Arsenic in Bangladesh’s Drinking Water: Evaluating Factors That Have Hindered Two Decades of Mitigation Efforts, and the Opportunities to Address Them

by

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Dedication

To my grandparents, Leela Dhote, Narayan Dhote, Vasundhara Devi and Ramamurti Reddi

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Abstract

The discovery in the late 1990s that as many as 70 million people in Bangladesh were exposed to naturally occurring arsenic through their drinking water sources sparked widespread efforts to mitigate the risks. The intensity of these efforts declined after the mid-2000s and the limited monitoring done since has raised concerns about their long-term sustainability. The most recent Multiple Indicator Cluster Survey conducted by the Government of Bangladesh and UNICEF indicated that in 2012-2013 over 40 million people still drank water that tested above the World Health Organization (WHO) guideline for arsenic in drinking water, showing that it remains a major public health concern.

This dissertation aims to elucidate barriers to reducing arsenic exposure in Bangladesh, pilot strategies to address them, and generate specific recommendations for the broad range of water supply stakeholders. The research was performed by researchers at the University of Michigan and Asia Arsenic Network, a water focused NGO in Bangladesh. The researchers worked closely with a diverse range of stakeholders to define problems and design study approaches. Field data collection was done in Phulsara and Goga unions in the southwest of Bangladesh.

We investigated the state of arsenic mitigation efforts in the two study unions through an assessment of existing water supply infrastructure and surveys of rural households to understand their perceptions and behaviors regarding drinking water. The results indicate a need for better water supply planning, with mitigation strategies currently in place failing due to crumbling community water infrastructure and low levels of adoption of safe water practices. The effect of a low-cost (<USD 9/household) informational intervention on reducing arsenic exposure in arsenic affected rural households was evaluated through a randomized control trial study. The intervention consisted of sharing arsenic awareness messaging, an individual household water quality test result, and specific recommendations for alternate sources with improved water quality. The results show that the intervention led to a significant number of households changing water sources, thereby lowering arsenic exposure. This work highlights the benefit of continued well

testing and educational programming in Bangladesh, efforts that have declined sharply since 2006. While the majority of community operated water systems fail within three years of installation, our work with the user communities of two such systems, has identified initiatives that can improve their sustainability. We documented these cases in a short video, which is intended to inform and motivate other rural communities to better manage their water infrastructure. The research further included a critical assessment of eight commercially available arsenic field test kits. While arsenic test kits are widely used in Bangladesh, an up-to-date assessment of their accuracy was lacking in the scientific literature. The results of this study show that several test kits, including the one currently most commonly used in Bangladesh, can provide variable results and often significantly underestimate arsenic levels. Finally, specific recommendations based on the work performed in this dissertation are provided for a range of water supply stakeholders in Bangladesh including government agencies, donor organizations, non-governmental organizations, and field kit manufacturers.

The findings from this work are intended to draw attention to the continuing need for additional arsenic mitigation efforts and help the wide range of water supply stakeholders in Bangladesh make more informed decisions in their work.

Chapter 1: Introduction

1.1 Arsenic as a drinking water contaminant

Arsenic is a colorless, odorless and tasteless contaminant that is naturally present in groundwater sources[1]. Chronic exposure to low levels of arsenic can lead to various adverse health effects including unfavorable pregnancy outcomes and infant mortality[2], cardiovascular disease[3], and several types of cancer[4–6]. The World Health Organization (WHO) guideline for arsenic concentration in drinking water is currently 10 µg/L, having dropped progressively from 200 µg/L in 1958 as the scientific community gathered consensus on its deadly effects[7]. Some countries, including Bangladesh and India, have their national drinking water standard for arsenic currently at 50 µg/L.

Globally, arsenic is estimated to affect the drinking water sources of 100-150 million people[8,9]. The Bengal basin, encompassing Bangladesh and parts of India, Nepal, and Myanmar is the most severely affected geographical region due to the levels of natural arsenic contamination, high population densities, and a heavy reliance on groundwater wells. It is not uncommon to have arsenic concentrations above 150 µg/L in tube well water in this region[10]. An estimated 35-70 million people are at risk in Bangladesh alone[11–14].

1.2 Historical context for drinking water supply in Bangladesh

The issue of arsenic exposure through drinking water in the region surfaced toward the latter part of the twentieth century. In the late 1960s and early 1970s, the idea of promoting groundwater-based drinking water sources in rural Bangladesh gained traction as an alternative to combat the illness and mortality associated with water-borne pathogens present in surface waters[7,15]. After sustained media campaigns to promote tube well use, backed by the Bangladeshi government and international development agencies, it is estimated that by 1990 over 95% of rural Bangladesh had begun to drink water from tube wells[7]. Arsenic was first detected in Bangladesh tube wells in 1994 and subsequent country wide surveys by the Department of Public Health

Engineering (DPHE) and British Geological Survey (BGS) estimated that 46% of wells exceeded the WHO guideline value of 10 µg/L while 27% exceeded the Bangladesh national standard of 50 µg/L[16]. In 1997, the WHO declared the situation to be a "major public health issue" that needed to be dealt with on an "emergency basis"[15].

Over the next few years, significant resources were brought in from multilateral funding agencies and the government targeting arsenic mitigation activities. Between 2000 and 2004, over five million tube wells were tested through the Bangladesh Arsenic Mitigation and Water Supply Plan (BAMWSP). The largest intervention to reduce arsenic exposure has been to promote well switching[17] by running educational campaigns and marking tested wells as safe or unsafe. The second most common intervention was the introduction and promotion of alternate arsenic safe water options[18]. This umbrella term includes a range of alternative water sources, including deep tube wells (>150 m) that tap deeper uncontaminated aquifers, arsenic removing filters, and surface water treatment filters. Tube wells, the most common type of safe water option introduced, are much preferred as an alternate water source[19,20]. For example, people were willing to walk a long distance to avoid exposure if the source for arsenic-free water was a tube well. If the source for arsenic-free water was surface water, however, people were less likely to walk a long distance to take avoidance measures[21].

1.3 Current challenges

More than a decade after the BAMWSP was executed, and despite having faded from the media spotlight, this public health crisis associated with arsenic exposure through drinking water continues to be relevant. The convenience of private tube wells has led to a rapid growth in numbers, going from 2.5 million wells in 1990 to over 11 million wells in 2014[7,22] and this number continues to grow. A large fraction of these newer wells have likely not been tested for arsenic and the test results for the majority of those that were tested (in programs such as BAMSWP) are outdated and potentially inaccurate[10,23,24]. At the same time, a very small fraction (<6% as per the MICS survey[14]) of the country has access to piped water supply, which means that building the infrastructure to allow centralized drinking water treatment and distribution would be a massive undertaking. The most recent Bangladesh Bureau of Statistics and UNICEF Multiple Indicator Cluster Survey (MICS) indicated that 25.5% of households were drinking water from sources that tested above 10 μg/L, while 12.5% of households were drinking water from sources that tested above 50 μg/L of arsenic[14], indicating the extent of the unmet challenge.

Since the health effects of arsenic exposure are not unique, lay people may not believe they are connected to arsenic. Furthermore, arsenic induced-conditions may not manifest for decades[5,19,25], which adds to this confusion[7] and highlights the importance of education in mitigation efforts.

Community operated safe drinking water infrastructure is struggling to meet its purpose. Studies estimate that over 70% of community owned water points fail within three years of installation[26,27]. The utilization levels are even lower, meaning that several households who have access to these 'safe water sources' are choosing not to use them[19].

1.4 Research objectives and outline of dissertation

Despite considerable efforts over the past two decades to mitigate the arsenic crisis in Bangladesh, much work remains to achieve this goal. This dissertation research is part of an integrated assessment study on the sustainability of safe drinking water supply in Bangladesh. The integrated assessment approach uses stakeholder input to collectively define complex problems, incorporate diverse perspectives, and establish partnerships to identify options for making positive change[28]. This approach is important for the complex sustainability challenge of ensuring safe water in Bangladesh, a goal requiring integrated analysis of environmental, economic, and social dimensions.

This study that aims to characterize existing barriers to the long-term sustainability of safe water supply in Bangladesh and identify and pilot solutions that can address these barriers. The work was performed in close collaboration with Asia Arsenic Network, a water focused NGO, which has been working in Bangladesh since 1999. The field work for this dissertation was conducted in Phulsara and Goga unions in southwest Bangladesh. The dissertation is organized in six chapters.

Chapter 1 provides background to introduce the issue of safe drinking water supply in Bangladesh and presents my research goals. Chapter 2 provides an assessment of existing arsenic mitigation efforts in Bangladesh, attempting to understand why despite two decades of mitigation efforts it remains a critical public health concern. This study provided an understanding of the current status in our two study unions and helped frame the work presented in Chapters 3 and 4. Chapter 3 evaluates the effectiveness of a low-cost informational intervention, on reducing the arsenic exposure among affected rural households. This study was a randomized control trial conducted over 20 months and across 332 households in Phulsara union. Chapter 4 documents learnings from two case studies in community water infrastructure management. These two were part of five cases studied over 18 months with the intention of piloting user driven changes for improved management. Chapter 5 presents a critical analysis of eight commercially available arsenic field test kits by comparing results of tests using the various kits and a laboratory reference method on the same water sample. The study included two most used field kits in Bangladesh and six alternatives available on the international market. The study provides recommendations for manufacturers and water supply stakeholders to address the concerns identified and make informed decisions about their use of field kits for arsenic testing. Chapter 6 presents a summary of the key findings from this integrated assessment and resulting recommendations made to various water supply stakeholders in Bangladesh.

Chapter 2: Assessment of Why Arsenic Exposure in Rural Bangladesh Remains High Despite Two Decades of Mitigation Efforts

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2.1 Abstract

The discovery in the late 1990s that as many as 70 million people in Bangladesh were exposed to naturally occurring arsenic through their drinking and cooking water sources sparked widespread efforts to mitigate the risks. Despite two decades of mitigation efforts, recent studies indicate that up to 40 million people in Bangladesh remain exposed to unsafe levels of arsenic in their drinking water. This study attempts to understand why arsenic exposure remains high, and in doing so identifies priorities for mitigation efforts going forward. We evaluated the functional status of all 171 community safe water devices in two arsenic affected unions in Jessore District, Bangladesh, Phulsara union in Chowgacha Upazilla and Goga union in Sharsha Upazilla. We surveyed 901 households (~7.5% of the population) to assess water use behaviors and perceptions. We found that 57% of community safe water devices were not functional (they were either not operational or did not provide arsenic safe water) and 76% of households were drinking private

tube well water without treatment. Spatial analyses of household arsenic exposure overlaid with locations of existing community safe water devices provided valuable insights for water supply planning. More broadly, the fact that mitigation strategies did not align with observed user behaviors points to a need for stakeholders to re-evaluate arsenic mitigation efforts and highlights the importance of continuing program monitoring and evaluation.

