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Determinants of the use of alternatives to arsenic-contaminated shallow groundwater: an exploratory study in rural West Bengal, India

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ABSTRACT

Shallow groundwater containing toxic concentrations of arsenic is the primary source of drinking water for millions of households in rural West Bengal, India. Often, this water also contains unpleasant levels of iron and non-negligible fecal contamination. Alternatives to shallow groundwater are increasingly available, including government-built deep tubewells, water purchased from independent providers, municipal piped water, and household filters. We conducted a survey of 501 households in Murshidabad district in 2014 to explore what influenced the use of available alternatives. Socioeconomic status and the perceived likelihood of gastrointestinal (GI) illness (which was associated with dissatisfaction with iron in groundwater) were the primary determinants of the use of alternatives. Arsenic knowledge was limited. The choice amongst alternatives was influenced by economic, social, and aesthetic factors, but not by health risk perceptions. The use of purchased water was rarely exclusive and was strongly associated with socioeconomic status, suggesting that this form of market-based water provision does not ensure universal access. Demand for purchased water appeared to decrease significantly shortly after free piped water became available at public taps. Our results suggest that arsenic mitigation interventions that also address co-occurring water problems (iron, GI illness) could be more effective than a focus on arsenic alone.

Key words | arsenic-contaminated groundwater, behavioral determinants, Bengal Basin, co-occurring contaminants, household behavior change, independent water providers

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INTRODUCTION

In rural West Bengal, India, groundwater tubewells supply drinking water to 80% of 13.8 million households (Census of India 2011). Tubewell coverage is dense and yields are adequate, but the quality of shallow groundwater (typically 15–60 m deep) is poor. Toxic levels of naturally-occurring arsenic put an estimated 9.5 million people at risk of skin lesions, impaired cognitive functions, cardiovascular and lung diseases, cancers, and premature death (Chakraborti *et al.* 2009; Ravenscroft *et al.* 2009). In addition, high levels of iron alter the color and taste of water (Das 2011), and may be associated with gastrointestinal (GI) disorders (Shirk *et al.* 2006). Finally, high rates of open defecation (51%) (Census of India 2011) and the close proximity of latrines to tubewells, which are not always adequately sealed, lead to fecal contamination of shallow groundwater (Knappett *et al.* 2012), potentially causing diarrheal illnesses.

Alternatives to untreated shallow groundwater in the region can be sorted into three categories: source switching

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(e.g. publicly provided deep tubewells and piped water), household water treatment (with local filters), and purchased water from small-scale independent providers (SSIPs, predominantly informal). Deep tubewells have lower levels of iron and microbial contamination than shallow tubewells, and can also be arsenic-safe if sufficiently deep (typically >150 m) (Ravenscroft *et al.* 2009). Household filters are generally made of sand or ceramic and remove iron as well as some fecal contamination. When they have an additional iron or activated alumina component, filters can also remove (some) arsenic (Ravenscroft *et al.* 2009). Municipal piped water (treated) is available in some areas and supplied for free at public taps. Finally, 20-litre containers of treated water can be purchased from local water providers, usually informal and unregulated, who operate small treatment plants. These currently available alternatives to shallow groundwater are of unknown water quality, but all have the potential, if adequately implemented and regulated, to mitigate arsenic exposure.

Identifying what drives households to seek and use alternatives to contaminated groundwater is crucial to designing effective arsenic mitigation strategies. Many interventions in the region have focused on increasing arsenic awareness and disseminating information about arsenic levels in wells (Johnston & Sarker 2007; Madajewicz *et al.* 2007; Lucas *et al.* 2011). A growing body of evidence suggests, however, that perceptions and psychological factors are at least as important in changing water-related practices as actual water quality or knowledge about contaminants (Tobias & Berg 2011; Huber & Mosler 2013; Orgill *et al.* 2013; Amrose *et al.* 2015; Inauen & Mosler 2015). For example, studies in rural Bangladesh have found that social norms, self-efficacy, taste, and convenience influence the use of arsenic-safe alternatives (Mosler *et al.* 2010; Inauen *et al.* 2013).

With very few exceptions (e.g. the study by Tobias & Berg in Vietnam (2011)), studies on the uptake of arsenic-safe alternatives have not assessed the role played by co-occurring water problems, such as iron and GI illness, on household decisions to change their water source. A better understanding of households' drivers for selecting water sources when several contaminants co-occur can help inform arsenic-mitigation strategies and contribute to the literature on the respective roles of information and perceptions in shaping water practices. Our particular focus is on perceptions of quality, therefore 'alternatives' include all available water sources *perceived* by households to be of better quality than shallow tubewells.

Our study also investigates the potential for drinking water provision through SSIPs, a canonical case of water as a business. SSIPs are prevalent worldwide in areas where formal public water provision is insufficient (Kariuki & Schwartz 2005). Their critical role in filling a service gap for the poor and their ability to tailor services to low-income customers has been recognized (Kjellén & McGranahan 2006; Opryszko *et al.* 2009). In addition, they are usually not subsidized (Solo 1999), and as cost recovery has become a priority in water supply (e.g. World Bank 2004), SSIPs have gained attention. SSIPs are increasingly active in rural West Bengal: in Murshidabad district alone, there are approximately 700 'mini-plants' – predominantly informal – treating an estimated 1,200,000 litres of water per day (expert interview). However, little is documented about the number, type, and water consumption practices of households served by SSIPs in rural West Bengal. Such knowledge would help assess the extent to which SSIPs, when regulated and providing safe water, could be part of the solution to the arsenic crisis.

