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Water quality and unseen health outcomes: A cross-sectional study on arsenic contamination, subclinical disease and psychosocial distress in Bangladesh

Nameerah Khan [a,*], Sonia Ferdous Hoque [a], Zahid Hayat Mahmud [b], Mohammad Rafiqul Islam [b], Mohammad Atique Ul Alam [b], Md Shafiqul Islam [b], Katrina Jane Charles [a]

[a] School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK
[b] Laboratory of Environmental Health, Health Systems & Population Studies Division, International Centre for Diarrhoeal Disease Research, Dhaka, 1212, Bangladesh

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ABSTRACT

Health risks from water quality pose a major threat to billions of people globally. Most microbial contaminants have short subclinical periods, compared to chemical contaminants that can take years to manifest, which can translate to less attention in the policy sphere. Complex water quality issues in Bangladesh, including arsenic contamination, offer an ideal case study to highlight the wide-ranging health and social impacts of perceived and invisible contaminants. This paper presents a cross-sectional study where two tools are explored for understanding the less visible health impacts of water contamination: (1) measuring subclinical disease via nail arsenic measurements (n = 899) to better ascertain chronic exposure; and (2) understanding the relationship between water quality and psychosocial distress (n = 876), for men and women across three sites with varying water quality issues. Applying generalised linear regression models, subclinical arsenic showed strong positive correlation with water arsenic, while the relationship between severity of psychosocial distress and water arsenic was modified by perceived risk from arsenic. Subclinical disease was much more prevalent than what current exposure through drinking water would indicate, with 65.3% of participants having nail arsenic levels above the 1 μg/g cut-off for unexposed individuals (spanning across sites with average water arsenic as low as 2.51 μg/L and as high as 379 μg/L). Further demonstrating the breadth of unseen outcomes of water contamination, uncertainty was the most commonly expressed component of distress, followed by worry, fear, suffering, and lack of choice. The presence of psychosocial distress underscores how experiences of contaminated water go beyond physiological illnesses, while the use of subclinical biomarkers can shift the understanding of disease and provide a useful way of leveraging policy change by pinpointing exactly where and by whom intervention is needed.

1. Introduction

Chemical and microbial contamination of drinking water from naturally occurring and anthropogenic sources pose a severe threat to human health and wellbeing, impeding progress towards Sustainable Development Goal Target 6.1 of universal access to safely managed drinking water services. Exposure to microbial contaminants often have acute health outcomes, such as diarrhoeal and gastrointestinal diseases, while the health risks from chemical contaminants are more chronic in nature, including development impairments, chronic kidney diseases and various cancers (Collaborative on Health and the Environment, 2017). The long latency period, with several years between exposure and clinical outcomes, if any, often attracts less policy attention and delays responses, leading to an 'invisible' water quality crisis (Khan and Charles, 2022).

Arsenic contamination of groundwater in Bangladesh offers an ideal case study to highlight the wide-ranging health and social impacts of invisible water contaminants and demonstrate the trajectory of policy change and implementation (or lack thereof) that characterises many long-term water contamination crises. It was considered the largest-scale mass poisoning of a population (Yu et al., 2003), with 27.5 million people still exposed to arsenic above 10 μg/L (WHO guideline)

* Corresponding author.
E-mail address: nameerah.khan@ouce.ox.ac.uk (N. Khan).

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and 17.5 million exposed to arsenic above 50 μg/L (Bangladesh limit) (Charles et al., 2021). Policy change has been slow and stagnated (Atkins et al., 2007; Hanchett et al., 2014), with attention to the crisis declining over time (Fischer, 2019). Other naturally occurring contaminants like manganese often coexist in high arsenic regions, posing multiple long-term threats (Ghosh et al., 2020). In the southwestern coastal region, an estimated 24% of the country's land area is exposed to combined risks of arsenic and salinity (Shamsudduha et al., 2020). Thus people are faced with a water security landscape that can be complex and difficult to navigate due to multiple water quality issues.

Despite the public health community taking a broader view of health and wellbeing – with the WHO defining health as "a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity" (WHO, 1946) – health is still commonly perceived as a binary state of disease and non-disease. Those with conditions manifested through diagnosable symptoms often receive greater attention in policy circles: e.g. the Bangladesh government only identifying those with visible symptoms such as skin lesions as arsenic patients (Human Rights Watch, 2016; Loewenberg, 2016), despite it taking years to develop, and most people affected by arsenic never developing skin lesions (Loewenberg, 2016; UNICEF, 2018). Moreover, in the course of a disease, between exposure and onset of symptoms, there is an asymptomatic stage of subclinical disease – known as the 'incubation period' for infectious diseases and 'latency period' for chronic diseases (CDC, 2012).

Psychosocial distress involves a dynamic relationship between people's perceptions, emotions and coping mechanisms in response to their social and environmental conditions (Bisung and Elliott, 2017; Krieger, 2011). Psychosocial distress in relation to water insecurity is an emerging field of research, with studies from various countries showing a range of emotional responses, including fear, worry, anxiety, anger, and shame (Bisung and Elliott, 2016, 2017; Brewis et al., 2021; Bulled, 2016; Kangmennaang et al., 2020; Stevenson et al., 2012; Thomas and Godfrey, 2018; Wutich and Ragsdale, 2008). The majority of these studies look at water insecurity overall – not specifically how water quality relates to psychosocial distress, with a recent study from Bangladesh expressing the need for empirical testing for arsenic and other contaminants in order to understand environmental risks more fully (Broyles et al., 2023).

In the growing literature on water security and its wide-reaching impacts, there is increasing recognition of the concept of embodiment: i.e. the idea that an individual's social and environmental conditions can become incorporated into their biology, i.e. "get under the skin" (Brewis et al., 2020; Krieger, 2005). According to Krieger (2005), human bodies can often tell stories which people are unable or unwilling to tell. In this study, we examine two such unseen and untold impacts by examining particular forms of embodiment of water quality risks, i.e. subclinical disease and psychosocial distress.

The aim of this study is to understand how water quality hazards affect health beyond the commonly observed metrics of clinical disease outcomes. In this paper, we set out to (1) understand the distribution of water quality risks; (2) explore the prevalence of subclinical disease; and (3) analyse the impacts of water quality on subclinical disease and psychosocial distress; within the context of arsenic contamination in Bangladesh. A cross-sectional study design is applied to explore whether the magnitude of the subclinical and psychosocial outcomes correlate to the level of contamination, and other factors such as the perceived risk from the contaminant. This study contributes further knowledge and new insights to the field of water security by focusing on water quality specifically, and seeking to bring visibility to the unseen embodiments of contamination, in an effort to broaden the narrative around the public health impacts of water insecurity.

2. Methodology

A cross-sectional study was designed to collect empirical evidence from three rural sites in southwestern and southcentral Bangladesh in two phases. Phase one (August 2021 to March 2022) included (a) a household survey to collect socio-demographic, water usage and health information; and (b) sample collection and laboratory analysis for household water quality and arsenic in nails in women and men. Phase two conducted 6 months later involved the administration of the novel psychosocial distress scale (referred to as PSD scale, henceforth) alongside the standard Patient Health Questionnaire (PHQ-9). The PSD scale was developed using findings from a qualitative study (January–May 2022) of lived experiences of multiple water quality issues (Khan et al. under review).

2.1. *Ethical considerations*

Ethical approval for this study was obtained from the Oxford Tropical Research Ethics Committee (OxTREC reference number: 502-21) and the Institutional Review Board (IRB) of the International Centre for Diarrhoeal Diseases, Bangladesh (icddr,b) (Protocol no. PR-21064). The purpose of the research was verbally presented, and written informed consent was taken from the participants before they were interviewed. Oral informed consent was taken from those who could not read or write. Data privacy and the ability to ask questions and to withdraw from the study at any point were communicated to the participants.

2.2. *Study sites and sampling frame*

Contamination by naturally occurring arsenic, iron, manganese and salinity contributes to a severe drinking water crisis in southern Bangladesh (Ghosh et al., 2020; Shamsudduha et al., 2020). Based on water quality data from the 2019 Multiple Indicator Cluster Survey (MICS), three study sites with varying degrees of groundwater arsenic concentrations were chosen (Fig. 1). These were: Hajiganj *upazila* (sub-district) with a district average of 331 μg/L of arsenic (point of use water); Tala *upazila* with 50 μg/L; and Dumuria *upazila* with the lowest concentration of 12 μg/L. In each of these *upazilas*, a cluster of contiguous villages were sampled from.

2.3. *Sample size and sampling method*

The population-adjusted sample size was calculated using OpenEpi (Dean et al., 2014) with the calculator for cross-sectional studies (Sullivan, 2013) using the formula shown in Sullivan (2003). For the anticipated frequency, the prevalence of low mental health scores related to arsenic was considered here as a proxy, since psychosocial distress as addressed in this study had not yet been quantified. The 30% prevalence rate of lower mental health scores measured via the General Health Questionnaire in a large-scale study (n = 4099) in Bangladesh was used (Chowdhury et al., 2016). Population sizes were taken from the 2011 Population and Housing census (Bangladesh Bureau of Statistics, 2011). The sample size for each study site was estimated at 300 respondents – i.e., a total of 900 respondents. To maintain a gender balance, the target was to sample one male and one female member per household (i.e. 450 households).