2.2 Introduction

Since the late 1990s, when the magnitude of the public health concern posed by naturally occurring arsenic in groundwater was discovered[15,16,29], a range of mitigation strategies have been adopted by governmental and non-governmental organizations. The most effective strategy involved well testing, which led to affected users switching to alternate uncontaminated shallow tube wells.[24] The second most effective intervention involved users switching to newly installed deep tube wells (tube wells that tap into deeper aquifers that are void of arsenic). Both strategies rely on the considerable local heterogeneity in arsenic affected areas, whereby arsenic free wells often exist in close spatial proximity to contaminated wells.[29] Other mitigation strategies include the introduction of community level water treatment technologies, or safe water devices, to remove arsenic and/or microbial contaminants. Arsenic removal technologies such as Arsenic Iron Removal Plants (AIRP) and SIDKO filters have been installed to treat arsenic contaminated groundwater, while Pond Sand Filters (PSF) and Dug Well Sand Filters (DWSF) have been installed to treat surface and shallowest aquifer (<10m) waters, respectively, for removal of microbial contamination. In some cases, harvested rainwater and surface water from ponds or Ring Wells (RW) are used directly with little or no treatment.

Since 2006, the perceived urgency of mitigation efforts has declined and monitoring of existing mitigation efforts has been severely lacking.[30] The number of tube wells in Bangladesh has grown steadily from ~6 million in 2005 to over 11 million in 2014,[22] while well testing has not kept pace. Further, concerns have been raised about accuracy of field kits used in the past and to this day.[31,32] Several studies indicate that, despite two decades of mitigation efforts, arsenic exposure through drinking water continues to be of concern for up to 40 million people in Bangladesh.[10,14]

Mitigation strategies involving the use of tube wells have fared better over time, with rural households strongly preferring tubewells for drinking water provision.[19,20] On the other hand, community managed safe water devices typically require significant maintenance efforts and a change in user behavior that is more substantial than simply changing from one tube well to another. Recent studies have shown that up to 70% of such systems do not function properly or are abandoned within three years of installation.[10,26,33] Rainwater harvesting by individual households has also been adopted in some regions but is made challenging by the long dry season (~eight months) in Bangladesh[24].

This study aims to understand why arsenic exposure remains high by evaluating past mitigation efforts and user behaviors in an arsenic affected setting. The study was carried across two unions in Jessore District, Bangladesh. Phulsara union in Chowgacha Upazilla consists of ~5,900 households across 16 villages and Goga union in Sharsha Upazilla consists of ~6,250 households across 10 villages. Both unions are known to have widespread arsenic contamination in shallow aquifers while the geology of the region limits the use of deep tube wells as a viable safe water alternative[34]. Nationally, 75% of alternate water source installed in arsenic affected regions are tube wells, almost all of which are deep tube wells.[35] In contrast, tube wells only comprise about 20% of the alternate safe water options in Phulsara and Goga unions.[34] In this context, community safe water devices take on additional importance as the most common mitigation option employed. We visited every community safe water device in the two unions and surveyed 901 households (~7.5% of the population) to understand their perceptions and behaviors regarding drinking water use. In addition to an assessment of the current situation in these unions, analyzing both past mitigation strategies and user behaviors provides useful insights that will help guide future efforts.

2.3 Methods

2.3.1 Community water infrastructure assessment

Two trained staff members from Asia Arsenic Network (Jessore, Bangladesh) evaluated community safe water infrastructure in Phusara and Goga unions. This evaluation was performed by visiting all 171 designated community water supply points during the summer of 2016. For each of these community safe water devices, the following steps were taken: 1) recorded GPS location, 2) performed a physical inspection and evaluated functional status of the system, 3) spoke with a user (when possible, the designated caretaker) to determine user issues, if any, and 4) collected a water sample for subsequent laboratory analysis.

GPS locations were recorded using handheld Garmin eTrex 10 units (Garmin, USA). Spatial analysis was performed using the QGIS software (v 2.18). The physical inspection, evaluation of functional status, and user interview were conducted based on a multi-point inspection list developed by the study team (viewable at https://doi.org/10.7302/955e-0877).

The water sample collection protocol was as follows. For shallow and deep tube wells, a minimum of 50 and 100 presses of the hand pumps, respectively, were made before sample collection to allow for the sample to be representative of the aquifer water, rather than water that had been standing in the pipe boring. For all other types of water systems, the finished water was sampled directly. Acid-washed 125 ml plastic sample containers were rinsed three times with the sample before collecting approximately 100 ml of water. Field samples were transported to the laboratory within 72 hours. Once delivered to the laboratory, they were acidified with 6 N hydrochloric acid (Merck, Darmstadt, Germany) at 2% v/v per standard protocols.[36]

Arsenic analyses were performed using Hydride Generation Atomic Absorption Spectroscopy (HG-AAS; Shimadzu Scientific Instruments, Kyoto, Japan) at the Asia Arsenic Network laboratory (Jessore, Bangladesh) per standard protocols[37]. The detection limit of the method was determined to be 0.7 μg/L. The instrument was set to allow a maximum relative standard deviation (RSD) of 5% between triplicate absorption reads. A calibration curve was generated daily and, if the internal standard (run every ten samples to check for instrumental drift) varied by more than 10%, the system was recalibrated, and samples were re-run. Recoveries of standard additions to distilled water and groundwater sample matrices were between 80-120%. A random selection of samples were sent to a commercial laboratory (Bangladesh Council of Scientific and Industrial Research-BCSIR, Dhaka) for cross laboratory verification and showed consistent results with RSD between the sets of <10%.

2.3.2 Household survey

A household survey was developed to capture household perceptions and behaviors around drinking water use. It consisted of several modules: key informant and household demographics, household assets and consumption, water use behaviors in the dry season, water use behaviors during the rest of the year, and water supply maintenance and repair. The survey is viewable at https://doi.org/10.7302/955e-0877. The survey script was translated from English to Bangla by Asia Arsenic Network personnel and survey administrators used this Bangla script to administer surveys. Survey data were recorded on electronic tablets using the Qualtrics survey platform.

Survey administrators were recruited locally in each union by Asia Arsenic Network personnel. The study team devoted several days to train survey administrators, first in a classroom setting and later in the field conducting practice surveys. As a quality control measure, audio recordings of all surveys were made and the study team randomly checked ~5% of these recordings against the data entered.

Households were surveyed uniformly across both unions by visiting every 10^{th} household in Phulsara and every 12^{th} household in Goga between May 2016 and September 2016. In this way, 1,177 household surveys were collected. Of these, 276 were discounted due to data completeness and quality issues. In total, 901 surveys were included for final analysis – 465 in Goga union and 436 in Phulsara union.

2.3.3 Ethics Statement

The study protocol was approved by the University of Michigan Institutional Review Board (HUM00113851). In addition, we obtained approval from Asia Arsenic Network and the Upazilla Nirbhaya Officer and Union Chairman in each union. Verbal consent was obtained from all study participants or, in the case of respondents under 18 years of age, their legal guardians.

2.4 Results and discussion

2.4.1 Household demographics

Figure 2.1 describes household demographics for the self-reported head of household. Male-headed households dominate in both Goga and Phulsara unions, with greater than 90% of key informants indicating they were part of households in which a father, husband, brother, or other male relative was the household's main decision maker. As was expected with heads of household typically away from home during working hours when the surveys were conducted, only 34% of surveys in Goga and 37% in Phulsara were completed by the head of household. In our study as well as in other studies of household distribution of work by gender[14], women were generally responsible for collection of water and use of water. Connected to this, the high proportion of female key informants in this study was of benefit to understanding the household needs, use, and perceptions related to water. It was reported that 38% and 17% of the heads of households in Goga and Phulsara unions, respectively, held no formal education (Figure 2.1). A further 36% in Goga and 34% in Phulsara had completed primary school education, either in part or in whole. Heads of households who completed levels of higher education, including partial or completed secondary school or higher education, were reported as 25% and 37% in the respective unions.

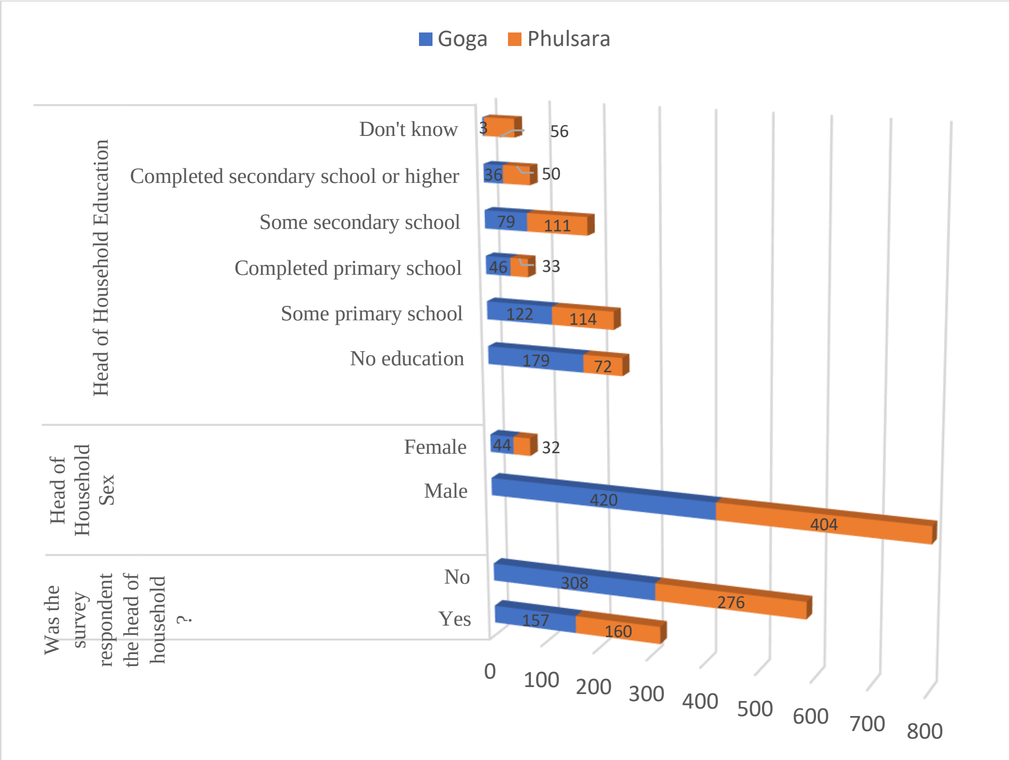

Figure 2. 1 Key informant demographics by union. N_{Goga} = 465, $N_{Phulsara}$ = 436

2.4.2 Household income, assets, and consumption

Across both unions, agricultural work composed greater than 60% of professions held by main income earners, reflecting the high employment in the agricultural sector across greater Bangladesh. While households often consisted of a compound including several buildings for people, livestock, grain and other housing or storage, typically only one household lived within a single compound.

