3.22$, SE = 0.47, $p \leq 0.001$), and conflict with neighbours ($B = 4.07$, SE = 0.46, $p \leq 0.001$). The association with gender approached significance ($B = 1.68$, SE = 0.93, $p = 0.073$), and age, household size, PSS score, social standing and household income were not associated with the HWISE scale. The multivariable model demonstrated good fit ($R^2 = 0.69$), meaning that our set of covariates accounted for 69% of the variation in HWISE scores.

Table 3. Multivariable regression model of the relationship between household water security and household socio-demographics, food insecurity, perceived stress and conflict over water (n = 197 households).

Measure	B	SE	95% CI for B	P	VIF
Age	0.03	0.02	−0.01–0.08	0.153	1.11
Gender	1.68	0.93	−0.16–3.52	0.073	1.05
Household size	−0.04	0.12	−0.27–0.20	0.766	1.05
Minutes fetching water, round trip	0.04	0.01	0.02–0.06	< 0.001	1.17
Food insecurity (HFIAS)	0.17	0.07	0.03–0.31	0.021	1.55
Perceived stress (PSS-4)	−0.11	0.21	−0.51–0.30	0.607	1.19
Self-reported relative wealth (ladder)	−0.20	0.14	−0.47–0.08	0.160	1.18
Monthly income (US$)	−0.01	0.01	−0.02–0.01	0.476	1.09
Intra-household conflict	3.22	0.47	2.28–4.15	< 0.001	1.49
Conflict with neighbours	4.07	0.46	3.17–4.97	< 0.001	1.58

Note: SE, standard error; CI, confidence interval; VIF, variance inflation factor.

Discussion

This study explored the micro-scale spatial heterogeneity of household water insecurity experiences and related phenomena in five communities in rural Uganda. Mean scores for measures of water insecurity, food insecurity, perceived stress and water conflict generally varied within and between the communities, and our analysis identified at least one local cluster or outlier within each of the communities for nearly every measure. The variation in mean scores between the communities and the identification of spatial patterning within the communities provide evidence of spatial heterogeneity in water insecurity experiences at both the household and community levels. Our findings of spatially clustered water insecurity experiences within communities are consistent with patterns seen elsewhere in rural Uganda (Cooper-Vince et al., 2018). Such heterogeneity affirms the importance of community involvement, particularly during the needs assessment phase of water projects, to better tailor interventions to address varying local conditions, experiences and needs.

Although spatial analysis has been widely applied to the study of water-associated diseases such as cholera (Azman et al., 2018), shigellosis (Tang et al., 2014) and dengue fever (Anders et al., 2015), a limited body of research has demonstrated spatial patterns of water supply and demand at different scales, generally related to infrastructure and demographic factors such as race and class (Cooper-Vince et al., 2018; Habeeb et al., 2023; Kulinkina et al., 2016; Nguyen et al., 2020; Stoler et al., 2012). Similar relationships have been demonstrated with plumbing and sanitation services (Deitz & Meehan, 2019; De Moura & Procopiuck, 2020).

Spatial patterns of household water security in rural Africa are shaped at the community level by physical environmental factors – e.g., roads, surface water bodies and wells – because water is cumbersome to move over long distances, and at the individual level through demographics such as age and gender, physical fitness, and social relations such as kinship and ethnicity, which can also influence access to water sources (Smiley & Stoler, 2020). Our results highlight the complexity of these interactions, as very few households persist in spatial clusters of water insecurity, food insecurity, perceived stress and conflict, even though several of these constructs were associated in multivariable analysis. We would expect these relationships to persist in other places, particularly where residents use multiple water sources. If they do, it may help explain why some water interventions yield such heterogeneous effects on water insecurity (Clasen et al., 2007). Despite the best of intentions, new water services likely become absorbed into the various patchworks of fragmented socio-spatial water needs observed around the world (Drew et al., 2021; Peloso & Morinville, 2014; Wright-Contreras et al., 2017).

Our case study of Arua suggests that WASH projects should integrate local spatial context into their implementation plans. Water interventions most commonly prioritize the microbial quality of drinking water and may also address secondary issues related to water quantity, aesthetics, proximity and carriage, financial cost, predictability, gender dynamics, social exclusion, and governance. But few projects address all these factors, and this is precisely why a higher resolution view of household needs may help WASH interventions more accurately target the type and location of water services to maximize community impact. The collection of these types of data may present an opportunity for community engagement and building trust to avoid repeating past WASH failures (Barrington et al., 2022; Sindall et al., 2023) and is supported by a variety of participatory research designs (Roque et al., 2022). The complexity of human behaviour, and how it interacts with technology and market-based approaches, is also increasingly being recognized as an under-appreciated driver of the sustainability of water interventions (Brunson et al., 2013; Smiley & Stoler, 2020). This means that development programmes should either improve baseline assessments of water insecurity to understand socio-spatial issues and embrace multipronged (and potentially more expensive) interventions informed by diverse community needs (where appropriate), or have more realistic expectations about project impact.