Households were selected using systematic random sampling based on locally available population data. If participants were not present, enumerators went back or forward one household, and continued the interval count from that point. The inclusion criteria for respondents were adult man or woman within the study area aged between 18 and 60 years old. Those less than 18 or more than 60 years old; living in the village for less than a year; unable to consent to participate and who may be put at risk by participating were excluded.

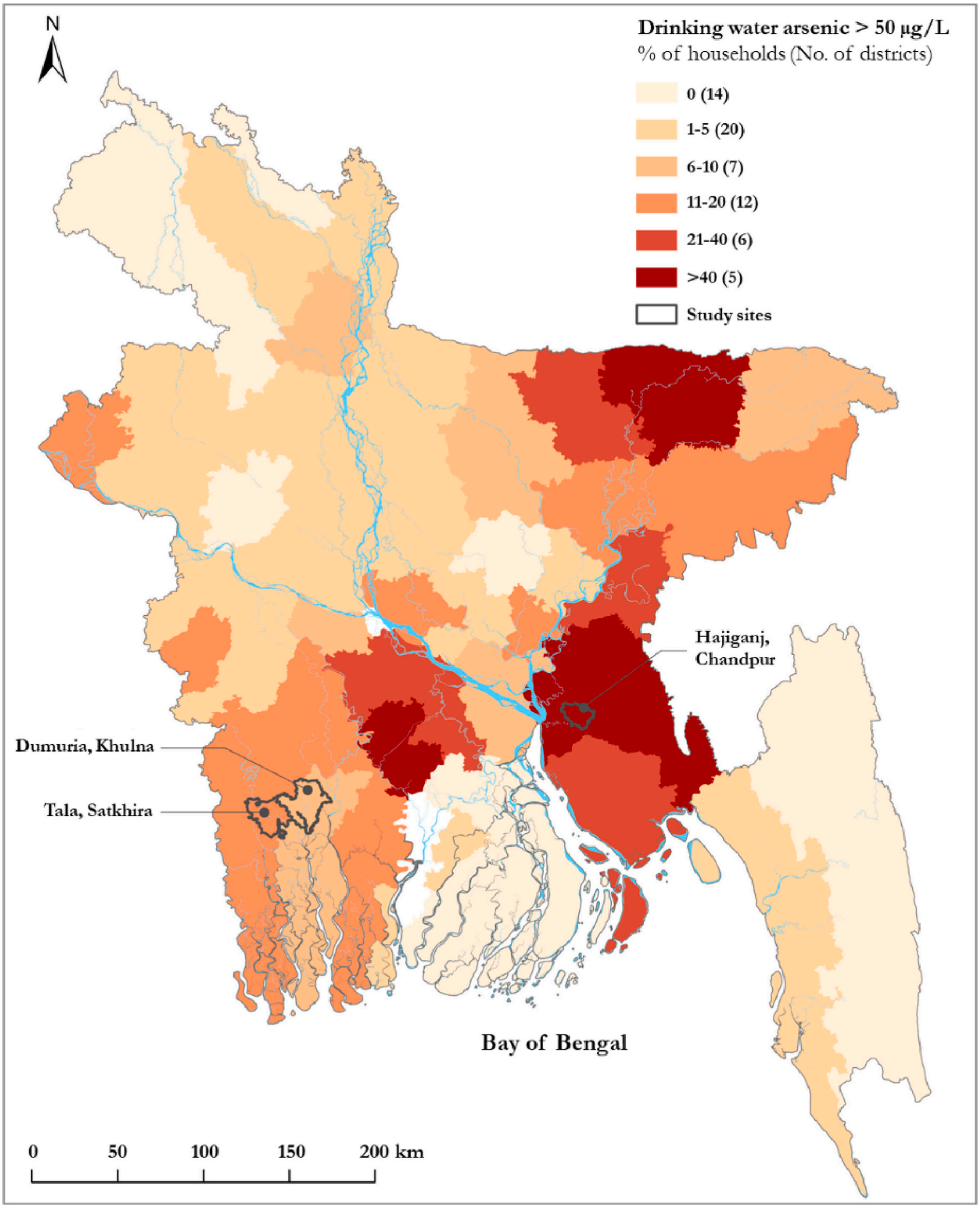

Fig. 1. *Location of the three study sites and district-level groundwater arsenic in Bangladesh* (Data: UNICEF, 2019).

2.4. Data collection

2.4.1. Household survey

The household survey was used to collect data on household demographic profile, housing characteristics, asset ownership and water usage (Supplementary Table S1) and was administered in Bangla through ONA (a mobile data collection platform). The survey was conducted by a team of local enumerators supervised by field managers. A total of 462 households were surveyed, with all but 8 having both a male and female participant.

2.4.2. Water and nail sample collection

For water samples, study participants were asked to provide a glass of water from a water container stored within their home, and were asked if they believed this water sample contained arsenic. For chloride and salinity testing, plastic bottles 3-times pre-washed with deionised water were used to collect the water samples; and for arsenic, manganese and iron analysis, samples were collected in acid-washed pre-acidified (with 1.5 mL conc. HNO_3/L) HDPE bottles to avoid possible metal contamination and to maintain the pH of the samples at <2 (Baird et al., 2017). Water samples were analysed in the Laboratory of Environmental Health, icddr,b for arsenic (As), iron (Fe), manganese (Mn), chloride (Cl^-) and salinity (Supplementary Table S2).

For nail samples (collected at the same time as water samples), participants were given new stainless steel nail clippers and asked to clip nails from all toes on both feet. Those who were not used to or comfortable with nail clippers were asked to use their usual implement. The nail samples were sealed separately in labelled polyethylene ziplocked bags and were not opened until analysis. With two participants (one household) lost to follow-up and 15 nail samples of insufficient quantity for analysis, the total water and nail participant sample size was n = 899. All water and nail samples were stored at room temperature and transported to icddr,b.

2.4.3. Nail sample laboratory analysis

Nail samples were cleaned with 1% Triton X-100 with mechanical shaking for 20 min, and rinsed in deionised water, to remove surface contamination, and dried at 60°C overnight in a drying oven and stored in a desiccator (Chen et al., 1999). Nail samples were digested following the procedure for digestion of human biological samples described elsewhere (Chen et al., 1999; Sansoni and Panday, 1994; Wasiak et al., 1996). Samples were digested in a microwave digestion system (Ethos Easy, Milestone, Italy) with HNO_3 and H_2O_2. After cooling, the digest was diluted up to 10 mL with ultrapure water. Samples were analysed by a graphite furnace atomic absorption spectrometer (GFAAS) (iCE 3000 series, Thermo Scientific, USA) equipped with a Zeeman background correction system following the procedure described by Yüksel et al. (2015). A boosted-discharge hollow cathode lamp (Thermo Scientific, USA) was used as the excitation source for arsenic. A calibration curve was developed and used to calculate arsenic concentrations. Finally, the amount of arsenic in the nail clippings was converted into μg/g of dry weight.

2.4.4. Psychosocial distress survey

The psychosocial distress scale (Supplementary Table S3) was administered to participants from phase one in Bangla (after which the result of the water-As test for each household was provided, with a summary statement on the relationship between water and nail arsenic levels). Considering losses to follow-up at this stage, the total sample size for the psychosocial survey was n = 876. In the 52-item novel PSD scale, questions were sectioned into degrees of specificity (i.e. the columns: water overall, water quality, health issues in relation to water quality, and social/economic issues in relation to water quality). For each section, questions were asked on specific components of psychosocial distress (i.e. worry, fear, lack of choice, uncertainty, discomfort, conflict, suffering). Responses were on a Likert-type scale: never (0), sometimes (1), often (2), and always (3). Sub-questions which involved selecting all responses that apply were meant to gauge further information and did not count into the scores. Since some PSD components consisted of more questions than others (Supplementary Table S3), scores were weighted (total score for component divided by number of questions); the scores of all the components were summed for a total PSD score.

Social and cultural insights are critical when designing safe water services (Hanchett et al., 2014), and it is to research as well. A culturally-grounded novel scale that uses local expressions of distress was developed and applied in this study, since the aim was to capture experiences in a way that is meaningful to the participants, using words they normally use to express such emotions and feelings. According to Bisung and Elliott (2017), such tools help reflect lived realities of the participants. To triangulate the findings and assess the validity of the novel scale, the Patient Health Questionnaire (PHQ-9) was administered alongside it (Spitzer et al., n.d.). This standardised scale was chosen due to its thematic similarities with the novel scale, the similar 4-point Likert-type responses, and the general sensitivity of the questions. Following the precedence set by Brewis et al. (2021), the suicidal ideation question was removed and replaced with a more culturally-appropriate item on feeling worried or anxious, since suicide is a culturally tabooed topic which could unnecessarily distress the respondents. Further information on measuring subclinical As and PSD are in Supplementary Text Box S1.