2.4.3 Sanitation and hygiene

In Goga union, 69% of households had access to pit latrines (both improved and unimproved) and 27% reported use of flush or pour toilets. Similarly, in Phulsara union, 61% and 38% of households indicated pit latrine and flush or pour toilet usage, respectively. Only two of 465 households surveyed in Phulsara indicated they had no toilet or were free range, practicing open defecation. Open defecations was practiced by five of 436 households in Goga, with an additional two households using buckets or pans. Just under one-quarter of households in Goga and Phulsara reported sharing toilet facilities with other households. 77% and 75% of households in Goga and Phulsara, respectively, indicated they had private access to sanitation. These findings indicate greater access to improved sanitation than had been anticipated based on information provided in previous studies.[14] When asked about the way households store water, the vast majority reported storing water in containers with a lid (97% or 550 of 566 in Goga union and 96% or 447 of 465 in Phulsara union). It is important to note that some households reported multiple types of in-home water storage systems. These data indicate the accepted practice of water storage in these two unions involved practices that considered concerns of recontamination of water during storage. What is unclear is whether this practice is based upon information delivered via government or other hygiene education or via other methods of information dissemination, or whether this practice stems from simple common sense based on experience. In other words, the households appear concerned with preventing dirt or other debris from entering the water, but it is unclear if they are aware of recontamination through other means (e.g., introduction of pathogens through handling of water) or the presence of contaminants in the source water.

2.4.4 Water source and quality

Figure 2.2 presents a distribution of the types of drinking water sources used in each union. While the types of drinking water sources were more diverse in Goga than Phulsara, the majority of users across both unions obtained their drinking water from shallow tube wells (91.7% and 60.8% in Phulsara and Goga, respectively). Based on prior work in the area[34], several of these shallow wells were expected to be arsenic contaminated. Meanwhile, only 8.3% and 33.2% of households reported collecting water from a community safe water device in Phulsara and Goga, respectively.

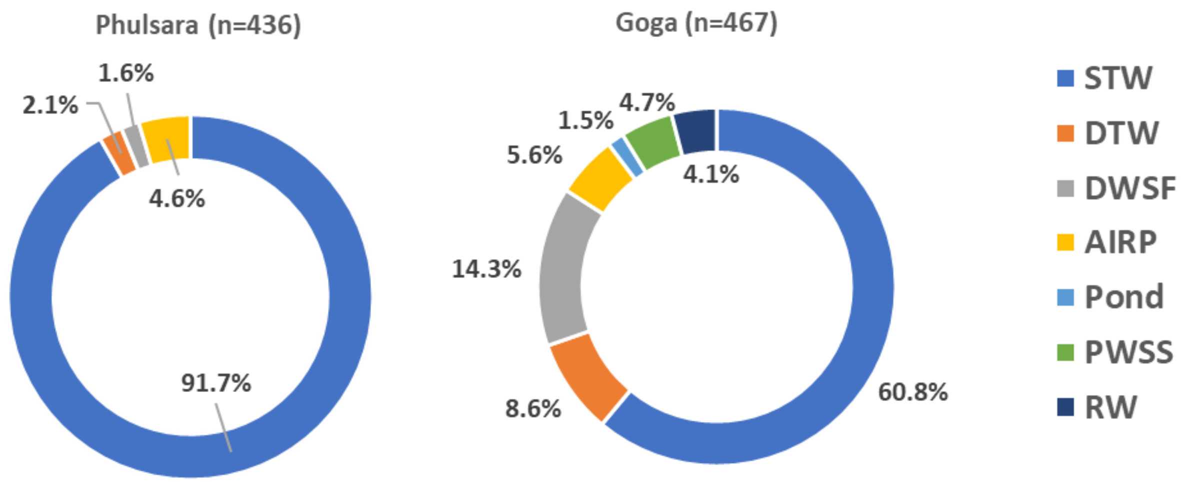

Figure 2. 2 Primary household drinking water source type across both unions. STW = Shallow Tube Well, DTW = Deep Tube Well, DWSF = Dug Well with Sand Filter, AIRP = Arsenic and Iron Removal Plant, PWSS = Piped Water Supply System, RW = Ring Well.

Awareness of water quality was poor; only 39% of households reported that their water had tested arsenic safe, 43% of households did not know if their water was arsenic safe, and 18% knew that their water had tested unsafe but were still using it. Among those drinking arsenic unsafe water, 22% reported being satisfied with the safety of their drinking water implying that they did not associate high arsenic levels to safe water. The remaining 78% who were knowingly drinking arsenic contaminated water indicated they were unsatisfied with their water safety, but this apparent dissatisfaction had not resulted in a change in behavior.

Water quality testing frequency was low with only 5% and 25% of users reporting that their water had been tested within the last 12 months and 5 years, respectively. There was an unmet demand for water quality testing with 68% of households indicating that they would like to have their water tested and would be willing to pay a nominal charge for it.

2.4.5 Community safe water infrastructure

Among the 171 community safe water devices evaluated in this study, only 61% were operational (Figure 2.3). The non-functioning systems were predominantly filter-based options (80%) and ranged from requiring small repairs to major repairs. Only 43% of community safe water devices were providing water with arsenic concentrations below 50 µg/L (the current drinking water standard in Bangladesh) and only 25% were providing water below the WHO standard of 10 µg/L (Figure 2.3).

Many reasons can be offered to explain these findings, including device failure, improper use, wells going dry, thefts of parts, and lack of maintenance[34]. Further, based on the household survey, only 51% of the 210 households that obtained drinking water from a community safe water device reported paying for it and this lack of involvement in the upkeep of this community infrastructure in itself is a cause for concern. Paying for water use is a barrier that inhibits the growth of arsenic removal technologies.

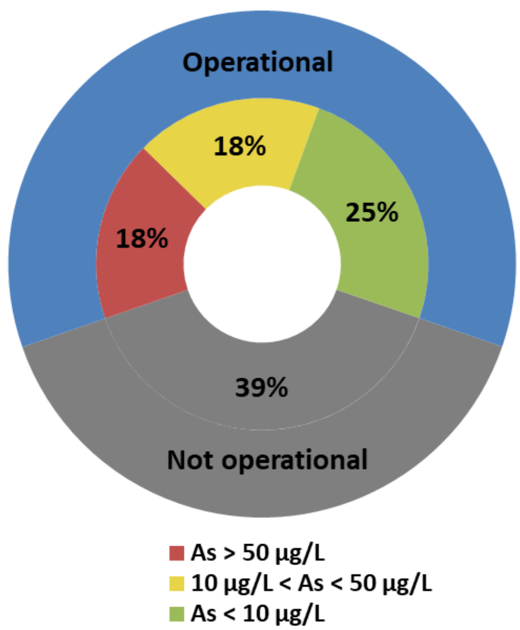

Figure 2. 3 Functional status of community safe water devices across all 171 systems evaluated in both unions. Systems classified as not operational were those for which it was not possible to collect water.

2.4.6 Spatial analysis

Overlaying functional community water points and household distribution for Phulsara union (Figure 2.4) provided valuable insights for water supply planning. In Figure 2.4, household locations are represented by the brown circles and since household surveys were performed at a uniform interval of one in twelve households across the entire union, we can consider this distribution representative of the household distribution in the union. The green circles represent functional community safe water devices.

Several populated areas in Phulsara union lack a functional community safe water device, while there are other regions that contain multiple water points in close proximity (Figure 2.4). The Bangladesh National Policy for Safe Water Supply & Sanitation defines water supply service level as the fraction of households living within 150 m of a community safe water device[38] and the Government of Bangladesh's 7th five year plan (2016-2020) targets providing safe water to every Bangladeshi by 2020[39]. Thus, by measuring the fraction of households that are within 150 m of an arsenic safe water point we can obtain a quantitative metric of the progress toward this goal. This analysis indicated that only 23% of households were within 150 m of a functional community water point. Additionally, the fact that often multiple water points are located in close proximity indicates that the allocation of these systems could be carried out more efficiently.

To our knowledge, local government units and non-governmental implementation agencies did not employ spatial analyses in their planning efforts and doing so could significantly improve the effectiveness of ongoing efforts. Further, we observed water points that were installed in close proximity to non-functional or abandoned water points that could have been repaired at a fraction of the cost. There appears to be a preference from implementing agencies toward installing new systems over repairing existing infrastructure. While the reasons for this are not clear, it is apparent that the lack of coordination between implementing agencies and the local government units have hampered the effectiveness of past efforts.

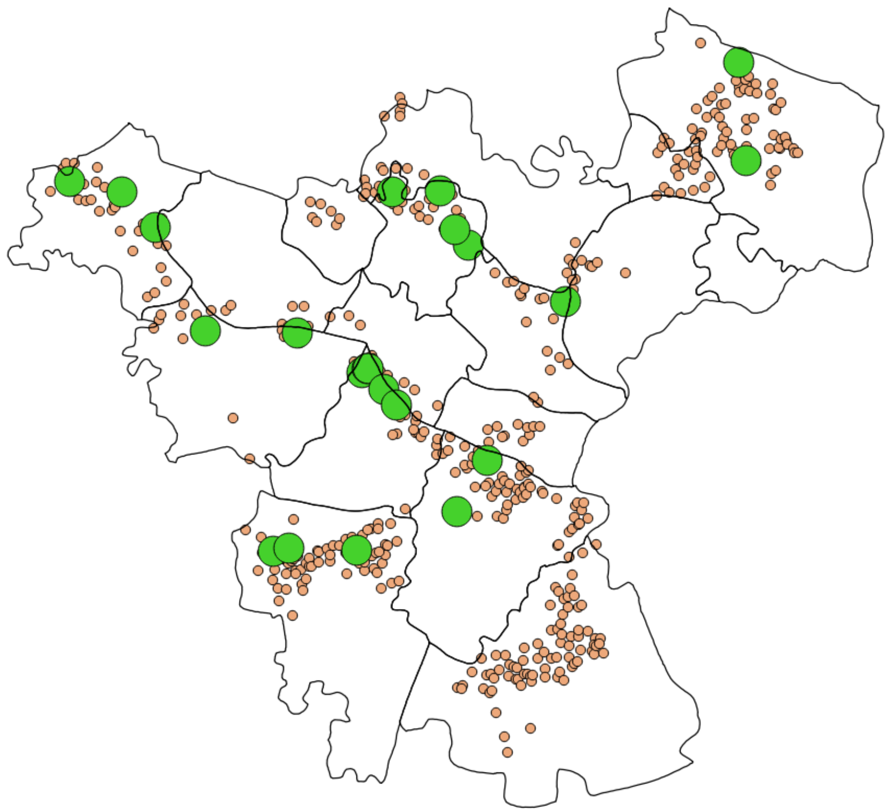

Figure 2. 4. Household distribution (represented by the brown circles) overlaid with locations of functional community safe water devices (green circles) in Phulsara union. The size of the green circles corresponds to a 150-m radius around each system.

2.6 Conclusions

The results of this study indicate that arsenic exposure remains a major concern in Phulsara and Goga unions despite two decades of mitigation efforts. Community safe water infrastructure is insufficient in coverage. Meanwhile, household surveys indicate that the majority of households drink from private shallow tube wells. This is a major concern given that the majority of tube wells are expected to be contaminated by arsenic, water sources are not tested for arsenic with sufficient frequency, and most users were unaware of arsenic test results. These observations indicate that the mitigation strategies in place generally do not align with observed household behaviors and that arsenic exposure remains a significant public health threat. Integrated water supply planning using spatial analyses and better coordination between various implementing agencies working in parallel can improve the efficacy of ongoing efforts. It is imperative that water supply stakeholders critically assess past arsenic mitigation efforts and incorporate learnings in future work.