Two questions motivated this study: (1) What alternatives to shallow groundwater are currently used in rural West Bengal, and to what extent? (2) What factors determine the use of these alternatives overall, and of each alternative in particular? Of the available alternatives, we explored the demand for, and use of, purchased water in greater detail. If, in the future, the sale of safe water through regulated SSIPs becomes a significant mitigation strategy, it would be useful to understand the potential and limits of this market-driven approach.

To answer these questions, we conducted a systematic survey of 501 households in the severely arsenic-affected and relatively low-income district of Murshidabad, in the fall of 2014. We documented the water sources used by households for drinking in two distinct areas, with and without access to piped water ($n = 409$ and 92, respectively), and used multivariate regressions to investigate the determinants of the use of different alternatives. We note that this was an exploratory study, meant to generate rather than to test hypotheses. It shows the complexity of household water

decisions in rural West Bengal where arsenic co-occurs with other contaminants, and analyzes the competition amongst different alternatives to shallow tubewell water. Our results can be useful for the design of arsenic mitigation interventions in the Bengal Basin, and possibly other similar regions.

METHODS

Selection of field site

Murshidabad district has a population of 7.1 million, predominantly Muslim (66%) and rural (80%) (Census of India 2011). It is one of the poorest and most severely arsenic-affected districts in the state (Chakraborti *et al.* 2009), where arsenic mitigation efforts of recent decades have largely failed (Das *et al.* 2016).

We selected our study areas based on three criteria: (1) the extent of arsenic contamination, defined as the fraction of wells tested by the West Bengal Public Health Engineering Department (WBPHED) exceeding 50 μg/L of arsenic (WBPHED 2006) (the World Health Organization (WHO) maximum contaminant limit (MCL) is 10 μg/L (WHO 2011)), (2) the population size, and (3) the availability of alternatives to shallow groundwater. These criteria led to two distinct areas within Berhampore block, with 2,945 and 1,370 households, respectively. Both are classified as 'rural' by the Census of India although they are close to Berhampore city (population of 195,000 in 2011) (section 1, Supplementary Information (SI), available with the online version of this paper). The demographic and socioeconomic characteristics of Areas 1 and 2 (SI, Table S1) indicate that they are broadly representative of rural West Bengal.

Tubewells are the main source of water for over 99% of households in both areas. Measurements conducted by the National Rural Drinking Water Program (NRDWP) indicate high levels of arsenic for Area 1 (20 to 210 μg/L, $n = 20$) and Area 2 (10 to 220 μg/L, $n = 9$) (NRDWP 2014). Our own measurements in Area 1 showed even higher levels (30–300 μg/L; section 2, SI). Iron concentrations in tubewell water were also high, as we regularly observed from water discoloration, and as confirmed by NRDWP measurements of 0.4–5.0 mg/L (NRDWP 2014) (the WHO MCL is 0.3 mg/L). In addition, high rates of open defecation (41% and 60% respectively, Table S1) increased the risk of fecal contamination of groundwater.

Area 1 had three alternatives to shallow groundwater: government-provided deep tubewells, purchased water, and household filters. Purchased water was mainly sourced from a 'mini-plant' operated by an informal entrepreneur (SI, Figure S1). Water packaged in 20-litre plastic containers was delivered to households for INR 20–30 (INR 61 = USD 1 in 2014). Filters varied widely in type and price (INR 100–14,000), from self-made sand-based filters to off-the-shelf ceramic or activated-alumina filters (SI, Figure S2). Area 2 also offered three alternatives to shallow groundwater: filters, purchased water, and piped water. Piped water had become available 1–18 months prior to our survey and was supplied for free at seven public taps reportedly built by community members (~6 hours/day).

Data collection

Because this study was exploratory, our sample size, 501, was determined by logistical constraints rather than by power calculations. The proportion of the study population allocated to each area was determined by the diversity in water practices that we observed: we surveyed only 92 households in Area 2 where almost all households used the same drinking water source, but 409 households in Area 1 where water consumption practices were more diverse. Socioeconomic and demographic characteristics of surveyed households are presented in Table 1 and compared to Census data in Table S1 and section 3 of the SI.

In each area, we systematically sampled every fourth household, starting from the beginning of each street. If household members were unavailable or unwilling to be interviewed, the next house was selected. We sought gender balance in order to capture gender specificity in responses, if any; 52.7% of respondents were female.