2.5. Data analysis

The aim of this study was to understand the associations between water quality and subclinical disease, as well as water quality and psychosocial distress and how other factors modify these associations. Descriptive statistics were generated in SPSS 28. Principal Component Analysis was performed (KMO = 0.8) on the socio-economic data (i.e. durables, housing materials and education from the household survey) in SPSS 28 to generate a categorical variable 'socioeconomic status' for multidimensional wealth using the method applied by Hoque et al. (2019). Regression analyses were done on RStudio using the Bayesian package brms which computes Bayesian models in R using Stan, a probabilistic programming language (Bürkner, 2017). Since neither of the outcome variables are normally distributed (see next section), a statistical package which could apply generalised linear models as well as handle zero-inflated continuous data was required. The bayestestR package was used to calculate the Bayesian equivalent of the p-value (Makowski et al., 2019).

For data analysis, water quality and nail-As readings that were below the detection limit were converted to half the detection limit (Giskeødegård and Lydersen, 2022), which for water-As is 1 μg/L; water-Fe is 0.1 mg/L; water-Mn is 0.1 mg/L; and nail-As is 0.1 μg/g.

2.5.1. Regression analysis

Distributions of water quality parameters, nail arsenic levels, and psychosocial distress (PSD) and PHQ scores are in Supplementary Figs. S1–6. Both nail arsenic levels and PSD scores showed right-skewed distributions, indicating that lognormal or gamma regression models (appropriate for positive continuous data with right-skewed distributions (Dick, 2004; Zuur and Ieno, 2016)) would be suitable. The PSD distribution has a large amount of zeroes which need to be taken into account during analysis – and for this purpose, two-part models which account for the zero-inflation are most suitable (Boulton and Williford, 2018; Zuur and Ieno, 2016).

For nail-As, lognormal and gamma regression models were applied and a leave-one-out cross-validation was performed, which determined the gamma model a better fit. For zero-inflated continuous PSD data, hurdle models were applied – which consist of a binary part and a continuous part (Zuur and Ieno, 2016). For the binary part, a Bernoulli distribution is applied; and for the nonzero (positive) continuous part, a gamma or lognormal distribution can be applied (Zuur and Ieno, 2016). Leave-one-out cross-validation was performed, which determined the hurdle lognormal model a better model fit. The scores for the quality-specific portions of the PSD scale (i.e. PSDQ), were also tested for comparison. The same principles also apply to the PSDQ variable as it is distributed quite similarly (Supplementary Fig. S5). The distribution for the PHQ scores (Supplementary Fig. S6), also shows zero inflation, but since the PHQ scores are count data, either a Poisson regression or negative binomial regression would be appropriate. Since Poisson is only applicable when the mean and variance are equal, and negative binomial otherwise (Zuur and Ieno, 2016) – a hurdle negative binomial model was most applicable to the PHQ data. All continuous numerical predictors were centred (Goldstein, 2015; Robinson C, 2009). To estimate the associations between the dependent variables and explanatory variables of interest, first we fitted a series of regression models, each of which included only a single variable adjusted for water-As. We then fitted a multivariable regression model including all variables together.

Control variables included organoleptic and non-organoleptic water quality parameters – (chloride, iron and manganese) that co-occur with arsenic in the selected regions. Microbial contamination was considered so prevalent – i.e. 81.9% of household drinking water (Charles et al., 2021) – as to not be a useful variable. Other variables included socio-economic status, age, length of residence in household, length of residence in village, gender, religion, education, occupation, chronic illness, and arsenicosis symptoms. Variables which could potentially influence distress, such as tubewell ownership, tubewell arsenic status, number of water sources, and belief in presence of arsenic were included in the distress models. For the regression analyses, certain categorical predictor variables were modified by removing extremely low frequency categories which would not be very meaningful in a regression model and/or cause the model not to function (see Supplementary Table S4).

3. Results

The distribution of water quality hazards, prevalence of subclinical disease as indicated by arsenic concentrations in toenails, and the state of psychosocial distress are presented here, followed by regression analyses. The demographic data from the survey (n = 916; from 462 households) is shown in Table 1.

3.1. Distribution of water quality risks

Water quality risks were uneven (Table 2, Supplementary Table S5 and Supplementary Figs. S7–9). Hajiganj had the highest As contamination, where all households reported using (mostly privately-owned) shallow tubewells (<150m deep) (Supplementary Tables S6–7). The lowest levels of As, Mn, and Fe concentrations were found in Dumuria, where households mostly used deep tubewells (98.7%); however, chloride levels were slightly elevated, indicating salinity.

Previous knowledge of As contamination generally aligned well with measured water-As (Supplementary Fig. S10). If the source had been tested previously, it is assumed that it would have been reported to them (via information or paint on the tubewells; Supplementary Fig. S11) whether the As content was above or below the national guideline value.

Table 2
Water quality parameter distribution across sites (average concentrations and by guideline values).

Parameter	Threshold	Dumuria	Tala	Hajiganj	Overall
Arsenic	*Average (μg/L)*[a]	2.51	7.89	378.98	134.92
Threshold	≤10 μg/L	95.4%	75.3%	–	55.7%
	>*10 but* ≤50 μg/L	4.6%	24.0%	–	9.3%
	>50 μg/L	–	0.7%	100.0%	34.9%
Iron	*Average (mg/L)*[a]	0.47	4.54	2.55	2.52
Threshold	≤0.3 mg/L	54.3%	12.0%	5.6%	23.6%
	>*0.3 but* ≤*1.0* mg/L	36.4%	7.3%	4.4%	15.8%
	>*1.0* mg/L	9.3%	80.7%	90.0%	60.5%
Manganese	*Average (mg/L)*[a]	0.05	0.17	0.05	0.09
Threshold	≤*0.1* mg/L	100.0%	32.0%	95.6%	76.4%
	>*0.1* mg/L	–	68.0%	4.4%	23.6%
Chloride	*Average (mg/L)*[a]	228.19	164.73	107.57	165.67
Threshold	≤150 mg/L	55.0%	80.7%	76.9%	70.9%
	>*150 but* ≤600 mg/L	35.8%	13.3%	21.9%	23.6%
	>600 mg/L	9.3%	6.0%	1.3%	5.4%

[a] *Note: WHO guideline value for As is* 10 μg/L *& Bangladesh guideline values for As is* 50 μg/L*; Fe is 0.3-1.0* mg/L*; Mn is 0.1* mg/L*; and* Cl^- *is 150-*600 mg/L (DPHE, 2019).

Overall, 8.6% of households that were previously unaware of the As status of their tubewell had As levels between 10 and 50 μg/L, and 29.1% had above 50 μg/L. Moreover, 7.6% of households who had been informed that their water source was safe had As levels above 50 μg/L.

Belief in the presence of arsenic aligned well with measured As levels (Supplementary Fig. S12). However, 11.7% of those who did not believe

Table 1
Demographic data from the household survey.

Indicators		Dumuria		Tala		Hajiganj		Overall	
Gender	*Female (%)*	50.3		50.3		50.0		50.2	
Household size	*Average*	4.2		3.6		4.9		4.3	
Socioeconomic status	*Extreme poor (%)*	59.5		40.0		23.8		40.6	
	Poor (%)	22.6		35.7		38.8		32.5	
	Middle (%)	10.8		15.3		31.9		19.7	
	Rich (%)	7.1		9.0		5.6		7.2	
		Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Age	*Average (years)*	34.9	39.3	35.2	40.6	35.8	37.4	35.3	39.1
Length of residence in HH	*Average (years)*	20.1	36.0	17.4	32.4	18.9	29.1	18.8	32.4
Length of residence in village	*Average (years)*	20.8	37.0	20.3	38.1	20.8	34.3	20.6	36.4
Religion	*Muslim (%)*	94.6	94.6	88.7	88.6	93.1	93.1	92.2	92.1
	Hindu (%)	5.4	5.4	10.6	10.7	6.9	6.9	7.6	7.7
	Christian (%)	0.0	0.0	0.7	0.7	0.0	0.0	0.2	0.2
Education	*Unknown (%)*	0.7	–	–	–	–	–	0.2	–
	None (%)	6.0	5.4	6.0	3.4	3.8	2.5	5.2	3.7
	Can sign name (%)	27.5	27.2	15.9	18.1	10.6	13.8	17.8	19.5
	Pre-school (%)	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.4
	Primary (%)	38.3	34.7	48.3	43.0	48.1	46.9	45.0	41.7
	Secondary (%)	22.1	21.1	23.8	28.2	36.3	30.6	27.6	26.8
	Post-secondary (%)	5.4	11.6	6.0	6.0	1.3	6.3	4.1	7.9
Occupation	*Homemaker (%)*	96.0	–	94.7	–	98.1	–	96.3	–
	Agriculture (%)	0.7	51.7	0.7	60.4	0.0	23.8	0.4	44.7
	Business (%)	–	12.2	–	12.8	–	30.0	–	18.6
	Casual/skilled labour (%)	–	15.0	0.7	12.8	0.6	18.8	0.4	15.6
	Service job (%)	1.3	13.6	0.7	6.0	0.6	13.1	0.9	11.0
	Other (%)	–	–	–	0.7	–	–	–	0.2
	Student (%)	2.0	4.1	2.0	5.4	0.6	8.1	1.5	5.9
	Unemployed (%)	–	3.4	1.3	2.0	–	6.3	0.4	3.9
Chronic illness	*Yes (%)*	19.5	25.9	13.2	12.8	23.1	14.4	18.7	17.5
	No (%)	79.9	74.1	84.8	85.9	76.9	85.6	80.4	82.0
	Don't know (%)	0.7	–	2.0	1.3	–	–	0.9	0.4