Chapter 3: Low-cost Informational Intervention Reduced Arsenic Exposure from Drinking Water in Rural Bangladesh

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3.1 Abstract

Up to 40 million people in Bangladesh continue to drink water with unsafe levels of arsenic. Changing households' drinking water sources or providing water treatment can significantly reduce this number. This study investigated the effect of a low-cost (<$10/household) informational intervention on reducing arsenic exposure through a randomized control trial (RCT) design. The intervention consisted of providing (i) awareness material, (ii) the concentration of arsenic in the household's drinking water, and (iii) information about alternate drinking water sources with better water quality. Here we show that the informational intervention lowered household arsenic exposure (p=0.0002). There was no further reduction in exposure (p=0.3899) when a subset of households was given the intervention a second time, implying barriers to further improve mitigation efforts should be studied. These findings demonstrate that continued well testing programs in conjunction with specific recommendations for improved water provide an inexpensive yet effective means of reducing the public health burden posed by arsenic in Bangladesh's drinking water.

3.2 Main

Chronic exposure to low levels of arsenic has several adverse health effects.[2–6] Despite over two decades of mitigation efforts, over 25% of households in Bangladesh (~40 million people) are drinking water with arsenic levels above the WHO guideline value of 10 μg/L and about half of those are exposed to drinking water with arsenic concentrations above the Bangladeshi standard of 50 μg/L.[14] The highly decentralized nature of water supply in rural Bangladesh – less than 6% of the population has access to piped water supply[14] – means that setting up water treatment and distribution infrastructure would be a massive undertaking.

Informational intervention are by far the least expensive approach to addressing problems but are often viewed as ineffective in promoting behavior change. Awareness about potential detrimental health impacts can have a strong and similar effect to wealth on the demand for improved environmental quality.[40] However, due to the spatial heterogeneity of well water arsenic concentrations[41] and the fact that level of contamination is largely an unobservable attribute, it is expected that the social learning processes in such communities will be slow.[42] Aziz et al. report that access to arsenic awareness alone (without individual water quality testing data) did not significantly affect a household's likelihood to adopt avoidance measures.[21] However, providing specific information on well water quality has the potential to impact choice of drinking water source. Following mass well testing by the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) program between 2000-2004, 29% of the people with arsenic levels of over 50 μg/L in their drinking water well shifted their drinking water source.[24] In a study in Araihazar, which provided source water quality information and arsenic awareness messaging, 65% of 6,500 tube well users who learnt their well was unsafe changed to another well within one year while only 15% of those with safe wells at the baseline changed.[43] These studies indicate that providing awareness and information on well specific water quality can result in positive behavior change.

However, it is also important to note that testing accuracy is paramount.[32] Opar et al. reported that when safe wells were either mislabeled by BAMWSP or unmarked, nearly two-thirds of households installed new wells, abandoning safe wells for potentially unsafe wells.[43] Fee based testing could offer a sustainable solution to the unmet need for frequent water testing. George et al. showed through a Randomized Control Trial (RCT) study that household education could improve the demand for fee based testing.[44] In their study, households were offered arsenic testing by the Econo-Quick field kit at USD 0.28 per test (~20% of the cost of administering the intervention). Household education and a local media campaign were both shown to increase the demand for fee based arsenic testing.[44] A different RCT study showed that testing by a community member as opposed to an external member did not lead to a significantly different outcome in terms of well switching.[45]

Identifying an alternate safe drinking water source is the next logical step for households drinking contaminated water, but this is not as straightforward as it may seem. Various factors such as water source location, water source type, and social factors can influence selection, while the questionable accuracy of prior arsenic testing compound the complexity of making a safe selection. Tube wells are much preferred as an alternate water source.[19,20] For example, people were willing to walk a long distance to avoid exposure if the source for arsenic-free water was a tube well. If the source for arsenic-free water was surface water, however, people were less likely to walk a long distance to take avoidance measures.[21]

Therefore, it is important to know if and when information alone can induce people to seek safe water with their own resources, and measure not only whether a change was made but also whether this change lowered arsenic exposure. This study aimed to build on existing literature by evaluating through an RCT an informational intervention that included arsenic awareness messaging, well testing, and a specific recommendation for households to make more informed choices. The outcomes of this study are useful to guide policy on future arsenic mitigation efforts.

3.3 Overview of study area and methods

This study was carried out in Phulsara Union, Chowgacha Upazilla, Jessore District, Bangladesh. Phulsara union consists of ~6500 households in 16 villages and has a high incidence of arsenic contamination in shallow tube wells. The geology of this area means that deep tube wells are generally not a viable safe water alternative. Therefore, mitigation options are mostly limited to implementing arsenic removal technologies and using surface water as the drinking water source. Specifically, only 15% of 94 alternate safe water options in Phulsara Union consisted of tube wells (Chapter 2). This observation sits in sharp contrast with national statistics that indicate that 75% of alternate water sources installed in arsenic affected regions are tube wells, almost all of which are deep tube wells.[35] Deep tube wells clearly are the preferred option of water supply stakeholders and users alike.[19,20]

We used a staggered intervention design (Figure 3.1) such that all households received an informational intervention over the course of the study. Households for the baseline data collection were selected by visiting one of every twelve houses across all 16 villages in Phulsara Union, resulting in 481 households. Analysis of arsenic levels in drinking water source samples at the baseline revealed that of 481 initial study households, 127 (26.4%) tested below the WHO guideline of 10 µg/L, 116 (24.1%) tested above the WHO guideline but below the Bangladesh national standard of 50 µg/L, and 238 (49.5%) tested above the Bangladesh national standard. The 127 households that tested below the WHO guideline value for arsenic were provided with educational materials and the water quality test results but were not a part in the study thereafter. The remaining households (n=354) were assigned randomly to one of two equally sized groups, Group A and Group B. Group A was split randomly into equally sized groups, Group A1 and Group A2. Group A (A1 and A2) received the intervention at Stage I, while Group B received the intervention at Stage II only. Group A1 also received the intervention at Stage II. In this way, all households received the intervention over the course of the study, with Group A1 households receiving it twice. Measurements were made across all groups about four weeks after the intervention.

The informational intervention for study households consisted of providing three elements: (i) educational materials on arsenic as a drinking water contaminant, its long-term adverse health impacts, and knowledge of the Bangladesh and WHO drinking water guidelines for arsenic (Supplementary Figure S3-1), (ii) arsenic test results of the water sample we had collected from their drinking water source during the prior round of surveys, framing the test results in context of the Bangladesh national standard and the WHO guidelines (Supplementary Figure S3-2), (iii) recommendations for alternate sources of safer water (private and public) near the household based on our database of water sources in the area (Supplementary Figure S3-3).

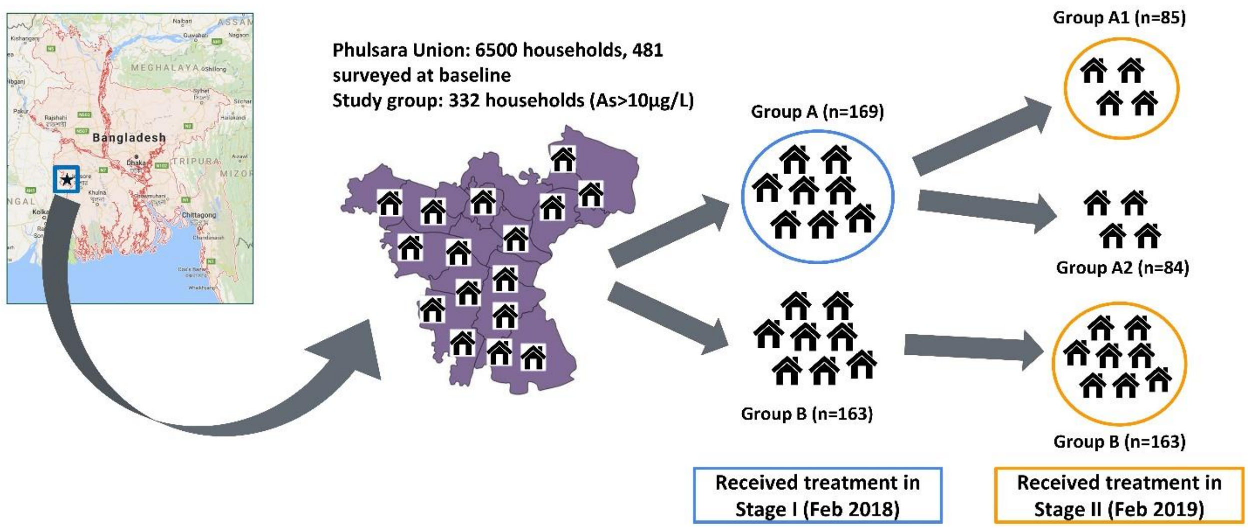

Figure 3. 1 Study design and study groups: The study was conducted in Phulsara Union (~6,500 households total) in south-western Bangladesh. Of the 481 households initially included in the study, only households whose water tested above the WHO guideline value for arsenic (10 µg/L) were included in the informational intervention. The final study group size was 332 households. Intervention stage I was applied in February 2018 to Group A, but not to Group B. Midline measurements were made in March 2018 for both Group A and Group B. Intervention stage II was applied in February 2019 to Group A1 and Group B, but not to Group A2. End-line measurements were made in March 2019 for all household remaining in the study (22 households were excluded from final analyses due to dropout or incomplete data collection at some point during the study).

3.4 Results

3.4.1 The informational intervention reduced exposure to arsenic

Across stage I of the study, drinking water arsenic concentrations declined significantly in households that received the intervention (Group A, p=0.0002), but remained unchanged in households that did not receive the intervention (Group B, p=0.9338). Specifically, the number of households with drinking water arsenic concentrations above the Bangladesh national standard declined from 120 (71%) to 96 (57%) in Group A, and remained almost the same in Group B (103 (63%) vs 104 (64%)) (Figure 3.2). Across stage II of the study, we again observed a decrease, although less statistically significant (Group B, p=0.1710), with the number of households drinking water that tested above the Bangladesh national standard declining from 104 (64%) to 86 (53%) (Figure 3.2).

We did not observe a further decrease in arsenic levels among Group A1 households, who had received the intervention a second time (p=0.3899). Group A2 households, who had not received the intervention a second time, also showed no change (p= 0.7737). This lack of a change is further illustrated by the distributions shown in panels 'c' and 'd' of Figure 3.2.