Our survey was administered by four local enumerators trained by our research team. We collected detailed information on all sources of drinking water, their frequency of use, and the household members using them. We also collected data on a number of demographic, socioeconomic, behavioral, and risk perception factors. Questions testing factual knowledge about arsenic were asked at the end to minimize respondent bias. Data were collected on Android

Table 1 | Demographic and socioeconomic characteristics of surveyed households in Areas 1 and 2

	Study area 1 ($n = 409$)	Study area 2 ($n = 92$)
Respondents		
Gender	51.3% F, 48.7% M	58.7% F; 41.3% M
Age	41.6 (22.3–65.0)	38.6 (20.6–57.5)
Years of schooling	4.5 (0–12)	4.0 (0–13)
> 0 years of schooling ($\approx$ literacy rate)	70.2%	65.2%
Household concerns (% times listed in top three)		
Poverty	53.5	60.9
Health, diseases	39.6	28.3
Water	38.9	17.4
Food	32.3	51.1
Education, school	27.6	34.8
Unemployment	18.8	23.9
Households		
Religion	100% Muslim	44.6% Muslim; 55.4% Hindu
Size	4.1 (2–7)	4.3 (2–6)
Number of children	1.5 (0–4)	1.5 (0–3)
Number of rooms	2.8 (1–5)	2.9 (1–5)
Land ownership	59.2%	20.7%
Metered electricity connection	82.9%	80.4%
Member abroad	9.0%	1.1%
Member away in country	9.3%	14.0%
Type of income source	54.5% agriculture 42.1% daily labor 24.7% business 17.6% remittances	16.3% agriculture 66.3% daily labor 20.7% business 15.1% remittances
Monthly expenditures	Phone: INR 205 (0–600) Soap, cosmetics: INR 259 (40–800) Cigarettes: INR 157 (0–600)	Phone: INR 140 (0–490) Soap, cosmetics: INR 157 (40–400) Cigarettes: INR 156 (0–434)

Note: INR 61 = USD 1 in 2014. When applicable, averages and 90% confidence intervals (CI, 5th and 95th percentiles) are reported.

tablets (Datawind UbiSlate 3G7) using Open Data Kit Collect (version 1.4.4). Each household interview took 45–60 min. The lead author (with working knowledge of Bangla) accompanied enumerators in the field every day. At the end of each sampling day, the team checked the new datasets for quality and completeness.

Outcome variable and conceptual framework for analyzing household choices

Our binary outcome was the regular use, for drinking, of alternatives to untreated shallow groundwater. An 'alternative' was any water source that (1) was not a private tubewell (the default source) and (2) was *perceived* by (at least some) households to be of better quality than private tubewells. Alternatives included government tubewells, household filters, purchased water, and municipal piped water. Government tubewells were not counted as alternatives for the 45 households that did not have access to a private tubewell. We did not test the water quality of these available alternatives. However, our observations of the technologies used in the mini-plant and in the available filters suggested that most alternatives were not optimized for arsenic removal.

Surveyed households displayed five levels of adoption in the use of alternatives for drinking: (1) no use; (2) occasional use (for celebrations, visitors, or when a household member was sick); (3) regular use by only some members (while others used private tubewells); (4) regular use by all members, but concurrent with private tubewells; and (5) exclusive use. In our statistical analyses, we aggregated levels of adoption 3, 4, and 5 (all corresponding to regular use) and termed this 'use', while levels 1 and 2 were aggregated and defined as 'no use'.

Our conceptual framework for analyzing household choices of drinking water source is presented in Figure 1. Drawing from the literature on safe water practices, this framework recognizes that behaviors are influenced by structural factors (e.g. household composition and socioeconomic status), social factors (e.g. behavior of peers, advice from influential individuals or groups), risk perception factors (e.g. knowledge about a contaminant, perceived likelihood or severity of a health problem), psychological factors (e.g. aspirations or perceived agency), and attitudinal factors (e.g. perceived taste, safety, and convenience of an alternative) (Kremer *et al.* 2008; Rosa & Clasen 2010; Huber *et al.* 2011; Mosler 2012; Huber & Mosler 2013; Etmannski & Darton 2014; Aziz *et al.* 2015). For this hypothesis-generating study, drawing on all five categories, we defined 14 potentially explanatory ('independent') variables relevant to our survey areas (Figure 1).

The socioeconomic index included asset ownership and two non-subsistence expenditures (personal care products and phone recharge), with weights assigned using principal component analysis (PCA) (following Filmer & Pritchett 2001). External and doctor's advice quantified whether a household received recommendations about drinking safe water from a school, a non-governmental organization, a women's group, political and religious leaders, relatives and friends, or medical staff. The peer behavior variable, designed to reflect norms, assessed whether the household knew no/few/many people purchasing water, and whether some of these were friends or relatives. We assessed proxies for risk perception for the three groundwater problems: arsenic, iron, and GI illness. For arsenic, given the low level of awareness in the study population (see Results), we could only evaluate factual knowledge (about visibility, health effects, and treatment methods); we gave each household a score of −4 to +4 based on how many of four questions they correctly answered. Iron, which is visible at high concentrations, was often used by respondents as an indication of 'bad' water and blamed for 'gastric' problems; therefore, we included a variable for expressed dissatisfaction with iron. For GI illness, we assessed perceived likelihood and perceived severity; we dropped the latter for data quality reasons (SI, Table S2). We used perceived agency as a proxy for aspirations; following Bernard *et al.* (2011) we