the contaminant was present had As between 10 and 50 μg/L and 31.1% had arsenic above 50 μg/L. Whether or not respondents believed there was arsenic in the water sample they provided to the research team aligned well with the previous knowledge of the arsenic status of their water sources (Supplementary Fig. S13). 5.1% of respondents who were previously informed there was arsenic in their tubewell reported that they did not believe the contaminant was present, and 3.8% of them reported they did not know if they believed the contaminant to be present.

3.2. Prevalence of subclinical disease – arsenic concentrations in nails

Prevalence of nail-As was higher than expected based on water-As: only 44% of people had water-As over 10 μg/L, while 65.3% had nail-As above 1 μg/g, i.e. the cut-off for As in nails in unexposed individuals (Agency for Toxic Substances and Disease Registry, 2007) based on the United States reference value where the standard for As in drinking water is 10 μg/L (US EPA, 2022). This includes 23.8% of analysed nail samples from Dumuria, 69.4% from Tala, and 100% from Hajiganj (Fig. 2; Supplementary Fig. S14). Visible symptoms of arsenicosis – either reported by the respondent and/or observed by the enumerators – were uncommon: only 31 of the survey respondents (3.4%) exhibited visible symptoms of arsenic poisoning (7.4% of those exposed to water-As above 10 μg/L) – of which 30 were from Hajiganj. This illustrates that subclinical disease, people at risk of developing adverse health outcomes (Freeman et al., 2004; Orloff et al., 2009; Rehman et al., 2020), is much more prevalent than visible skin lesions.

3.3. State of psychosocial wellbeing

Three different psychosocial distress scores are presented: PSD, the overall PSD score from the novel scale; PSDQ, the scores from the PSD scale from the quality column onward; and PHQ, the scores from the standardised PHQ-9 scale (Supplementary Fig. S15). For the PSD scale, the responses were 0 if no distress was experienced (i.e. 'never'), and between 1 and 3 if experienced (i.e. 'sometimes', 'often', and 'always') with a higher score indicating higher severity of distress. Hajiganj had the highest average scores for all three (Supplementary Figs. S15–16). The average PSDQ score was slightly higher than the average overall PSD score, and the PHQ scores showed a wider range. Furthermore, the psychosocial distress scores above zero were 40.4% and 38.8%, based on PSD and PHQ scores respectively. Across all sites uncertainty was the most commonly experienced component of PSD (Supplementary Fig. S17), followed by worry, fear, suffering and lack of choice – while discomfort and conflict were much less common. Discomfort was also experienced by only a few participants – which aligns with the small minority of participants exhibiting visible symptoms of arsenicosis.

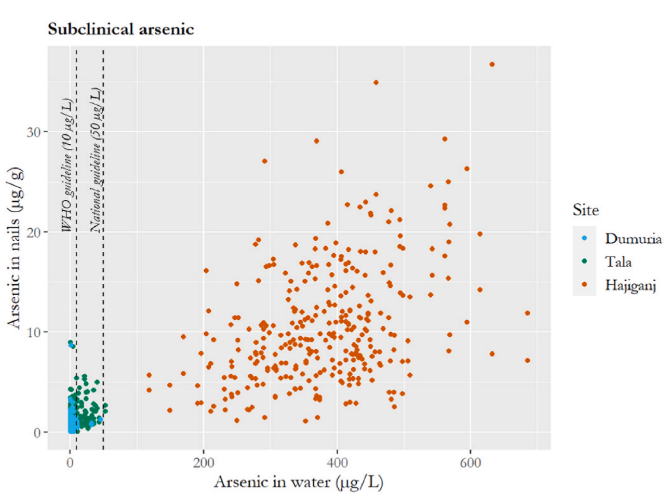

Fig. 2. Nail arsenic vs water arsenic levels.

3.4. Nail arsenic levels – regression analysis

This section presents results of simple and multiple gamma regression for the nail-As outcome variable (Table 3). Interactions were tested to see if predictors had a joint effect on the outcome variable (Supplementary Table S8). Table 3 compares covariates separately to understand how they affects the water-As and nail-As relationship (column showing unadjusted models), and also tested together in one model (adjusted column).

Water-As shows a positive correlation with nail-As. When all water quality parameters are modelled together, water-Fe shows a positive correlation to nail-As as well. However, the relationship between water-As and nail-As remains. Controlling for socioeconomic status, belonging to the poor wealth category was associated with higher nail-As compared to the rich, but the extreme poor showed no significant difference compared to the rich (it should be noted that the low and medium arsenic sites had higher proportions of people in the extreme poor wealth category). Controlling for gender shows that men had significantly higher nail-As compared to women, but it does not modify the water-As to nail-As relationship. Controlling for age, length of residence in household, length of residence in the village, religion, chronic illness, and arsenicosis symptoms had no significant effect.

The adjusted model with all the covariates modelled together shows similar results – i.e. water-As and water-Fe are still significantly associated with nail-As – however, none of the sociodemographic and health covariates are significant. Thus, when all covariates are modelled together, none of the other variables confound or modify the relationship between water-As and nail-As – although at $p = 0.08$, gender and poor wealth category are relatively close to the $p \leq 0.05$ threshold.

Following the previous models, some of the variables were tested for interactive (i.e. multiplicative) effects with water-As (Supplementary Table S8), based on the supposition that some variables might work synergistically (e.g. sex-based predisposition for arsenic uptake). Most variables did not show interactive effects with water-As on nail-As with the exception of length of residence in village, gender, and arsenicosis symptoms. The interaction of water-As with length of residence decreases the effect of water-As on nail-As by 0.10 units ($p \leq 0.01$); with gender (i.e. being male) decreases this by 0.26 units ($p \leq 0.001$); and with arsenicosis symptoms by 0.63 units ($p \leq 0.01$).

3.5. Psychosocial distress – regression analysis

Simple and multiple hurdle regression models were used to analyse the psychosocial distress scales (Table 4; Supplementary Table S9). Since a two-part hurdle model was applied, the following subsections will describe the relationships between the predictor variables with both the zero and nonzero (positive) PSD, PSDQ and PHQ scores. The zero scores represent the frequency of experiencing distress (i.e. whether or not it is experienced at all), while the nonzero scores represent the severity. As with nail-As, the distress scales were modelled with each covariate separately (Supplementary Table S9), as well as all together in an adjusted model (Table 4).

Water-As is positively associated with the severity of PSD, PSDQ and PHQ, and negatively associated with scoring zero for all three (Supplementary Table S9). That is, the higher the level of arsenic, the higher the frequency and severity of psychosocial distress. To assess if any of the other contaminants were correlated with psychosocial distress, the other water quality parameters were tested individually. Water-Fe shows no association with any of the scales. Water-Mn is associated with lower distress scores, although it is not clear why. It shows a positive association with scoring zero for all three scales, and also a negative association with the severity of PHQ scores. Water-Cl^- shows a positive association with scoring zero for all three scales but also shows a positive association with the severity for PSD and PSDQ.

Table 3
Regression analysis for nail arsenic (n = 899) [*p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001].