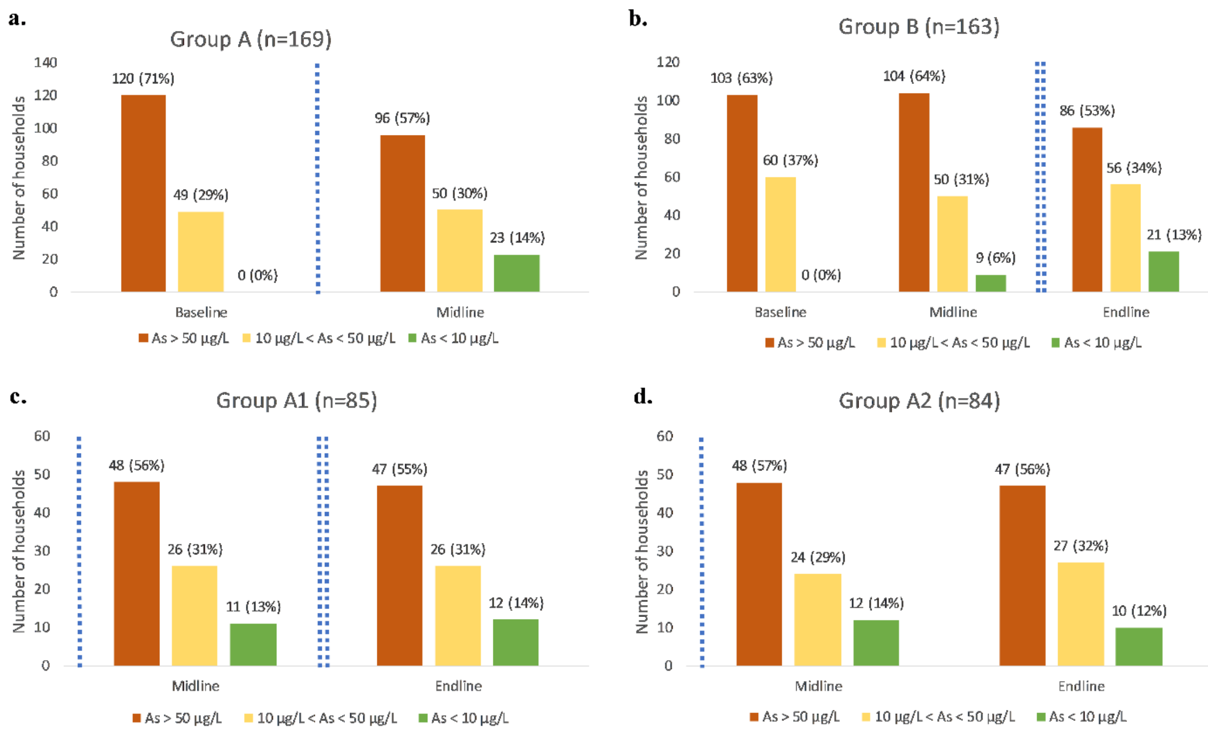

Figure 3. 2 Number of households with drinking water arsenic levels less than the WHO standard (arsenic level < 10 µg/L) and Bangladesh national standard (arsenic level < 50 µg/L) before and after the intervention. A single dotted blue line represents intervention at Stage I while two dotted blue lines represent intervention at Stage II. (a) Group A household arsenic concentrations before and after the intervention at Stage I. (b) Group B household arsenic concentrations at all three measurement timepoints. Group B households received the intervention between the midline and endline measurements, at Stage II. (c) Group A1 (a subset of Group A) household arsenic concentrations before and after receiving the intervention for a second time at Stage II. (d) Group A2 (a subset of Group A) household arsenic concentrations at midline and endline measurements. This group did not receive the intervention a second time at Stage II but the arsenic concentrations at equivalent timepoints provide a reference to assess the effect of the second round of intervention on Group A2.

The distribution of arsenic concentrations across groups at the three measurement timepoints is summarized in Table 3.1. The mean arsenic concentrations at baseline in Group A and Group B were 149±115 µg/L and 138 ±122 µg/L. After Group A received the intervention, the mean arsenic concentration declined to 118 ± 138 µg/L, while it remained similar for Group B at 138±147 µg/L. Given the high variance in the concentrations, which ranged from 0-650 µg/L, the median values (Table 3.1 and Supplementary Figure S3-5) present a clearer picture of the effect of the intervention. The median arsenic concentration reduced from 143 µg/L to 60 µg/L in Group A following the intervention (Stage I) and reduced from 90 µg/L to 53 µg/L in Group B following the intervention (Stage II). At the Stage I measurement timepoint (midline), the median arsenic concentration in Group B, which had not received the intervention, had changed from 106 µg/L to 90 µg/L, while at the Stage II measurement timepoint (endline) the median concentration in Group A2 had increased from 60 µg/L to 75 µg/L. Following a second round of intervention, the median concentration in Group A1 households at the Stage II measurement timepoint remained constant at 60 µg/L. More detailed arsenic distribution data are presented in Supplementary Figures S3-6, S3-7, S3-8 and Table S3-2.

Table 3. 1 Arsenic concentrations across households in each study group

		% households with arsenic concentration			Arsenic concentration (µg/L)		
		<10 µg/L	10-50 µg/L	>50 µg/L	Mean	Stdev	Median
Group A (n=169)	Baseline	0	29	71	149	115	**143**
	Midline	14	30	57	118	138	**60**
	Endline	13	31	56	125	128	62
Group B (n=163)	Baseline	0	37	63	138	122	106
	Midline	6	31	64	139	147	**90**
	Endline	13	34	53	123	136	**53**
Group A1 (n=85)	Baseline	0	27	73	143	113	138
	Midline	13	31	57	104	126	**60**
	Endline	14	31	55	114	125	**60**
Group A2 (n=84)	Baseline	0	31	69	155	117	148
	Midline	14	29	57	133	149	61
	Endline	12	32	56	136	131	75

3.4.2 Factors contributing to the response to the informational intervention

The primary mechanism observed for reduced household arsenic exposure was through making an informed change in water source. Households that received the intervention were more likely to change their water source, and this change was more likely to result in lower arsenic exposure. For example, across Stage I of the study, the group that received the intervention (Group A) was 3.52 times more likely to change their water source or water treatment. This finding is similar to that of Opar et. al who reported that households informed that their water was unsafe were 4.3 times more likely to change their water source compared to households who were told their water was safe.[43]

Of the 63 Group A and Group B households that made a change either during Stage I or Stage II of the study, water quality improved significantly ($p<0.0001$, mean arsenic concentrations decreased from 170 µg/L to 76 µg/L, median arsenic concentrations changed from 167 µg/L to 41 µg/L). In contrast, among the 17 Group B households that made a change during Stage I of the study, water quality did not change significantly ($p=0.1116$, mean arsenic concentrations changed from 144 µg/L to 98 µg/L, median arsenic concentrations changed from 162 µg/L to 90 µg/L). For the subset of intervention households that did not report making a change (n=107), we observed that there was not a significant change in arsenic levels ($p=0.5036$). This implies that households that received the intervention and responded by changing their water collection or intervention were able to make more informed choices and reduced their arsenic exposure.

When considering only the subset of Group A households that were below 150 ug/L at the baseline, no significant difference in arsenic levels is observed after the intervention ($p=0.3896$). This indicates that the level of arsenic measured in source drinking was a strong predictor for the likelihood of a household to make a change to their water source or treatment steps, a correlation that other studies have reported as well[46].

3.4.3 Household characteristics and robustness checks

A comparison of household characteristics across the various randomized study groups (Table 3.2) indicates that they are quite similar in composition. The number of households with electricity, a proxy measure for household income, ranged between 73-89% across groups and the overall average was 84%. The key informant education level was secondary or above in 53% of households with the number varying in study groups between 49-55% Average family size was 4.6 and varied between 4.5-4.8 across study groups. 80% of households used the same source for drinking and cooking purposes and only 6% of households utilized community safe water infrastructure.

Awareness of arsenic in household drinking water was low, despite this being an area known to have high levels of contamination. 42% of all households indicated they were drinking from a source that had not been tested. This number was similarly high across study groups, ranging between 40-44%. Concerningly, 45% of households reported that a family member had skin problems such as discolored spots or skin lesions, common symptoms of arsenic exposure. Despite the low levels of awareness, there appeared to be a strong demand for water quality testing. 79% of households indicated they would be willing to pay a fee of 150 Bangladeshi Taka (BDT) to have their water tested.

Table 3. 2 Study group characteristics

Study Group	Households with electricity *(proxy for HH income)*	Highest level of education secondary or above (for key informant)	Avg. size of house-hold	Using a water source that (per key informants' knowledge) hasn't been tested for arsenic *(proxy for awareness about arsenic in DW)*	Do you or anyone in your family currently have any skin problems such as discolored spots or patches on the skin, or skin lesions? *	Number using a community water source	Same source for drinking and cooking?	If there was a service to test your drinking water for arsenic levels, would you want to pay BDT 150 to check arsenic levels of your drinking water?
Overall (n=332)	278 (84%)	177 (53%)	4.6	139 (42%)	148 (45%)	21 (6%)	267 (80%)	261 (79%)
Group A (n=169)	137 (81%)	88 (53%)	4.6	73 (43%)	73 (43%)	12 (7%)	143 (85%)	134 (79%)
Group B (n=163)	141 (87%)	89 (55%)	4.5	66 (40%)	75 (46%)	9 (6%)	124 (76%)	127 (78%)
Group A1 (n=85)	62 (73%)	42 (49%)	4.5	37 (44%)	41 (48%)	5 (6%)	74 (87%)	73 (86%)
Group A2 (n=84)	75 (89%)	46 (55%)	4.8	36 (43%)	32 (39%)	7 (8%)	69 (82%)	61 (73%)

*total=330, 2 respondents in group B opted not to answer)

3.5 Discussion

The informational intervention had a significant impact on reducing household drinking water source arsenic levels, an observation consistent across all study groups. Our results suggest that when households are given information that enables an informed choice about changing water sources, they make better decisions. The implications of this are that creating water supply maps that supplement well testing campaign efforts has compounding benefits.

The average cost of the intervention evaluated in our study (including materials, arsenic analyses, field worker wages, and transportation) was under $9 per household (Supplementary Table S3-1). Laboratory analyses of arsenic accounted for approximately half this amount. This cost could be reduced by 30-40% by using arsenic field test kits[32] for measurements instead of laboratory measurements.

The low-cost of the informational intervention and its clear benefit in reducing arsenic exposure make a compelling case for an expansion of such interventions in Bangladesh, in the effort to combat the massive public health burden that arsenic contamination has created.

3.6 Limitations of this study

Our observations indicate difficulty in identifying a representative 'source water' sample since several (over 55% at the final measurement stage) households (especially those using tube wells) used more than one source at a given time and over the year. Further, due to self-reporting of 'primary drinking water source' we are unable to verify the accuracy of the information provided by the key informant during a survey. On occasion, this may have led to errors when the key informant was a household member not involved in water collection. At the final measurement stage, there were concerns of possible false reporting of drinking water source since households may have been interested in having a new water source tested for arsenic levels.

In this study, we measured changes in the drinking water source arsenic concentrations as a proxy for household arsenic exposure but are aware that arsenic levels may fluctuate during water storage and water treatment. We noted that some households reported adopting some water treatment post collection. Some practices, such as allowing water to settle in a bucket and discarding the precipitate, likely reduced arsenic levels slightly. At the midline measurement, we simultaneously collected samples of source drinking water and an additional 'household drinking water sample' and found no significant difference between the two (p=0.3364).