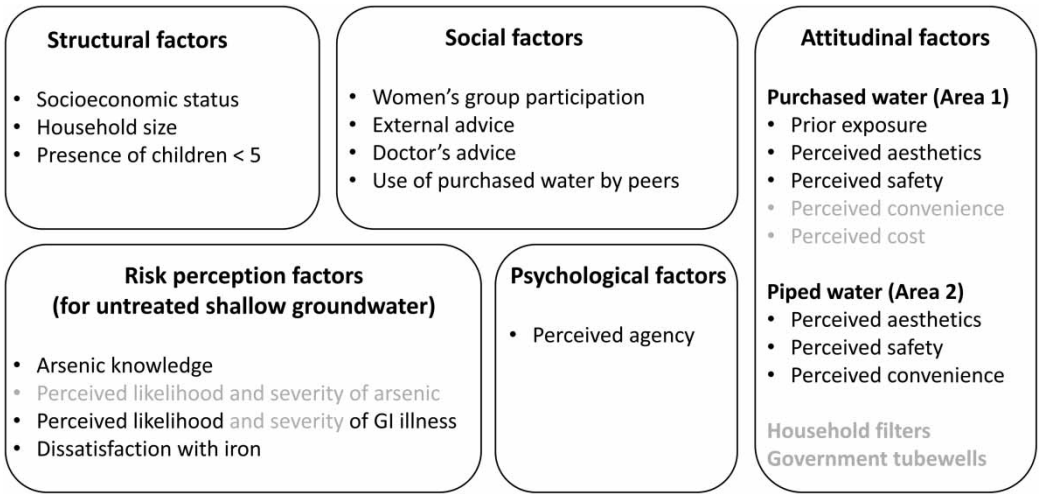

Figure 1 | Conceptual framework and list of variables used in our investigation of the determinants of household drinking water practices. The variables indicated in grey were excluded from our quantitative analyses because of poor data quality or difficulties in measuring them (details are presented in the SI, Table S2, available with the online version of this paper).

defined this as the perceived predominance of personal effort over chance or fate to succeed in life. Prior exposure to purchased water was approximated as prior or ongoing residence of one household member in an urban area (where bottled water is common). Perceived aesthetics of purchased and piped water combined evaluations of their taste, color, and smell; perceived safety of an alternative was a proxy for trust (in that alternative); and perceived convenience reflected the time and effort required to collect (or treat) water. We document the detailed rationales and derivations for each variable in the SI, section 4. After piloting the survey questions in our study communities, we chose scoring systems (binary or higher resolution) based on the gradations that made intuitive sense to, or could be easily understood by, respondents. Details of the variables that we excluded from our final list on account of poor data quality or difficulty in measuring them are presented in the SI, Table S2. All variables were normalized to avoid overweighting variables with high resolution (e.g. socioeconomic status) compared to binary variables (e.g. participation in a women's group).

Statistical analysis

We first used PCA to examine correlations among the independent variables listed in the framework in Figure 1. We then investigated correlations between the independent and outcome variables using both univariate and multivariate logistic regressions. In a logistic model, the probability of a binary outcome p for household i is defined by the following equation:

$$ln\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \sum_{j=1}^{K} \beta_j * \mathrm{EV_{j,i}}$$

where β_0 is the intercept, β_j are the regression coefficients, EV_j are the independent variables, and K is the number of independent variables included in the regression. In our models, the outcome was successively defined as the use of *any* alternative, and then of purchased water, filters, government-built tubewells, and piped water individually (versus the use of no alternative to shallow groundwater). Regressions for the use of any alternative and of purchased water were also conducted on two socioeconomic subsets (below and above median socioeconomic status). All statistical analyses were conducted using R (version 3.2.0).

Ethics

Our study protocol was approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley (protocol number 2014-06-6433; 08/13/2014 and 10/20/2014). All respondents provided informed verbal consent.

RESULTS

Description of households and water practices

Study households had >4 members on average (4.1 and 4.3 in Areas 1 and 2, respectively) with 1.5 children (Table 1). The primary income source was agriculture in Area 1 where 59% of households owned land, and daily labor in Area 2 where only 21% owned agricultural land (Table 1). Seventeen percent of households received remittances from members working in Indian cities or in the Gulf countries (Table 1). Over 80% of households had a metered electricity connection and over 90% had a private tubewell (Table 1). Water was cited as a primary concern by 35% of all study households, after poverty, health, and food (Table 1). Study households in Area 2 had lower socioeconomic indicators than in Area 1 (Table S1), consistent with lower land ownership and higher prevalence of insecure daily labor.

Figure 2(a) and 2(b) show the breakdown of household drinking water sources in the two study areas. In Area 1, purchased water, filters, and government tubewells were used by 25%, 19%, and 8% of households, respectively, while 54% used no alternative to private tubewells (Figure 2(a)). In Area 2, where piped water was available, it was used by 78% of households and the proportion of households using no alternative was only 17% (Figure 2(b)). Before the installation of piped water (18 months prior to our study), drinking water practices in Area 2 resembled that of Area 1. Specifically, the use of purchased water dropped substantially (from 24% to 7% of households) after public taps were installed (Figure 2(b)).