Our regression model results were generally consistent with previous studies that have demonstrated similar associations between measures of household water insecurity and food insecurity (Stoler et al., 2020), time spent fetching water, female gender and conflict (Pearson et al., 2021). Although other studies have demonstrated associations between the HWISE scale and age, household size, PSS score, social standing and household income (Jepson et al., 2021; Shah et al., 2023; Stoler et al., 2020; Wutich et al., 2022), the conflict items had the strongest effect size on the HWISE scale in Arua. In a study of the relationship between water insecurity and conflict among nine Sub-Saharan African sites, Arua had the highest proportion of households experiencing any conflict with neighbours over water (44.7%) and was among the highest experiencing intra-household conflict over water (Pearson et al., 2021). It is important to remember that these associations do not establish causation, but are related to complex interdependencies with causation often going both ways (Workman et al., 2021b). Water insecurity, for example, may be a more likely driver, rather than consequence, of food insecurity (Brewis et al., 2020) and mental ill-health (Wutich et al., 2020).

Because refugee status was beyond the scope of these studies, we do not know if this strong association between water insecurity and conflict in Arua – or any of the spatial heterogeneity we observed – was attributable to heightened regional anxiety from the waves of South Sudanese and Congolese refugees, or other local factors. For example, water-sharing between households has been shown to be an important coping mechanism during times of water scarcity (Wutich et al., 2018). But water-sharing has also been shown to increase distress among participants (Wutich et al., 2022), which is especially plausible for newly arriving refugees with a limited local social network who may be more vulnerable to exploitative water-sharing relationships. Conflict aside, the remaining relationships between food and water insecurity, demographics, and water source and fetching times were typical of other Sub-Saharan African water-stressed communities. Despite these similarities with other communities in the region, the observed spatial heterogeneity may also be related to Arua's high degree of water and food insecurity, generally speaking, and could be confounded by refugee status, length of time living in Arua and other ethnic differences that were not measured in this study.

Our results were also limited by our research design. First, our cross-sectional approach provided a snapshot of the 2017 rainy season that may not be representative of water insecurity in other seasons or years. Although water insecurity can change from day to day in urban Sub-Saharan Africa (Price et al., 2021), it is unclear whether these temporal effects would persist in rural communities and yield even more complex patterns of spatio-temporal heterogeneity. In addition, our non-spatially contiguous sampling design limits the detection abilities of the spatial statistical tests, particularly given the small sample size and irregular distribution of households in each community. The global test for spatial autocorrelation, Moran's *I*, identified fewer patterns overall than LISA, but it is not unusual to find local pockets of spatial autocorrelation within a globally random pattern. LISA generally has high sensitivity and specificity and is most likely to yield false positives with high sample sizes (Moraga & Montes, 2011). By using more appropriate sample sizes, spatial sampling procedures, and explicit incorporation of existing water access locations, future studies could reduce the likelihood of detecting spurious clusters and outliers and provide more context for spatial patterns.

The spatial heterogeneity of water insecurity, food insecurity, water worry and water conflict observed in Arua underscores the complexity of these processes at the community scale and emphasizes the importance of participatory engagement and inclusivity in community-level WASH programmes. Fine-scale spatial variation of community members' experiences, expectations and needs may well be another reason for the underperformance of WASH interventions. We suggest that WASH interventions may be better informed by spatial patterns in household-level water insecurity experiences than by community-level estimates of resource insecurity alone, and we advocate for further investigation into the potential of micro-scale geographical approaches in helping to improve WASH programme efficiency and equity.

Water insecurity's dynamic relationship between people and water, shaped by policy, climate change, livelihoods and ability to flourish, requires that WASH interventions be tailored to the diverse needs of the communities and households they serve. Many interventions use a one-size-fits-all approach to water interventions – such as community pumps with disinfection media, or household point-of-use filtration and disinfection technology – with the tacit assumption that demographically similar households in a given community experience water insecurity in similar ways. But our results demonstrate that rural communities may display considerable variation in resource stress and conflict, despite appearing to be relatively socio-demographically homogenous according to census statistics and global development indicators. Local spatial approaches to household water insecurity can highlight diverse patterns of water insecurity experiences within and between regions and communities which could help WASH interventions better target those who would most benefit from new infrastructure investments.

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CRediT author statement

E.S.: formal analysis, visualization, writing – original draft, writing – review and editing; J.S.: conceptualization, supervision, visualization, writing – original draft, writing – review and editing; A.L.P.: data curation, investigation, writing – review and editing; G.A.: investigation, writing – review and editing.

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