Finally, it is important to note that food could also be a significant source of arsenic exposure for rural households[47]. This aspect was not considered in the current study.

3.7 Methods

3.7.1 Intervention groups and implementation

Randomization was done using the list of HHIDs and a randomizing function on Microsoft Excel. Groups A1 and A2 received the intervention at Stage I while Groups A and B received the intervention at Stage II. 22 households (~6%) were excluded from final analyses due to dropout or incomplete data collection at some point during the study. This resulted in a final study group size of 322 households split among Group A1 (n=85), Group A2 (n=84), and Group B (n=163).

The three components of intervention (educational material, arsenic test result, and recommendation on alternate sources of water) were administered during a visit to the household and provided to all household members available. When the head of household was not available, a follow up visit was made and the test result certificate was only handed over to the head of the household. Approximately one week after the household visit, we made a follow up phone call to the head of household to remind them of the three components of the intervention and answer any questions. They were offered water quality testing free of cost if they had switched to a different water source of unknown quality or were considering switching pending water quality testing. Approximately one week after this phone call, we sent a follow up text message with an additional reminder.

The intervention was administered by community workers who were recruited from within Phulsara union and trained for the task. We made efforts to ensure that the community worker who visited a household was from the same ward.

3.7.2 Outcome measures

The concentration of arsenic measured in a household's drinking water sample was the key outcome measure of interest; more specifically the number of households that fell within the three concentration intervals defined above (<10 µg/L, 10-50 µg/L, >50 µg/L). Secondary outcome measures included choice of drinking water source, treatment steps post collection, and awareness levels about arsenic as a drinking water contaminant.

Measurements were made at baseline (August 2017), midline (March 2018) following intervention stage I, and endline (March 2019) following intervention stage II. We collected survey data on electronic tablets using the Qualtrics survey platform. The survey can be viewed at https://doi.org/10.7302/955e-0877. Survey administrators were local university students who had prior experience with survey data collection, spoke English and Bangla fluently, and were familiar with Phulsara union. Members of the study team visited all 94 designated community safe water options in Phulsara Union to assess functional status and collect a water quality sample. GPS locations of all households, water sources and community safe water options were recorded using handheld Garmin eTrex 10 units (Garmin, USA).

Following each round of surveys, household water quality was classified into three categories (As<10µg/L,10<As<50 µg/L, and As>50 µg/L) based on the current WHO guideline (10 µg/L) and Bangladesh national standard (50 µg/L) for arsenic concentrations in drinking water. For households receiving the intervention, their most recent water quality information was printed on a certificate coded in green, yellow, or red based on the three categories above and included corresponding messaging that aided in interpretation of the test result. Example certificates can be seen in Supplementary Figure S3.1 and Figure S3.2.

We created a set of maps for each village (see Supplementary Figure S3.3 for an example) with marked locations and each household and community water point surveyed, together with information about the level of arsenic contamination at each site. Field workers used these maps while administering the intervention.

3.7.3 Arsenic measurement

We collected water samples from the drinking water source identified by the household member being surveyed. The water samples were collected in 125 ml plastic containers directly from the source. For shallow and deep tube wells a minimum of 50 and 100 presses of the hand pump were made before sample collection in order to sample the aquifer directly. For all other types of water systems, the finished water was sampled directly. Sample containers (previously acid-washed in the laboratory) were rinsed thrice with sample, before collecting ~100 ml of sample and capping the container. Once brought back to the laboratory, they were acidified with 6 N hydrochloric acid to a final concentration of 2% (v:v) and analyzed with Hydride Generation Atomic Absorption Spectroscopy (HG-AAS; Shimadzu, Japan) using standard protocols[37]. We performed daily calibrations and ran a standard check once every ten samples on the HG-AAS, allowing us to reject and repeat any analyses where the relative standard deviation on the standard check varied by more than 5%. The method detection limit was determined to be 0.7 µg/L. The instrument was set to allow a maximum relative standard deviation (RSD) of 5% between triplicate absorption reads. A calibration curve was generated daily and, if the internal standard (run every ten samples to check for instrumental drift) varied by more than 10%, the system was recalibrated, and samples were re-run. Recoveries of standard additions to distilled water and groundwater sample matrices were between 80-120%. A random selection of samples was sent to a commercial laboratory (Bangladesh Council of Scientific and Industrial Research-BCSIR, Dhaka) for cross laboratory verification and showed consistent results with RSD between the sets of <10%.

3.7.4 Statistical analyses

A longitudinal analysis of outcome measures before and after intervention stages was conducted. Significance levels reported are based on a pairwise t-test.

3.7.5 Ethics Statement

The study protocol was approved by the University of Michigan Institutional Review Board (HUM00133042). In addition, we obtained approval from the Chowgacha Upazilla Nirbhaya Officer and Phulsara Union Chairman. Verbal consent was obtained from all study participants or, in the case of respondents under 18 years of age, their legal guardians.

3.8 Acknowledgements

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3.9 Supplementary information

Table S3- 1 Cost of intervention on a per household basis

Component of the intervention	Cost (BDT)	Cost (USD)
Collection of water samples	75	0.94
Analysis of arsenic in water samples	400	5.00
Intervention materials (maps, lists etc)	25	0.31
Household visit	70	0.88
Follow up phone and text message	25	0.31
Additional request-based testing (cost for households that requested it averaged across all households getting the intervention)	110	1.22
Total	705	8.8

Integrated Assesment Study on Sustainability
of
Safe Drinking Water Supply in Bangladesh

ক্রঃনং-

আর্সেনিক পরীক্ষার ফলাফল ঃ আর্সেনিক যুক্ত

বাড়ীওয়ালার নাম : --

পিতা/স্বামীর নাম : --

গ্রাম : ------------------------ পাড়া: ------------ ওয়ার্ড নং- ----------

ইউনিয়ন : ফুলসারা ------- উপজেলা: ---চৌগাছা--- জেলা : ---যশোর---

পরীক্ষিত পানির উৎসের বিবরণ

স্থাপনার ধরণ : ------------ জমিদাতা: ------------------------

বাংলাদেশ জাতীয় নীতিমালানুযায়ী আর্সেনিকের গ্রহণযোগ্য মাত্রা	৫০ পিপিবি বা তার নিচে
পরীক্ষিত পানির উৎসের আর্সেনিকের মাত্রা	১০৭

পরীক্ষার তারিখ : ----১৩-০৮-২০১৭---- মেয়াদ : ----১২-০৮-২০১৮----

কেমিষ্ট
ইনভাইরনমেন্ট ল্যাব
এশিয়া আর্সেনিক নেটওয়ার্ক, যশোর।

বি: দ্র : বাংলাদেশের জাতীয় নীতিমালা অনুযায়ী এই স্থাপনার পানি অতিমাত্রায় আর্সেনিকযুক্ত। ইহা খাওয়া ও রান্নার কাজে ব্যবহারের সম্পূর্ণ অনুপযোগী। এই পানি গ্রহণ আপনার ও আপনার পরিবারের স্বাস্থের জন্য ক্ষতিকর। ডাক্তারী মতে আপনি হয়তো কোন লক্ষণ এই মুহূর্তে দেখতে পারবেন না কিন্তু দীর্ঘদিন পর আপনার শরীরে ক্ষতিকর প্রভাব দেখা দিতে পারে। এই পানি আপনি গৃহস্থলির কাজে (কাপড় কাচা, থালা মোছা, গোসল ইত্যাদি) সাবধানে ব্যবহার করতে পারেন।

আপনি আপনার পানির আর্সেনিক পরীক্ষার ফলাফল বুঝতে পেরেছেন কি?

ইহা সম্পূর্ণ রূপে আর্সেনিকযুক্ত!
যেহেতু আপনার পানিতে মাত্রাতিরিক্ত (৫০পিপিবি এর উপরে) আর্সেনিক পাওয়া গেছে সেহেতু অপর পাতার চিত্রভিত্তিক তথ্যগুলি সর্তকতার সথে লক্ষ্য করুন--------

Figure S3- 1 Sample water quality test result certificate (front page)

Figure S3- 2 Sample water quality test result certificate (rear page)

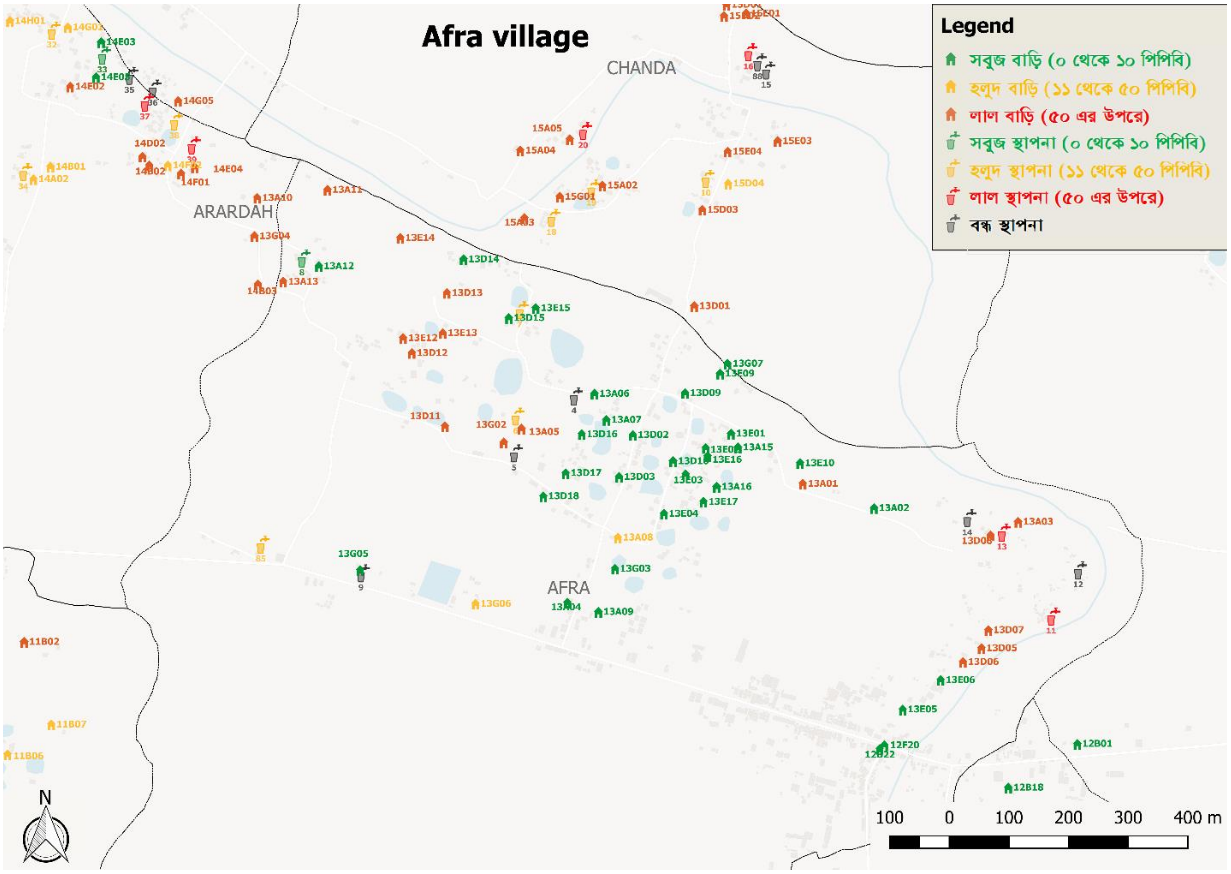

Figure S3- 3 Example of village map (Afra in this case) showing households, water sources and quality. Households (house symbol) and community water options (tap symbol) were labelled in green/yellow/red based on water quality information. Additionally, non-functional community safe water options were labelled in grey. The map was overlaid with a google hybrid layer and village maps to provide additional identifying features.