Predictors	Unadjusted models[a]	Adjusted model
Water quality parameters		
Arsenic only		
[nail-As ∼1 + water-As]		
Arsenic	**1.06***** (Error: 0.03; 95% CI: 1.01 to 1.12)	
All water quality parameters		
[nail-As ∼1+ water-As + water-Fe + water-Mn + water-Cl^-]		
Arsenic	**1.09***** (Error: 0.03; 95% CI: 1.04 to 1.15)	**1.09***** (Error: 0.03; 95% CI: 1.03 to 1.15)
Iron	**0.17***** (Error: 0.03; 95% CI: 0.12 to 0.24)	**0.18***** (Error: 0.03; 95% CI: 0.12 to 0.24)
Manganese	0.05 (Error: 0.03; 95% CI: −0.02 to 0.12)	0.03 (Error: 0.03; 95% CI: −0.03 to 0.10)
Chloride	0.02 (Error: 0.02; 95% CI: −0.03 to 0.07)	0.03 (Error: 0.02; 95% CI: −0.02 to 0.07)
Socio-demographics and health		
Socioeconomic status [reference category: rich]		
[nail-As ∼1 + water-As + socioeconomic status]		
Arsenic	**1.06***** (Error: 0.03; 95% CI: 1.00 to 1.12)	
Middle	0.16 (Error: 0.11; 95% CI: −0.05 to 0.37)	0.16 (Error: 0.11; 95% CI: −0.06 to 0.37)
Poor	**0.27*** (Error: 0.10; 95% CI: 0.07 to 0.47)	0.24 (Error: 0.10; 95% CI: 0.03 to 0.44)
Extreme poor	0.16 (Error: 0.10; 95% CI: −0.04 to 0.36)	0.16 (Error: 0.11; 95% CI: −0.06 to 0.36)
Age		
[nail-As ∼1 + water-As + age]		
Arsenic	**1.06***** (Error: 0.03; 95% CI: 1.01 to 1.12)	
Age	0.01 (Error: 0.02; 95% CI: −0.04 to 0.06)	0.04 (Error: 0.05; 95% CI: −0.06 to 0.13)
Length of residence in household		
[nail-As ∼1 + water-As + length in HH]		
Arsenic	**1.07***** (Error: 0.03; 95% CI: 1.01 to 1.12)	
Length in HH	0.02 (Error: 0.03; 95% CI: −0.02 to 0.08)	
Length of residence in village		
[nail-As ∼1 + water-As + length in village]		
Arsenic	**1.07***** (Error: 0.03; 95% CI: 1.01 to 1.12)	
Length in village	0.05 (Error: 0.03; 95% CI: 0.00 to 0.10)	−0.05 (Error: 0.05; 95% CI: −0.15 to 0.06)
Gender [reference category: female]		
[nail-As ∼1 + water-As + gender]		
Arsenic	**1.08***** (Error: 0.03; 95% CI: 1.03 to 1.13)	
Male	**0.24***** (Error: 0.05; 95% CI: 0.15 to 0.34)	0.48 (Error: 0.20; 95% CI: 0.07 to 0.86)
Religion [reference category: Muslim]		
[nail-As ∼1 + water-As + religion]		
Arsenic	**1.06***** (Error: 0.03; 95% CI: 1.01 to 1.11)	
Hindu	−0.09 (Error: 0.10; 95% CI: −0.27 to 0.10)	−0.03 (Error: 0.10; 95% CI: −0.21 to 0.16)
Education [reference category: primary]		
[nail-As ∼1 + water-As + education]		
Arsenic	**1.05***** (Error: 0.03; 95% CI: 1.00 to 1.10)	
No education	−0.15 (Error: 0.12; 95% CI: −0.38 to 0.10)	−0.04 (Error: 0.13; 95% CI: −0.28 to 0.21)
Can sign name	−0.11 (Error: 0.07; 95% CI: −0.25 to 0.03)	−0.10 (Error: 0.07; 95% CI: −0.24 to 0.05)
Secondary	0.06 (Error: 0.06; 95% CI: −0.06 to 0.18)	0.13 (Error: 0.07; 95% CI: 0.01 to 0.26)
Post-secondary	**−0.30*** (Error: 0.11; 95% CI: −0.52 to −0.08)	−0.21 (Error: 0.13; 95% CI: −0.46 to 0.04)
Occupation [reference category: homemaker]		
[nail-As ∼1 + water-As + occupation]		
Arsenic	**1.10***** (Error: 0.03; 95% CI: 1.05 to 1.16)	
Agriculture	**0.39***** (Error: 0.06; 95% CI: 0.26 to 0.51)	−0.08 (Error: 0.21; 95% CI: −0.47 to 0.35)
Business	0.11 (Error: 0.09; 95% CI: −0.06 to 0.28)	−0.32 (Error: 0.22; 95% CI: −0.73 to 0.12)
Casual & skilled labour	0.14 (Error: 0.09; 95% CI: −0.04 to 0.33)	−0.28 (Error: 0.22; 95% CI: −0.69 to 0.15)
Service job	0.09 (Error: 0.10; 95% CI: −0.11 to 0.29)	−0.24 (Error: 0.23; 95% CI: −0.67 to 0.20)
Student	0.17 (Error: 0.13; 95% CI: −0.08 to 0.44)	−0.20 (Error: 0.22; 95% CI: −0.63 to 0.23)
Unemployed	−0.18 (Error: 0.17; 95% CI: −0.51 to 0.16)	−0.56 (Error: 0.26; 95% CI: −1.07 to −0.02)
Chronic illness [reference category: no]		
[nail-As ∼1 + water-As + chronic illness]		
Arsenic	**1.06***** (Error: 0.03; 95% CI: 1.01 to 1.11)	
Chronic illness [yes]	−0.06 (Error: 0.07; 95% CI: −0.19 to 0.07)	−0.03 (Error: 0.07; 95% CI: −0.16 to 0.11)
Arsenicosis symptoms [reference category: no]		
[nail-As ∼1 + water-As + arsenicosis symptoms]		
Arsenic	**1.05***** (Error: 0.03; 95% CI: 1.00 to 1.11)	
Arsenicosis symptoms [yes]	0.13 (Error: 0.14; 95% CI: −0.15 to 0.42)	0.11 (Error: 0.14; 95% CI: −0.15 to 0.40)

[a] Column 1 displays the estimated regression coefficients from 12 separate gamma regression models fitted to the data, where the dependent variable is specified as nail-As and the covariates include water-As and the explanatory variable shown in the row header. Only the estimated regression coefficient for the variable in the row header is shown. Column 2 displays the estimated regression coefficients from a single multivariable gamma regression model fitted to the data. Thus this table displays the output from 13 gamma regression models in total. It should be noted that the length of residence in household was excluded from the adjusted model as it is similar to the length of residence in village variable.

When the water quality parameters are modelled together, the relationship of water-As with PSD and PSDQ remains the same, whereas for PHQ only the negative relationship of water-As with scoring zero remains; the positive association with the severity of PHQ scores is no

Table 4
Adjusted[a] regression analysis for psychosocial distress (n = 876) [*p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001].