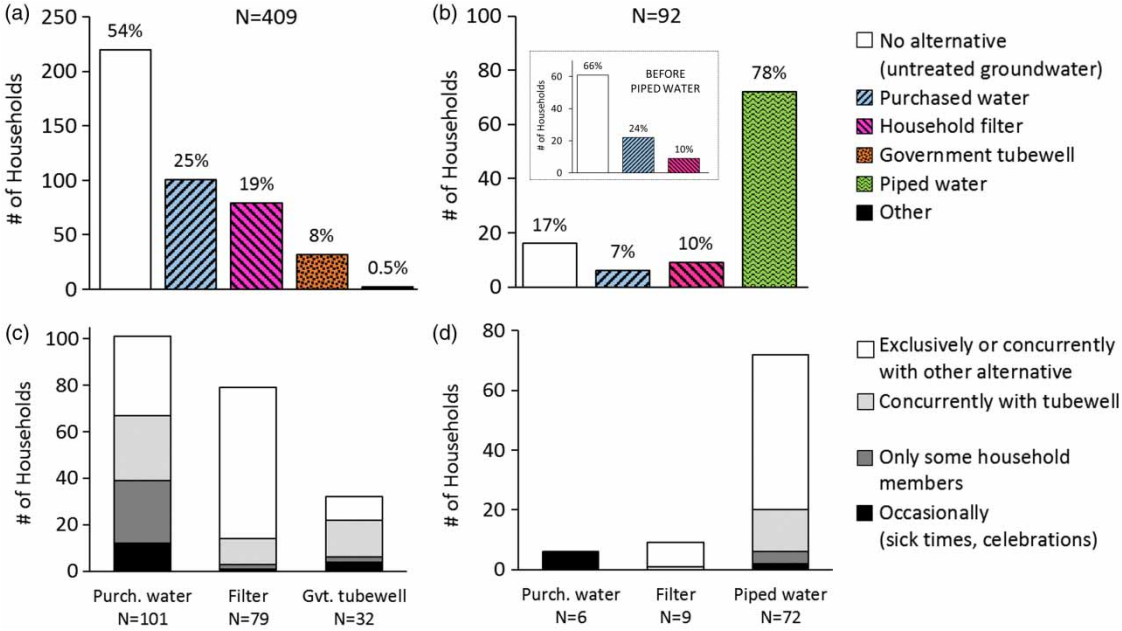

Figure 2 | Household water practices in Area 1 (panels a and c) and Area 2 (panels b and d). The top panels show the breakdown of household drinking water sources. Piped water was available only in Area 2. Some households used more than one source. The bottom panels show the level of use for each of the alternatives to private tubewells. In addition to drinking, purchased water, household filters, government tubewells, and piped water were used for cooking by 3%, 65%, 22%, and 61% of users, respectively. Alternatives were rarely used for cleaning, bathing, and washing (6% of users of alternatives overall).

Figure 2(c) and 2(d) describe the level of use of each alternative (for drinking). Among users of purchased water, only 34% reported using it exclusively or with another alternative. The rest used it only occasionally (for illnesses, celebrations, or guests: 12%), concurrently with untreated tubewell water (28%), or for only some household members (who had poor health or who did not dislike its taste: 27%) (Figure 2(c)). Exclusive use was similar for government-built tubewells (31%) but significantly higher for filters (83%) and piped water (72%) (Figure 2(c) and 2(d)). Filters and piped water were also frequently used for cooking (by 65% and 61% of users, respectively), in contrast with purchased water (3%) and government tubewells (22%).

Independent variables

Principal component analysis indicated a strong positive correlation between socioeconomic status and arsenic knowledge in both study areas, as well as between the perceived likelihood of GI illness and dissatisfaction with iron (SI, Figure S3). The two latter variables were also associated with higher perceived safety of alternatives – purchased water in Area 1, and piped water in Area 2, and with the use of purchased water by peers in Area 1 (Figure S3). The perceived likelihood of GI illness and dissatisfaction with iron were not strongly correlated with socioeconomic status (Figure S3).

The level of arsenic awareness was low: 69% of respondents in Area 1 and 84% in Area 2 had no knowledge of the contaminant. Only 21% in Area 1 and 5% in Area 2 correctly answered all four questions assessing (basic) knowledge about arsenic. Arsenic knowledge was significantly higher for male respondents (+0.5, $p < 0.001$). In contrast, the level of awareness and dissatisfaction with respect to more tangible water contaminants was high: 94% of households spontaneously complained about iron, and 58% about GI illness resulting from drinking tubewell water (only 11% complained about arsenic). We observed a widespread belief that iron causes GI illness (specifically, 'gas'), consistent with the correlations mentioned earlier (Figure S3). The perceived likelihood of GI illness and dissatisfaction with iron were not correlated with gender.

Determinants of the use of alternatives

Table 2 presents the results of multivariate logistic regressions for the use of alternatives to private tubewells in Area 1 (columns 1–7) and Area 2 (column 8). Only statistically significant associations are reported. For Area 1, similar regressions in two socioeconomic subsets, above and below the median socioeconomic index, are in Table S3 (SI).

In Area 1, the use of alternatives was primarily associated with socioeconomic status and with the perceived likelihood of GI illness, followed by dissatisfaction with iron (Table 2, column 1, and Table S3, columns 1–3). Specifically, socioeconomic status was a strong determinant for using paying alternatives (purchased water and filters) while the perceived likelihood of GI illness was strongly associated with all alternatives (Table 2, columns 2–4). For the use of purchased water, secondary drivers (with smaller effect sizes) were doctor's advice and peer behavior (Table 2, column 2), especially for households with lower socioeconomic status (Table S3, column 5). The use of filters was also associated with dissatisfaction with iron (Table 2, column 3), while the use of government tubewells was negatively correlated with household size, possibly reflecting the difficulty of carrying large volumes of water over long distances (Table 2, column 4).