Section S3-1 Heterogeneity in arsenic levels across the study area

Analysis of baseline data on water quality of drinking water source (Figure S3-4) revealed that of 481 initial study households, 26.4% tested below the WHO guideline of 10 µg/L, 24.1% tested above the WHO guideline but below the Bangladesh national standard of 50 µg/L, and 49.5% tested above the Bangladesh national standard. The highest concentration observed was 654 µg/L. Figure S3-4 shows the heterogeneity in arsenic concentrations between and within each village. The households whose water tested over 10 µg/L (n =354) were split equally using a randomization algorithm into control and intervention arms.

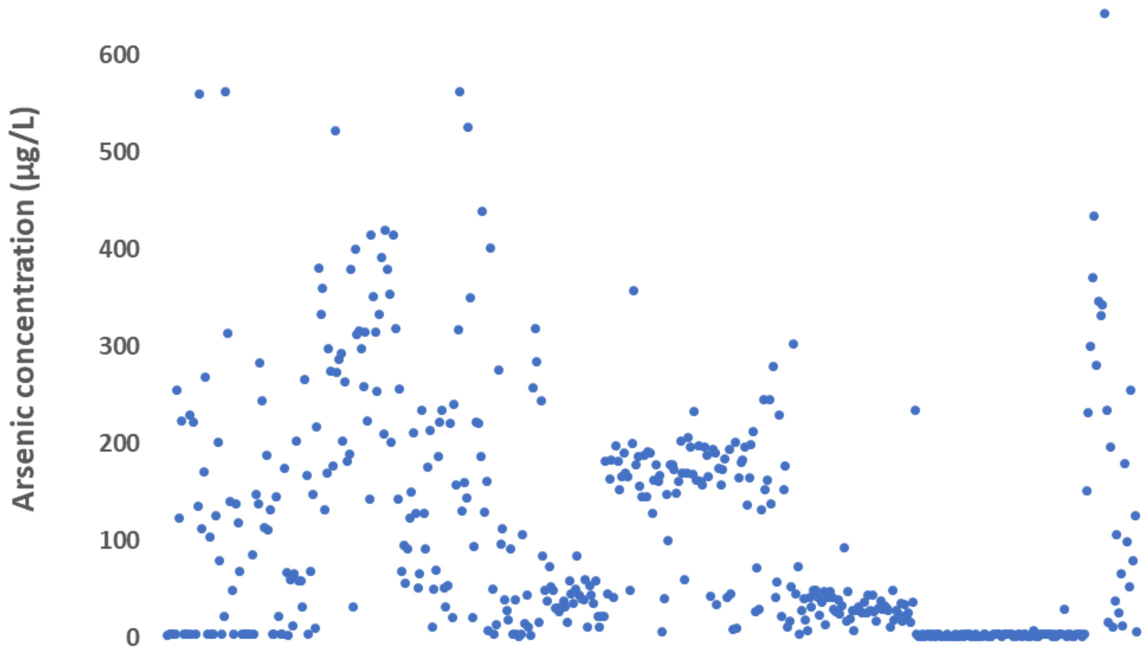

Figure S3- 4 Arsenic concentrations in household drinking water source water at baseline (n = 481). The x-axis is arranged by village and despite some instances of clustering shows the heterogeneity in water quality.

Section S3-2 Community safe water infrastructure in study area

Analysis of the community safe water infrastructure revealed that only 50% of the 94 options were functional at the time of surveying in December 2017. Only half of these functional options (26% of total) provided water that tested below 50 µg/L. The functional and safe options are plotted along with study households in Figure S3-5. The Bangladesh DPHE target is to ensure that each household in arsenic affected unions is within 150 m of a safe water source. However, as can clearly be seen by the coverage of the green circles in Figure S3-5, only 23% of households met this target.

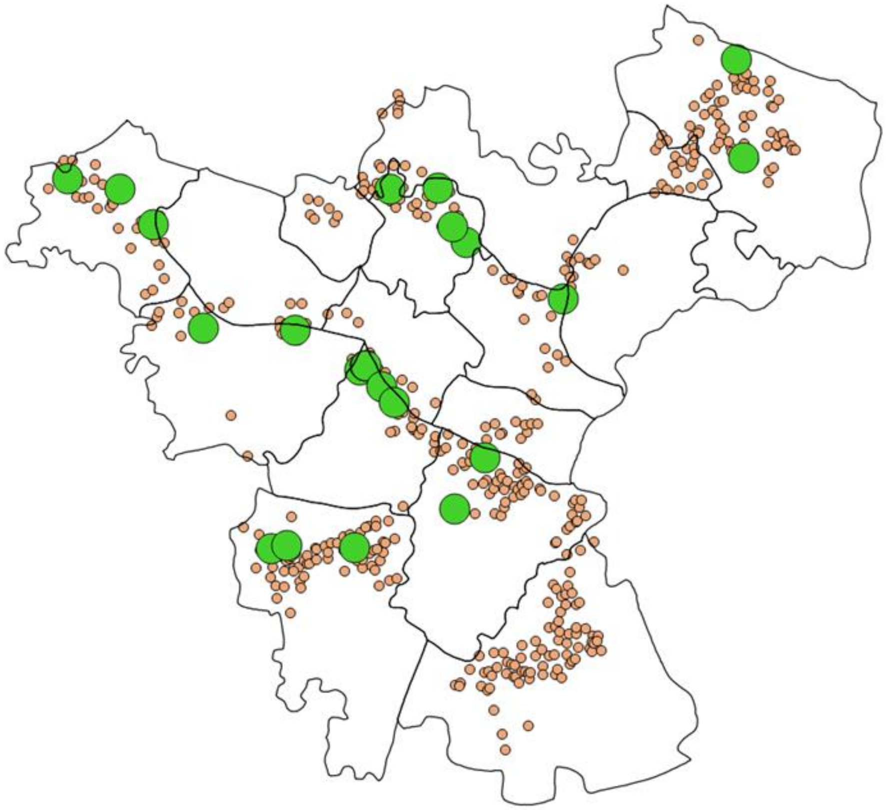

Figure S3- 5 Phulsara Union map with study households marked in brown and operational + safe community safe water sources in green. The size of the green label is scaled to represent a 150m radius around the water source.

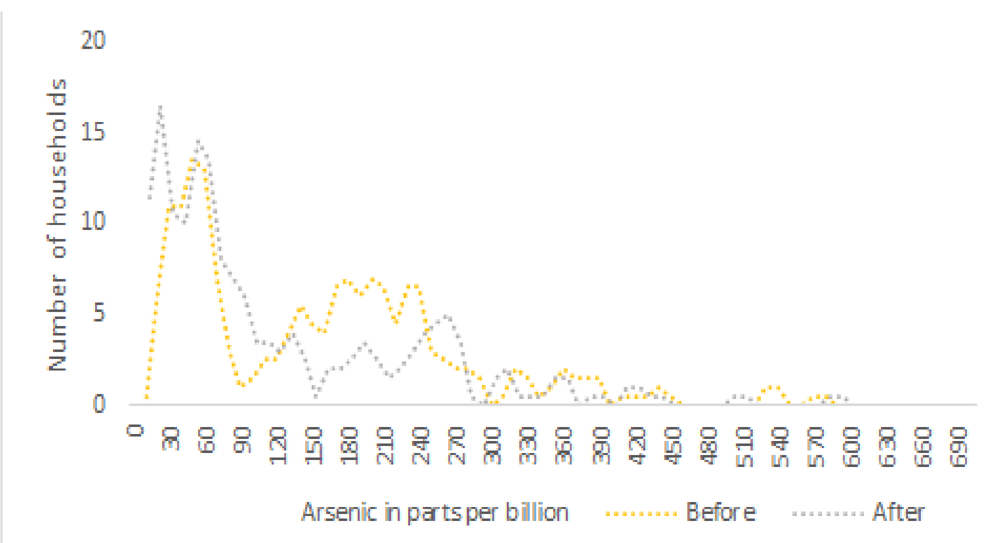

Figure S3- 6 Frequency distribution of arsenic concentrations in Group A before and after receiving the intervention at Stage I.

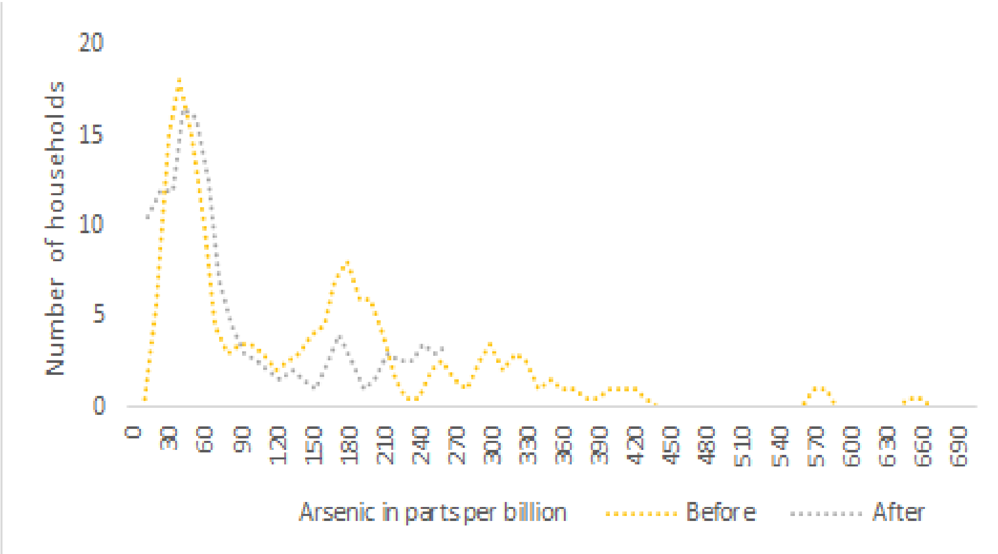

Figure S3- 7 Frequency distribution of arsenic concentrations in Group B before and after receiving the intervention at Stage II.