Predictors	PSD (frequency)	PSD (severity)	PSDQ (frequency)	PSDQ (severity)	PHQ (frequency)	PHQ (severity)
Water quality parameters						
Arsenic	**−3.58***** (Error: 0.35; 95% CI: −4.30 to −2.94)	0.08 (Error: 0.05; 95% CI: −0.01 to 0.17)	**−3.64***** (Error: 0.36; 95% CI: −4.38 to −2.98)	0.07 (Error: 0.04; 95% CI: −0.01 to 0.16)	**−1.15***** (Error: 0.13; 95% CI: −1.41 to −0.91)	−0.01 (Error: 0.04; 95% CI: −0.10 to 0.08)
Iron	−0.15 (Error: 0.16; 95% CI: −0.45 to 0.18)	−0.02 (Error: 0.06; 95% CI: −0.13 to 0.09)	−0.20 (Error: 0.16; 95% CI: −0.51 to 0.12)	−0.07 (Error: 0.05; 95% CI: −0.17 to 0.03)	−0.09 (Error: 0.10; 95% CI: −0.29 to 0.10)	−0.01 (Error: 0.04; 95% CI: −0.10 to 0.08)
Manganese	0.13 (Error: 0.19; 95% CI: −0.20 to 0.56)	0.07 (Error: 0.06; 95% CI: −0.05 to 0.19)	0.12 (Error: 0.19; 95% CI: −0.22 to 0.50)	0.07 (Error: 0.06; 95% CI: −0.04 to 0.18)	0.02 (Error: 0.11; 95% CI: −0.18 to 0.24)	**−0.24***** (Error: 0.08; 95% CI: −0.40 to −0.09)
Chloride	0.28 (Error: 0.16; 95% CI: 0.00 to 0.64)	**0.21***** (Error: 0.06; 95% CI: 0.10 to 0.33)	0.28 (Error: 0.16; 95% CI: −0.01 to 0.63)	**0.25***** (Error: 0.06; 95% CI: 0.14 to 0.36)	0.23 (Error: 0.13; 95% CI: −0.01 to 0.50)	0.06 (Error: 0.06; 95% CI: −0.05 to 0.17)
Water sources						
Tubewell ownership [reference category: respondent]						
Ownership [neighbour]	**−1.10*** (Error: 0.40; 95% CI: −1.88 to −0.31)	−0.03 (Error: 0.11; 95% CI: −0.24 to 0.18)	−0.94 (Error: 0.41; 95% CI: −1.76 to −0.14)	−0.09 (Error: 0.10; 95% CI: −0.29 to 0.11)	0.07 (Error: 0.27; 95% CI: −0.46 to 0.62)	−0.13 (Error: 0.11; 95% CI: −0.34 to 0.08)
Ownership [community]	1.21 (Error: 0.91; 95% CI: −0.33 to 3.25)	−0.01 (Error: 0.46; 95% CI: −0.91 to 0.87)	1.17 (Error: 0.92; 95% CI: −0.34 to 3.22)	**−1.31*** (Error: 0.45; 95% CI: −2.20 to −0.45)	−0.04 (Error: 0.37; 95% CI: −0.74 to 0.72)	−0.27 (Error: 0.19; 95% CI: −0.64 to 0.08)
Ownership [institute]	0.17 (Error: 0.65; 95% CI: −1.05 to 1.51)	−0.30 (Error: 0.35; 95% CI: −1.01 to 0.39)	0.08 (Error: 0.65; 95% CI: −1.11 to 1.41)	−0.28 (Error: 0.34; 95% CI: −0.95 to 0.37)	0.22 (Error: 0.41; 95% CI: −0.54 to 1.06)	−0.24 (Error: 0.25; 95% CI: −0.74 to 0.22)
Tubewell arsenic status from previous testing [reference category: safe]						
Tubewell [unsafe]	**−2.57*** (Error: 0.88; 95% CI: −4.35 to −0.90)	−0.41 (Error: 0.17; 95% CI: −0.75 to −0.07)	**−2.72**** (Error: 0.90; 95% CI: −4.51 to −0.98)	−0.33 (Error: 0.16; 95% CI: −0.64 to −0.01)	0.00 (Error: 0.42; 95% CI: −0.80 to 0.82)	0.17 (Error: 0.16; 95% CI: −0.13 to 0.48)
Tubewell [unknown]	−0.45 (Error: 0.38; 95% CI: −1.24 to 0.28)	**−0.39*** (Error: 0.15; 95% CI: −0.71 to −0.09)	−0.36 (Error: 0.40; 95% CI: −1.14 to 0.43)	−0.27 (Error: 0.15; 95% CI: −0.56 to 0.03)	−0.09 (Error: 0.24; 95% CI: −0.57 to 0.39)	**0.29*** (Error: 0.12; 95% CI: 0.07 to 0.52)
Number of sources						
Number of sources	−0.65 (Error: 0.51; 95% CI: −1.57 to 0.41)	−0.28 (Error: 0.15; 95% CI: −0.58 to 0.02)	−0.60 (Error: 0.50; 95% CI: −1.54 to 0.44)	−0.24 (Error: 0.14; 95% CI: −0.52 to 0.04)	0.08 (Error: 0.36; 95% CI: −0.62 to 0.81)	−0.25 (Error: 0.14; 95% CI: −0.54 to 0.03)
Demographic & health						
Socioeconomic status [reference category: homemaker]						
Middle	−0.10 (Error: 0.61; 95% CI: −1.29 to 1.12)	−0.07 (Error: 0.15; 95% CI: −0.36 to 0.21)	0.06 (Error: 0.60; 95% CI: −1.12 to 1.24)	−0.06 (Error: 0.14; 95% CI: −0.33 to 0.23)	0.05 (Error: 0.42; 95% CI: −0.79 to 0.86)	0.07 (Error: 0.16; 95% CI: −0.25 to 0.39)
Poor	1.31 (Error: 0.61; 95% CI: 0.16 to 2.54)	0.05 (Error: 0.15; 95% CI: −0.24 to 0.34)	1.44 (Error: 0.62; 95% CI: 0.25 to 2.64)	0.03 (Error: 0.14; 95% CI: −0.24 to 0.31)	−0.07 (Error: 0.40; 95% CI: −0.87 to 0.70)	0.19 (Error: 0.16; 95% CI: −0.13 to 0.51)
Extreme poor	1.00 (Error: 0.59; 95% CI: −0.15 to 2.20)	0.09 (Error: 0.16; 95% CI: −0.21 to 0.40)	0.91 (Error: 0.60; 95% CI: −0.31 to 2.06)	0.07 (Error: 0.15; 95% CI: −0.21 to 0.36)	−0.06 (Error: 0.41; 95% CI: −0.85 to 0.73)	0.28 (Error: 0.17; 95% CI: −0.05 to 0.61)
Age						
Age	0.48 (Error: 0.31; 95% CI: −0.11 to 1.11)	0.08 (Error: 0.06; 95% CI: −0.04 to 0.21)	0.35 (Error: 0.31; 95% CI: −0.24 to 1.01)	0.03 (Error: 0.06; 95% CI: −0.08 to 0.15)	−0.19 (Error: 0.16; 95% CI: −0.50 to 0.14)	0.10 (Error: 0.06; 95% CI: −0.02 to 0.23)
Length of residence in village						
Length in village	−0.19 (Error: 0.34; 95% CI: −0.87 to 0.44)	−0.07 (Error: 0.07; 95% CI: −0.21 to 0.08)	−0.14 (Error: 0.34; 95% CI: −0.86 to 0.51)	−0.04 (Error: 0.07; 95% CI: −0.18 to 0.09)	−0.01 (Error: 0.18; 95% CI: −0.37 to 0.34)	0.01 (Error: 0.07; 95% CI: −0.12 to 0.14)
Gender [reference category: female]						
Male	−0.21 (Error: 1.10; 95% CI: −2.58 to 1.84)	0.12 (Error: 0.32; 95% CI: −0.49 to 0.74)	−0.35 (Error: 1.13; 95% CI: −2.72 to 1.70)	0.11 (Error: 0.30; 95% CI: −0.49 to 0.69)	0.77 (Error: 0.69; 95% CI: −0.59 to 2.15)	0.03 (Error: 0.28; 95% CI: −0.50 to 0.62)
Religion [reference category: Muslim]						
Hindu	−0.73 (Error: 0.68; 95% CI: −2.01 to 0.66)	−0.14 (Error: 0.13; 95% CI: −0.39 to 0.10)	−0.73 (Error: 0.68; 95% CI: −2.02 to 0.63)	−0.13 (Error: 0.12; 95% CI: −0.37 to 0.11)	0.55 (Error: 0.39; 95% CI: −0.20 to 1.33)	−0.02 (Error: 0.14; 95% CI: −0.29 to 0.25)
Education [reference category: primary]						
No education	−0.38 (Error: 0.80; 95% CI: −1.86 to 1.24)	−0.22 (Error: 0.18; 95% CI: −0.58 to 0.14)	−0.42 (Error: 0.80; 95% CI: −1.90 to 1.22)	−0.20 (Error: 0.17; 95% CI: −0.53 to 0.14)	−0.26 (Error: 0.44; 95% CI: −1.14 to 0.61)	0.13 (Error: 0.16; 95% CI: −0.19 to 0.44)
Can sign name	0.15 (Error: 0.46; 95% CI: −0.73 to 1.06)	−0.03 (Error: 0.11; 95% CI: −0.24 to 0.18)	−0.03 (Error: 0.48; 95% CI: −0.97 to 0.93)	−0.02 (Error: 0.11; 95% CI: −0.23 to 0.19)	0.15 (Error: 0.27; 95% CI: −0.37 to 0.67)	0.06 (Error: 0.10; 95% CI: −0.14 to 0.26)
Secondary	−0.39 (Error: 0.39; 95% CI: −1.16 to 0.37)	0.20 (Error: 0.09; 95% CI: 0.04 to 0.37)	−0.52 (Error: 0.42; 95% CI: −1.34 to 0.32)	0.14 (Error: 0.08; 95% CI: −0.01 to 0.29)	−0.18 (Error: 0.23; 95% CI: −0.64 to 0.26)	−0.02 (Error: 0.09; 95% CI: −0.19 to 0.15)

(*continued on next page*)

Table 4 (*continued*)