Arsenic knowledge was not a determinant of the use of alternatives in multivariate regressions (Table 2 and

Table 2 | Multivariate logistic regression results for the regular use of alternatives to private tubewells in Area 1 (columns 1 through 7) and Area 2 (column 8)

Variable	1 Any alt. vs. none	2 KJ vs. none	3 Filter vs. none	4 GTW vs. none	5 KJ vs. Filter	6 KJ vs. GTW	7 Filter vs. GTW	8 Piped vs. none
Socioeconomic status	0.7***	0.7***	1.2***	0.1	–0.3°	0.8*	1.2**	1.0*
Household size	–0.1	0.0	0.0	–0.6*	0.1	1.1*	0.9*	0.2
Children < 5	0.1	0.2	0.0	–0.1	0.3	0.5	0.1	–0.4
Women's group participation	–0.1	0.1	–0.3°	–0.3	0.4*	0.6°	0.0	–0.2
External advice	0.0	0.2	–0.1	0.0	0.4°	–0.1	–0.2	0.4
Doctor's advice	0.2°	0.4**	0.1	0.4°	0.4*	–0.2	–0.3	0.2
Use of KJ by peers	0.2	0.4*	0.0	0.1	0.5*	0.1	0.2	NA
Arsenic knowledge	0.2	0.1	0.2	0.2	–0.4*	0.2	0.1	–0.6
Perceived likelihood of GI illness	0.6***	0.6***	0.5**	0.8***	0.3	–0.5	–0.7°	0.8°
Dissatisfaction with iron	0.3*	0.2	0.5*	0.0	–0.5	0.6	0.7	–0.5
Perceived agency	–0.2°	–0.2	–0.1	–0.1	–0.1	0.4	–0.2	–0.8*
Exposure to KJ	0.1	0.2	–0.1	–0.2	0.3	0.3	–0.1	NA
Perceived aesthetics of KJ	0.1	0.2	–0.1	–0.2	0.4*	0.5	0.1	NA
Perceived safety of KJ	0.1	0.3	0.2	–0.1	0.3	0.3	0.3	NA
Perceived aesthetics of piped	NA	NA	NA	NA	NA	NA	NA	1.0**
Perceived safety of piped	NA	NA	NA	NA	NA	NA	NA	0.1
Perceived convenience of piped	NA	NA	NA	NA	NA	NA	NA	0.8*
Intercept	–0.3**	–1.2***	–1.4***	–2.4***	0.4°	1.8***	1.2**	2.1***
Sample size (broken down by water source)	409 (178, 231)	320 (89, 231)	309 (78, 231)	259 (28, 231)	155 (89, 66)	113 (89, 24)	103 (78, 25)	89 (70, 19)
Goodness-of-fit (p-value)[a]	0.34	0.56	0.63	0.87	0.91	0.73	0.73	0.23

Note: The outcome was the use of different alternatives versus no alternative (columns 1–4 and 8) or versus another alternative (columns 5–7). NA (not applicable) indicates that a variable was not included in the multivariate regression.

KJ, purchased water (kena jol in Bangla); GTW, government tubewell; piped, piped water.

[a]Hosmer-Lemeshow goodness-of-fit. A p-value <0.05 indicates a poor fit.

Statistical significance is indicated as follows: °$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table S3). In Area 1, 36% of households with no arsenic knowledge used an alternative; for this subset, the associated drivers were socioeconomic status and the perceived likelihood of GI illness (data not shown). For the households with some arsenic knowledge, the perceived likelihood of GI illness was not associated with using alternatives (but socioeconomic status, peer behavior, and doctor's advice were; data not shown).

In Area 2, the use of piped water was associated with socioeconomic status, perceived aesthetics and perceived convenience (Table 2, column 8). Although the small sample size ($n = 89$) for this regression does not allow for strong conclusions, univariate regressions confirmed that the use of piped water was strongly associated with perceived aesthetics and convenience (SI, Table S4).

In Area 1, among those who used alternatives to shallow groundwater, we analyzed the factors favoring the choice of one alternative over another (Table 2, columns 5–7). The use of purchased water or filters over government-built tubewells was associated with socioeconomic status and household size. This result is understandable since government tubewells are free and require transporting water (whereas purchased water is delivered at home). The use of purchased water over filters was associated with a number of social factors: peer behavior, women's group participation, doctor's advice, and external advice; and with a higher preference for the taste and smell of purchased water (perceived aesthetics).

Use of purchased water

To investigate the use of purchased water in more detail, we analyzed the independent variables associated with the quantity purchased (Table 3) and with the level of use (SI, Figure S4) in Area 1. Socioeconomic status was the only significant determinant of the volume of water purchased per person (Table 3, column 1), suggesting that price (20–30 INR per 20 L, or 0.3–0.5 USD) is a barrier to more widespread use. Consistent with this finding, 20% of non-purchasers reported that they would start purchasing if the price was five times lower. We note that at INR 20 for 20 L, providing 2 L of water per person per day for the average household (four members) costs ~280 INR per month, which is higher than, but comparable to, monthly household expenditures for phone credit, soap/cosmetics, or cigarettes (Table 1). Qualitative comparisons between exclusive (level 5) and non-exclusive (levels 2–4) users suggested that, in addition to socioeconomic status, perceived aesthetics, peer behavior, exposure to purchased water, the perceived likelihood of GI illness, and dissatisfaction with iron may foster a more consistent use of purchased water (Figure S4).

Finally, we found that 12% of study households in Area 1 had purchased water in the past but had since stopped.

Table 3 | Multivariate regression results for (1) the volume of water purchased per person per day (linear regression, among all users of purchased water) and (2) the interruption of purchased water use (logistic regression, among current and past users of purchased water) in Area 1

Variable	1 Volume of purchased water (L) per person per day [a]	2 Interruption of purchased water use
Socioeconomic status	0.4**	–0.4
Household size	–0.2	–0.2
Children < 5	0.0	–0.1
Women's group participation	0.0	0.1
External advice	0.1	0.0
Doctor's advice	0.0	–0.8**
Use of KJ by peers	0.0	–0.4°
Arsenic knowledge	0.0	0.5*
Perceived likelihood of GI illness	0.1	–0.8**
Dissatisfaction with iron	0.0	0.1
Perceived agency	0.1	0.2
Exposure to KJ	0.1	0.0
Perceived aesthetics of KJ	0.2	–0.6*
Perceived safety of KJ	0.1	0.3
Filter ownership	NA	2.0***
Intercept	1.0***	–1.2***
Sample size	101	150 (101 current, 49 past users)
Goodness-of-fit (R^2 or p-value)[b]	0.22	0.81

Note: NA (not applicable) indicates that the variable was not included in the multivariate regression.

KJ, purchased water (kena jol in Bangla).

[a]Children <5 were counted as 0.5 person.

[b]For the linear regression, a R^2 close to 1 indicates a good fit. For the logistic regression, we used the Hosmer-Lemeshow goodness-of-fit. A p-value <0.05 indicates a poor fit.

Statistical significance is indicated as follows: °$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

This behavior was associated with ownership of a filter, lower perceived likelihood of GI illness, less advice from their doctor, and lower preference for the taste/smell of purchased water (perceived aesthetics) (Table 3, column 2).

DISCUSSION

Use of alternatives to shallow groundwater in rural West Bengal

The limited proportion of households using alternatives in our study areas (52.9% overall) was consistent with older results in arsenic-affected Bangladesh, where only 62.1% of 1,268 households were found to use alternatives to shallow tubewells (Inauen *et al.* 2013). We found that socioeconomic status predicted the use of most alternatives, both paying (filters, purchased water) and free (piped water), which indicates asymmetries in both the desire and ability to pay for safer water. Therefore, to encourage people to switch from arsenic-contaminated groundwater to safer options – where these exist – behavior change strategies that specifically target the poorest households may be needed.

Socioeconomic status aside, we found that the perceived likelihood of GI illness was the primary determinant for using alternatives to untreated groundwater (Area 1). By contrast, arsenic knowledge was not significantly associated with the use of alternatives when controlling for all other variables. Consistent with prior research in Vietnam (Tobias & Berg 2011), our study indicates that households reacted primarily to the most tangible groundwater problems: households with greater arsenic knowledge were not more likely to switch (everything else being equal), whereas households with a high dissatisfaction with iron and GI illness were more likely to switch (everything else being equal). However, we note that this finding may not be generalizable to communities with more widespread arsenic knowledge. Also consistent with the Vietnam study, arsenic awareness was not a prerequisite for switching water sources, with 33% of study households using alternatives despite having no knowledge about arsenic.

Our results indicate that once a household has decided to switch away from shallow groundwater, the choice amongst several alternatives is influenced by structural factors (socioeconomics and household size), social factors, and attitudinal factors (convenience and aesthetics) — but not primarily by heath risk perception factors. This result is consistent with studies of microbial contamination, which have shown that preferences for safe water options are strongly influenced by convenience, taste, and odor (i.e. attitudinal factors) (Albert *et al.* 2010; Roma *et al.* 2014; Burt *et al.* 2017). Our findings suggest that households may perceive all alternatives as protecting health equally, which is problematic for arsenic mitigation: where traditional filters or government tubewells are not designed to be arsenic-safe, they may nevertheless be chosen as an alternative to untreated shallow tubewell water. Therefore, raising awareness about arsenic-safe alternatives is crucial to ensure that households choose alternatives that protect their health.

Overall, our research adds to the body of literature suggesting that health knowledge is often not the primary driver for the adoption of health-protecting behaviors (Thurber *et al.* 2013; Roma *et al.* 2014). In arsenic-affected West Bengal, the use of alternatives to shallow tubewells appears to reflect a high demand for iron-free and 'gas'-free water, more than a demand for arsenic-free water. This finding has implications for the design of arsenic-mitigation interventions since it can help understand how households choose among different water sources and treatment processes. In particular, arsenic mitigation strategies that also raise awareness about, and address, co-occurring water problems, such as iron and GI illness, could be more effective than a focus on arsenic alone. This finding also has implications for targeting the content of arsenic awareness campaigns: microbial pathogens and iron do not always co-occur with arsenic (van Geen *et al.* (2011) and section 5 of the SI (available with the online version of this paper)), and treatment methods against iron and pathogens (e.g. sand filtration, boiling) are not effective against arsenic, so it remains crucial for education campaigns to emphasize both the dangers of arsenic ingestion and the differences between arsenic and other contaminants.