Predictors	PSD (frequency)	PSD (severity)	PSDQ (frequency)	PSDQ (severity)	PHQ (frequency)	PHQ (severity)
Post-secondary	−1.02 (Error: 0.71; 95% CI: −2.38 to 0.41)	0.21 (Error: 0.17; 95% CI: −0.12 to 0.54)	−1.17 (Error: 0.70; 95% CI: −2.50 to 0.22)	0.17 (Error: 0.17; 95% CI: −0.16 to 0.49)	0.60 (Error: 0.51; 95% CI: −0.36 to 1.63)	0.05 (Error: 0.20; 95% CI: −0.36 to 0.44)
Occupation [reference category: homemaker]						
Agriculture	0.06 (Error: 1.17; 95% CI: −2.13 to 2.49)	−0.05 (Error: 0.33; 95% CI: −0.72 to 0.59)	0.20 (Error: 1.18; 95% CI: −1.96 to 2.73)	−0.09 (Error: 0.31; 95% CI: −0.70 to 0.55)	−0.44 (Error: 0.71; 95% CI: −1.84 to 0.93)	−0.30 (Error: 0.29; 95% CI: −0.90 to 0.27)
Business	0.71 (Error: 1.30; 95% CI: −1.79 to 3.30)	0.02 (Error: 0.33; 95% CI: −0.62 to 0.65)	0.67 (Error: 1.30; 95% CI: −1.71 to 3.47)	0.00 (Error: 0.31; 95% CI: −0.59 to 0.63)	0.26 (Error: 0.75; 95% CI: −1.22 to 1.77)	−0.17 (Error: 0.31; 95% CI: −0.80 to 0.40)
Casual & skilled labour	0.37 (Error: 1.19; 95% CI: −1.90 to 2.83)	−0.24 (Error: 0.33; 95% CI: −0.88 to 0.40)	0.33 (Error: 1.23; 95% CI: −1.93 to 2.94)	−0.26 (Error: 0.31; 95% CI: −0.85 to 0.37)	−0.09 (Error: 0.74; 95% CI: −1.52 to 1.34)	−0.07 (Error: 0.29; 95% CI: −0.67 to 0.47)
Service job	0.83 (Error: 1.20; 95% CI: −1.37 to 3.30)	0.04 (Error: 0.32; 95% CI: −0.57 to 0.66)	0.80 (Error: 1.22; 95% CI: −1.40 to 3.38)	0.01 (Error: 0.30; 95% CI: −0.56 to 0.62)	−0.92 (Error: 0.75; 95% CI: −2.34 to 0.57)	−0.18 (Error: 0.30; 95% CI: −0.76 to 0.38)
Student	2.33 (Error: 1.31; 95% CI: −0.04 to 5.07)	0.10 (Error: 0.34; 95% CI: −0.56 to 0.77)	2.19 (Error: 1.35; 95% CI: −0.22 to 4.96)	−0.03 (Error: 0.32; 95% CI: −0.67 to 0.61)	0.24 (Error: 0.79; 95% CI: −1.32 to 1.83)	0.23 (Error: 0.33; 95% CI: −0.41 to 0.85)
Unemployed	2.00 (Error: 1.60; 95% CI: −1.07 to 5.35)	−0.21 (Error: 0.38; 95% CI: −0.94 to 0.53)	1.92 (Error: 1.56; 95% CI: −0.99 to 5.08)	−0.20 (Error: 0.36; 95% CI: −0.88 to 0.51)	0.24 (Error: 0.86; 95% CI: −1.41 to 1.89)	0.15 (Error: 0.34; 95% CI: −0.54 to 0.81)
Chronic illness [reference category: no]						
Chronic illness [yes]	0.03 (Error: 0.42; 95% CI: −0.76 to 0.87)	0.01 (Error: 0.09; 95% CI: −0.16 to 0.18)	0.15 (Error: 0.44; 95% CI: −0.68 to 1.02)	−0.00 (Error: 0.09; 95% CI: −0.18 to 0.17)	−0.24 (Error: 0.25; 95% CI: −0.73 to 0.24)	0.16 (Error: 0.08; 95% CI: 0.00 to 0.32)
Arsenicosis symptoms [reference category: no]						
Arsenicosis symptoms [yes]	−1.01 (Error: 1.85; 95% CI: −5.02 to 2.19)	**0.41**** (Error: 0.12; 95% CI: 0.16 to 0.64)	−1.12 (Error: 1.74; 95% CI: −4.81 to 1.91)	**0.39**** (Error: 0.11; 95% CI: 0.17 to 0.62)	−1.46 (Error: 0.73; 95% CI: −3.02 to −0.19)	0.25 (Error: 0.12; 95% CI: 0.02 to 0.47)
Risk perception						
Belief in presence of arsenic [reference category: no]						
Yes	−1.85 (Error: 0.81; 95% CI: −3.46 to −0.31)	**0.46**** (Error: 0.15; 95% CI: 0.15 to 0.75)	−1.43 (Error: 0.76; 95% CI: −2.95 to 0.02)	**0.42*** (Error: 0.15; 95% CI: 0.14 to 0.71)	−0.12 (Error: 0.40; 95% CI: −0.91 to 0.65)	0.05 (Error: 0.15; 95% CI: −0.24 to 0.33)
Do not know	−0.87 (Error: 0.56; 95% CI: −2.05 to 0.15)	0.25 (Error: 0.15; 95% CI: −0.03 to 0.54)	−0.83 (Error: 0.54; 95% CI: −1.92 to 0.20)	0.14 (Error: 0.14; 95% CI: −0.13 to 0.42)	0.48 (Error: 0.28; 95% CI: −0.07 to 1.03)	0.05 (Error: 0.12; 95% CI: −0.19 to 0.29)

[a] This table shows the adjusted regression model with all covariates in a single model; Supplementary Table S9 shows the unadjusted models with each covariate modelled separately.

longer significant. Also, in this model Mn shows a negative association with the severity of PHQ scores, and Cl^{-} shows a positive association with the severity of PSD and PSDQ scores, indicating that while other water quality parameters are held constant, As is still associated with higher frequency and higher severity of PSD and PSDQ and higher frequency for PHQ; while Mn is associated with lower severity of PHQ; and Cl^{-} is associated with higher severity of PSD and PSDQ.

The adjusted model (Table 4) reconfirms what the unadjusted models show, that is, the negative relationships between water-As and frequency of PSD, PSDQ and PHQ remain significant (i.e. the higher the water-As, the lower the chances of scoring zero on all three scales), and the severity of distress becomes non-significant while other factors – such as belief in the presence of As and having arsenicosis symptoms – have a significant positive relationship with the severity of PSD and PSDQ. Water-Cl^{-} remains positively associated with the severity of PSD and PSDQ, while water-Mn remains negatively associated with the severity of PHQ scores, as is the case with the unadjusted models. This model also shows that awareness of having an unsafe tubewell (one that previously tested positive for As) is associated with higher frequency of PSD and PSDQ scores, and having a tubewell of unknown status was associated with higher severity of PHQ scores (similar to the unadjusted models for tubewell arsenic status), however, having a tubewell of unknown status is associated with lower severity of PSD scores in this model.

As with nail-As, some of the variables were tested again to see if they had any interactive effects with water-As on distress scores (Supplementary Table S10). None of the variables showed a statistically significant interaction effect, except for number of water sources which shows a positive interactive effect with water-As on scoring zero for PSD and PSDQ, i.e. the higher the number of sources the lower the frequency of distress.

4. Discussion

An overarching goal of this study was to provide empirical evidence to help further the narrative around a broader view of health and wellbeing with regard to the impacts of water quality. The findings of this study highlight how experiences of water insecurity can become embodied – or be incorporated into the biology – of those exposed (Brewis et al., 2020; Krieger, 2005). This can take the form of injuries and chronic stress, for example, and can also be expressed via biomarkers such as cortisol and blood pressure levels (Brewis et al., 2019; Rosinger et al., 2021; Rosinger and Young, 2020). This study demonstrates this concept of embodiment using two ‘unseen’ outcomes: subclinical disease and psychosocial distress. Subclinical arsenic in the body represents an objective outcome – a literal embodiment of the contaminant – while psychosocial distress represents a way in which water quality can become embedded under the skin in a way that is intangible as well as subjective. Both of these outcomes serve to demonstrate how the impacts of water quality go far beyond physiological illnesses and their symptoms.

The descriptive data on previous knowledge of arsenic contamination of water sources show some discrepancies in knowledge and actual presence of arsenic, indicating the need for accurate testing and risk communication. The prevalence of nail-As above the 1 μg/g cut-off indicates that a lot more people are exposed to the contaminant and at risk of developing adverse health outcomes such as cancers (Freeman et al., 2004; Orloff et al., 2009; Rehman et al., 2020), than would be indicated by the small number of respondents with visible skin lesions. This evidence, along with the strong correlation between water-As and nail-As, supports nail-As as a useful biomarker of chronic exposure (Adair et al., 2006; Orloff et al., 2009; Slotnick et al., 2007), and that monitoring subclinical disease can serve as a direct indicator of exposure as well as the efficacy of safe water interventions.

Most microbial contaminants have very short subclinical periods, often days (Gerba, 2009), compared to chemical contaminants such as arsenic that can take years to manifest (WHO, 2005). This essentially translates to how visible the contaminant is, which can influence how much attention it receives in the policy sphere (Khan and Charles, 2022) – with chemical contaminants often losing out. For contaminants that have been linked to various adverse health effects such as arsenic and lead (WHO, 2022a, 2022b), measuring subclinical disease via biomarkers can be an effective way to demonstrate the number of people exposed and at risk from the contaminant. This was done successfully in Flint, Michigan, where measuring blood lead levels in children (Hanna-Attisha et al., 2016) proved a turning point in the lead contamination crisis (Masten et al., 2016).

It is unclear why water-Fe shows correlation with nail-As. This could potentially be due to the fact that Fe intake can affect As metabolism (increasing and decreasing the excreted amount of certain As species) (Steinmaus et al., 2005), but further analysis is beyond the scope of this study. The unadjusted model indicates that being male and belonging to the poor wealth category are associated with higher nail-As levels (while both are just above the threshold of significance in the adjusted model), while the other sociodemographic factors also showed no significant association. Among previous literature, Slotnick et al. (2007) found neither age nor gender to have a modifying effect, while Kile et al. (2005) found age to have a significant modifying effect on the water arsenic to nail arsenic relationship, and Yu et al. (2014) showed that being female and having higher income was associated with lower nail-As. Further large-scale monitoring of biomarkers such as nail-As could help pinpoint specific sociodemographic groups that may be in need of greater attention.