SSIPs as a 'solution' to arsenic-contaminated groundwater?

Our interview with the entrepreneur providing most of the purchased water in Area 1 revealed that he had been

operating for 4 years, and was producing approximately 150 20-litre containers per day at a cost of INR 5–6 each. Containers were sold for INR 8–10 to distributors in charge of delivery, who charged households INR 20–30. In arsenic-affected areas, water from SSIPs can be safer in the long run than groundwater treated at home, because adequate filter maintenance in households is challenging (Hoque *et al.* 2004; Johnston *et al.* 2010). In addition, commonly used household filters (that we observed) are rarely designed to remove arsenic. In contrast, SSIPs may find it easier (i.e. more financially feasible) to access effective treatment technologies for arsenic removal, monitoring equipment, and maintenance services, than individual households do. In addition, this model of water provision has a direct mechanism for cost-recovery, which is important for financial sustainability and scale-up. Therefore, SSIPs can, if regulated appropriately, produce and sell safe water consistently. However, our study illustrates three limitations of this full cost-recovery approach to drinking water access.

First, purchased water may not provide universal access, i.e. access to safe drinking water for all income strata, given the widely varying ability to pay. Our results show that both the use and the degree of use of purchased water are strongly associated with higher socioeconomic status, illustrating the tension between unregulated cost-recovery and universal access (Jaglin 2002; Bakker 2014). If SSIPs are proposed as a way to address groundwater contamination in West Bengal (Times of India 2014; News – India Today 2016) and if the full costs of water treatment and distribution cannot be substantially reduced with technology innovation, subsidies will be needed in the interest of public health.

Second, purchased water is used less regularly than other alternatives such as filtered water and piped water, and virtually never used for cooking (Figure 2); therefore, at least at current prices and levels of arsenic awareness, it does not eliminate the ingestion of arsenic. However, unlike diarrheal diseases, which can be triggered by a one-time consumption of microbiologically-contaminated water, arsenic health effects arise with cumulative exposure (Ahsan *et al.* 2006). Therefore, even irregular use of alternatives is preferable to no use at all.

Third, consistent with the demand for free piped water observed previously in rural Bengal (Hoque *et al.* 2004; Ahmad *et al.* 2006), our findings in Area 2 suggest that the installation of free public taps in a community can – at least initially – decrease demand for purchased water. Although purchased water may become competitive with piped water over time, we recommend that this short-term business vulnerability be taken into account if state-level arsenic mitigation strategies are to include both public and private water provision (News – India Today 2016; WBPHED 2016). More generally, the sustainability of community-scale water treatment plants strongly depends on the popularity of the other available alternatives (deWilde *et al.* 2008), and, in some cases, purchased water may only be an interim solution to groundwater contamination until piped water becomes widespread.

Limitations

Our study had several limitations. First, we did not test the water quality of the various sources because we wanted to understand household water practices through the lens of people's *perceptions*. However, the safety of different alternatives should be rigorously tested before scaling them up as arsenic mitigation strategies. Second, in Area 2, piped water had only been available for 18 months or less, and water practices prevalent at the time of the survey may change in the long term. Third, in a number of our regressions (columns 4 and 6–8 in Table 2), the sample size may have been small relative to the number of independent variables (13 or 14), which could have biased the effect sizes and significance levels. Fourth, our study was exploratory, as opposed to hypothesis-testing. Although this approach allowed us to gain valuable insights into the determinants of seeking alternatives to shallow groundwater and the limits of water provision through SSIPs in rural West Bengal, it cannot provide evidence for the effectiveness of specific interventions. Fifth, several variables either could not be thoroughly assessed or had to be excluded from our analysis for data quality reasons. Finally, the level of knowledge of arsenic and its characteristics was low in our study communities, and it is possible that, with more knowledge, perceptions and preferences would be different. In particular, our study areas may not be representative of villages with higher prevalence of *visible* arsenicosis symptoms (see Rahman 2005), where arsenic risk perception may be a more important driver for the

use of alternatives. We also note that we did not assess knowledge about the intensity of arsenic toxicity or about its cumulative nature.

CONCLUSIONS

In this exploratory study, we investigated household drinking water practices in arsenic-affected Murshidabad in West Bengal, India. We found that despite low arsenic awareness, a substantial fraction of households (52.9% overall) used alternatives to shallow groundwater, including purchased water from SSIPs, household filters, government-built deep tubewells, and piped water. We found that the perceived likelihood of GI illness (correlated with dissatisfaction with iron) was a major predictor of the use of alternatives, in contrast to arsenic knowledge (which was limited). Understanding the current perceptions and priorities of households is important to design effective mitigation strategies and effective arsenic awareness campaigns. For example, arsenic mitigation interventions that also raise awareness about, and address, co-occurring water problems could be more effective than a focus on arsenic alone. Finally, our results show that small-scale private water providers can be financially sustainable and therefore, if their water is arsenic-safe, can contribute to mitigating exposure to contaminated groundwater. However, we found that exclusive use of purchased water was rare and strongly influenced by socioeconomic status, with a large proportion of users concurrently drinking untreated tubewell water. Therefore, without targeted subsidies, this form of private sector participation is unlikely to provide universal access.

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