In terms of components of psychosocial distress, the findings of this study are in alignment with the literature. Themes of worry, fear, and suffering are common in the literature around water security and psychosocial distress and emotional geographies (Bulled, 2016; Kangmennaang et al., 2020; Sultana, 2011; Thomas and Godfrey, 2018; Wutich and Ragsdale, 2008). Uncertainty was a prevalent theme reported in a review of the literature around water and mental health (Wutich et al., 2020). Lack of choice is a theme which is less prevalent in the literature – however, there are several studies that explore the flipside, i.e. what influences switching water sources (George et al., 2017; Madajewicz et al., 2007; Mosler et al., 2010). Ahmad et al. (2007) found that 29% of respondents reported drinking from arsenic-contaminated sources, and Hanchett et al. (2014) observed many respondents who had switched back to drinking contaminated water; thus there is a need for further in-depth exploration into the barriers faced by those who feel a lack of options.

The presence of psychosocial distress (i.e. the frequency, or zero versus nonzero scores) in relation to water-As indicates a further form of embodiment of this contamination crisis. It is in alignment with previous studies which have shown association between the presence of As in water and mental ill health (Chowdhury et al., 2016; Fujino et al., 2004). And the perceived risk being a predictor for the severity of psychosocial distress also aligns well with studies that show correlation between water security and psychosocial distress, where perceived water quality is often included as a component of water security (Achore and Bisung, 2022; Kangmennaang et al., 2020; Libey et al., 2022). Water-Cl^- showing a positive association with severity of distress is also reflected in the literature on the importance of organoleptic properties such as taste being an important factor in perceived water quality risks (Doria et al., 2009; Rosinger et al., 2021; Rosinger and Young, 2020). It is unclear why water-Mn shows a negative association with the PHQ scale specifically – the fact that Mn is associated with neurotoxicity and lower cognitive scores in children (Wasserman et al., 2006, 2011) could potentially be a mediating factor.

Sociodemographic factors, including gender, do not show any modifying effect on the relationship between water quality and distress. Much of the water-related psychosocial distress literature involves female-only study samples – including 9 of 15 studies identified by Bisung and Elliott (2017), as well as the studies by Bulled (2016) and Brewis et al. (2021). A study from Ghana by Kangmennaang et al. (2020) specifically sampled male and female participants to match census percentages, but they did not find gender to be a significant predictor of distress either. Since PSD is an emerging field of study, more research with gender-disaggregated data is needed to expand upon this area to understand it better.

These findings show that psychosocial wellbeing of people exposed to contaminated water may still be affected, even in the absence of physiological symptoms. It is an equally important outcome of water quality which needs further research and understanding. This study illustrates a way to quantify psychosocial distress using a culturally grounded tool, which has the potential to be used in other contexts and applied to other contaminants. Moreover, it adds to the growing literature on psychosocial distress in addition to illustrating it as a function of water quality specifically, rather than water insecurity more broadly as it currently stands. Furthermore, even though psychosocial distress is less prevalent than subclinical arsenic, the two invisible outcomes show analogous patterns of distribution across the low, medium and high arsenic regions – indicating that a shift in narrative is needed when it comes to arsenic mitigation, with greater attention needed towards recognising a broader spectrum of outcomes (including ones that may not be easily seen) – rather than focusing only on hydrogeological distributions of the contaminant or on visible symptoms.

4.1. Limitations and future research

There were several limitations to this study. Firstly, there are many biases inherent to quantitative research, especially with self-reported data. The household survey and psychosocial distress data could be prone to response bias and recall bias. Symptoms of arsenicosis were self-reported and/or observed by enumerators, who are not medical professionals. All associations discussed in this study are correlations – not causal relationships.

Furthermore, the PSD scale is a novel one being applied to a large-scale study for the first time. Its usefulness and transferability can only be determined with further use in different contexts. It should be noted, however, that the comparison of this novel scale with the standard PHQ-9 held up well – with most results being quite similar. The few cases where the PHQ scores were confounded and PSD scores were not (and vice versa) are likely due to the more general nature of the questions in the PHQ-9 scale.

For nail-As, a few collected samples could not be analysed due to insufficient quantity of nails, as mentioned previously. A further limitation is that the water quality conditions of the medium-As site were different to what was expected, i.e. it had lower average water-As than expected for the region. There is a jump in the primary data for water-As between 52.80 μg/L (the maximum in Tala) and 118.67 μg/L (the minimum in Hajiganj) in this study. This is due to the nature of groundwater As deposits in Bangladesh – even though there are large-scale regional patterns, there can be smaller-scale variability within a particular region (Yu et al., 2003). Additionally, other sources of As, such as in diets, were not assessed.

This study was not able to address seasonal variability of water quality and what means for different health outcomes. There are studies showing evidence that arsenic in groundwater can vary seasonally (Ayers et al., 2016; Bhattacharya et al., 2011), although seasonal changes in water source are likely to be more significant. With regard to nails, our aim was to test a biomarker of longer-term exposure (as opposed to measures of more recent exposure, such as urine). Further work is needed to understand the level of seasonal variation in nail-As. With regard to psychosocial distress, some drivers would be likely to change rapidly, such as climatic drivers in response to a cyclone or for regularly variable water quality parameters. For geogenic parameters where data is only made available irregularly, e.g. arsenic testing every few years, there would be limited seasonality expected.

5. Conclusion

This study demonstrates the relationships between a major water quality contaminant and two unseen health outcomes, specifically subclinical disease and psychosocial distress. Bringing visibility to these otherwise invisible outcomes can help further the narrative around water quality issues and how to address them. The arsenic crisis is invisible on many levels – the contaminant itself is imperceptible through the senses, it has not always received the policy attention it needed, and physiological health outcomes take years to develop. Knowledge production around further unseen aspects of the contaminant, as done in this study, can serve to make the crisis more visible. Furthermore, this study serves to further the scholarship on the phenomenon of embodiment of water-related impacts, that is, the incorporation of water insecurity within the human body. In this case, subclinical arsenic in the body and the experience of psychosocial distress demonstrate examples of how unsafe water can get under the skin.

The use of subclinical disease as an indicator of impact can be a useful way of leveraging policy change and opening windows of opportunity. The long latency period between exposure and displaying visible signs of disease is part of the reason arsenic loses out on being prioritised. Thus making this 'invisible' subclinical period visible can provide the evidence needed to drive change in the policymaking arena by conveying the actual wider reach of exposure and risk. Monitoring subclinical disease can also serve as an effective indicator for uptake of safe water interventions and thus help optimise resource allocation. Relevant service providers would not need to rely only on hydrogeological data to plan provisions of safe water sources. And the presence of subclinical disease among people who would otherwise be considered "covered" by arsenic mitigation interventions can provide evidence that areas previously intervened in need to be taken into further consideration and followed up.

Furthering our understanding of psychosocial distress in relation to water quality can help broaden the narrative on health and wellbeing. Psychosocial distress is still an emerging field within water security, and this is the first instance of studying the phenomenon in relation to water quality more specifically. It is a concept that is practically invisible in terms of mitigation measures (in that it is not really taken into consideration) and has only been gaining visibility in academic research recently. This study shows that among the contaminants tested in the study sites, arsenic is a major contributing factor associated with both the frequency of psychosocial distress as well as levels of severity when experiencing it. This example can be applied in other settings with different contaminants to further our understanding of water quality and psychosocial distress. Moreover, this study shows that while the measured physical presence of the contaminant can predict distress, the knowledge and perception of the contaminant are enough to create distress. The implication here for policy and practice is that monitoring, alongside effective and ethical communication of risks, is needed to assuage people's doubts and uncertainty. Believing in harms resulting from water quality issues, or on the other hand, not knowing if the water being consumed is harmful or not, are issues that need addressing as much as provision of technological solutions especially in the context of increasing complexity of emerging contaminants concern in the global water quality landscape.

Broadening our understanding of invisible issues such as subclinical disease and psychosocial distress as important aspects of wellbeing can help us change the traditional view of water quality as something that can simply be addressed via technological means, to a fuller understanding of its complexities. It can help tell stories beyond just the clinical outcomes, which tend to get more focus at the policy level, and help tailor mitigation measures appropriate to the needs of those exposed.

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CRediT authorship contribution statement

Nameerah Khan: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Sonia Ferdous Hoque:** Writing – review & editing, Supervision. **Zahid Hayat Mahmud:** Writing – review & editing, Investigation. **Mohammad Rafiqul Islam:** Investigation. **Mohammad Atique Ul Alam:** Investigation. **Md Shafiqul Islam:** Investigation. **Katrina Jane Charles:** Writing – review & editing, Supervision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmmh.2024.100344.

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