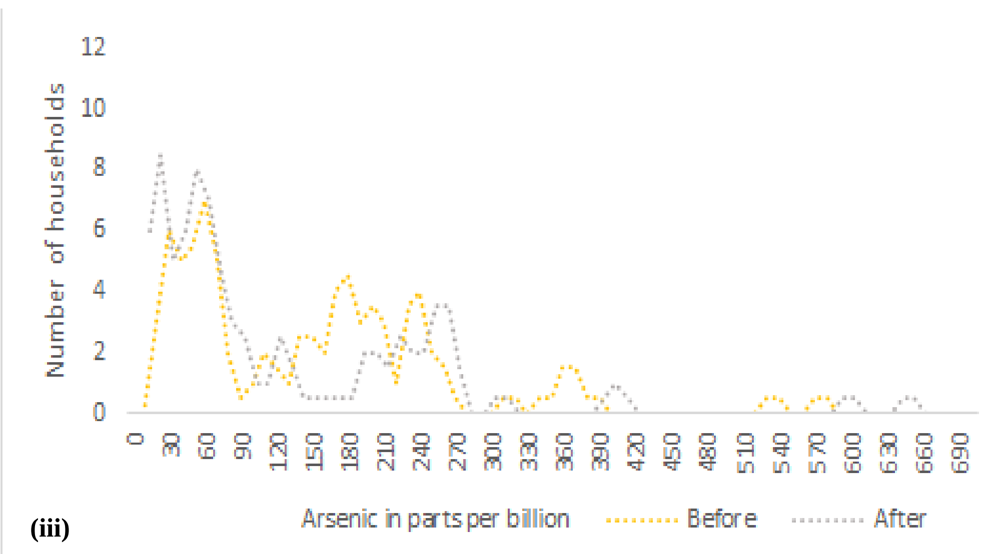

Figure S3- 8 Frequency distribution of arsenic concentrations in Group A1 before and after receiving the intervention for a second time at Stage II.

At the start of the study, 33% of the 332 study households were drinking water that met the Bangladesh national standards, while none were drinking water that met the WHO guideline. At the end of the study, 46% of the 332 households were drinking water that met the Bangladesh national standard and 13% were drinking water that met the WHO guideline. The highest arsenic concentration observed across three measurement stages was 1,050 µg/L, more than 20 times the Bangladesh national standard and over 100 times the WHO guideline.

Further, we observed that households with high initial arsenic concentrations of over 150 ug/L were largely responsible for the shift described above. The frequency distributions of household arsenic concentration within a group before and after the intervention (Table 3.1). When considering only the subset of Group A households that were below 150 ug/L at the baseline, no significant difference in arsenic levels is observed after the intervention (p=0.3896). This implies that households exposed to high levels of arsenic at the baseline were more likely to respond to the intervention than others.

Table S3- 2 Arsenic concentrations across households in each study group

		% households within respective group with arsenic concentration						Arsenic concentration in group		
		<10 µg/L	10-50 µg/L	50-100 µg/L	100-200 µg/L	200-300 µg/L	>300 µg/L	Mean	Stdev	Median
Group A (n=169)	Baseline	0.0	29.0	11.2	30.8	18.3	10.7	149.1	115.0	143.2
	Midline	13.6	29.6	18.9	14.8	15.4	7.7	118.0	138.1	60.4
	Endline	13.0	31.4	12.4	14.2	21.3	7.7	124.9	128.3	61.5
Group B (n=163)	Baseline	0.0	36.8	12.3	28.8	11.0	11.0	137.8	121.9	106.0
	Midline	5.5	30.7	17.8	16.6	18.4	11.0	138.5	146.9	89.8
	Endline	12.9	34.4	14.1	11.7	16.0	11.0	123.2	135.7	52.6
Group A1 (n=85)	Baseline	0.0	27.1	15.3	32.9	15.3	9.4	143.1	113.0	137.6
	Midline	12.9	30.6	23.5	14.1	14.1	4.7	103.6	126.2	60.4
	Endline	14.1	30.6	16.5	14.1	20.0	4.7	113.9	125.0	59.5
Group A2 (n=84)	Baseline	0.0	31.0	7.1	28.6	21.4	11.9	155.3	117.4	148.3
	Midline	14.3	28.6	14.3	15.5	16.7	10.7	132.6	148.5	61.4
	Endline	11.9	32.1	8.3	14.3	22.6	10.7	136.0	131.4	74.8

Chapter 4: Improving the Management of Community Safe Water Infrastructure: Lessons from Two Case Studies in Goga Union, Sharsha, Bangladesh

4.1 Introduction

In the early 1990s when widespread arsenic contamination in shallow groundwater aquifers in Bangladesh was discovered, over 95% of the rural populace relied on these sources for their drinking water.[7] Country wide surveys by the Department of Public Health Engineering (DPHE) and British Geological Survey (BGS) estimated that 46% of wells exceeded the WHO guideline for arsenic of 10 μg/L, while 27% exceeded the Bangladesh national standard of 50 μg/L.[16]

The Bangladesh Arsenic Mitigation and Water Supply Plan (BAMWSP) that tested over five million tube wells across the country between 1999-2005 provided rural households with information about the quality of their drinking water[24]. Well switching to an existing safe well was found to be the most successful intervention for affected households but was not always an option due to widespread arsenic contamination of groundwater[24]. In areas of high arsenic contamination, mitigation efforts focused on installation of alternate community safe water options such as deep tube wells, arsenic removing filters, and pond sand filters. These systems were typically installed by donor agencies, with the user community paying a nominal fee of USD 40-150 (7-15% of installation cost), although the systems were designed to be owned and operated by the community.[20] This approach continues to be used to this day. [35]

With the exception of deep tube wells, which require very little maintenance for their upkeep,[20] other systems such as Arsenic Iron Removal Plants (AIRP), Dug Well Sand Filters (DWSF), Pond Sand Filters (PSF), and Piped Water Supply Systems (PWSS) rely on good management practices to continue to function properly[26]. Such practices include regular filter backwashing, cleaning of sand and gravel chambers, replacing damaged parts (e.g., aeration trays, metal covers, nets, piping, taps), handpump maintenance, and keeping the filter surroundings clean. Most systems were set up such that households would pay a small fee (typically USD 0.13-0.25 per month for filter-based systems and USD 0.5-1.2 for piped water supply) that would be used toward management of the infrastructure.[20]

Unfortunately, a large fraction of these community managed systems failed soon after installation and households for which they were intended reverted to using water sources that were frequently contaminated with arsenic. A recent study reported that 75% of 135 community safe water options in a particular village in rural Bangladesh failed within three years of installation.[26] In the study presented in Chapter 2, we surveyed all 171 designated community safe water points across 26 villages in two unions to assess functional status and water quality and found that only 61% were operational. Further, of the operational systems, only 43% provided water that tested below the Bangladesh national standard of 50 µg/L. There are over 27,000 such systems across Bangladesh intended to provide safe water to 13.5 million people[35], making such low levels of operation very concerning. Utilization levels are another course of concern[19], which means that even if households have access to these 'safe water sources' they often chose not to use them.

It can be expected that an engaged user base is more likely to manage their water supply system well, so that it maintains its functionality. Furthermore, the lack of functionality of safe water systems causes users to shift to alternate water sources. These realities make functionality and utilization interdependent factors.

This study aims to provide insights into how the vicious cycle of lack of engagement and safe water system failure can be broken. We worked with the user communities of five community owned water supply systems for 18 months to identify and document examples of improved management of community owned water systems that led to better filter performance and higher user engagement. We were particularly interested in solutions that did not depend on an influx of external capital as these could serve as sustainable models that can be more easily replicated elsewhere in Bangladesh. The findings and recommendations provide insights for water supply stakeholders to improve the management of existing systems and delivery of future programs across Bangladesh.

4.2 Methods

4.2.1 Selection of cases

The study was conducted in Goga union, Sharsha Upazilla, located in the south west of Bangladesh. Our research partner Asia Arsenic Network (AAN) has worked in this area for over 20 years and had considerable familiarity with communities and existing water supply infrastructure. Our prior work in the region (Chapter 2) indicated that the various types of community drinking water systems in Goga included Dug Well Sand Filters (DWSF), Deep Tube Wells (DTW), Pond Sand Filters (PSF), Arsenic and Iron Removal Plants (AIRP), Ring Wells (RW) and Shallow Tube Wells (STW). RWs involve direct collection of shallowest aquifer (<10 m) water while the STW and DTW involve direct collection of water from underground aquifers. Meanwhile the PSF, DWSF and AIRP, involve treatment (typically through sand and gravel filters) of surface, sub-surface or underground aquifer water respectively and are referred to as filter-based systems. PSFs, DWSFs and AIRPs are collectively referred to as filter-based systems.

Our survey of all community safe water devices in the area found that there were a total of 83 designated community water sources in Goga Union, of which 57 were functional and 26 had stopped working. Figure 4.1 shows a breakdown of the various types of filters and their operational

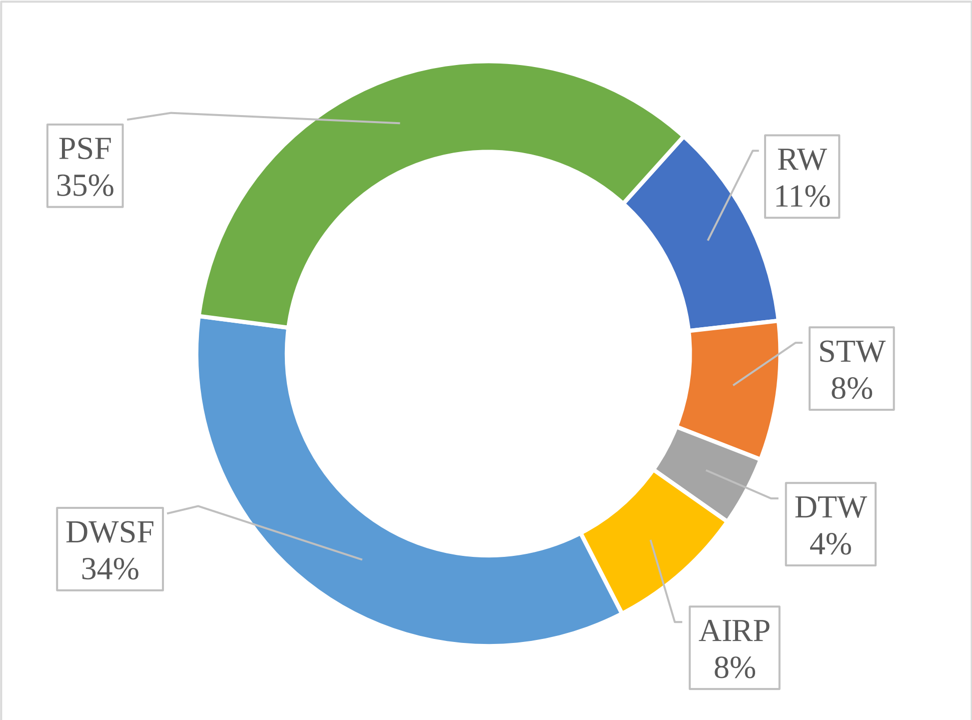

Figure 4. 1 Inactive community safe water options in Goga Union (n=26) by type. The filter-based treatment systems (PSF, DWSF and AIRP) account for the majority of failed systems

status as of July 2016. It shows that the 'filter-based' safe water devices (PSF,DWSF,AIRP) account for 20 of the 26 systems that have failed (77%). This can be explained by the fact that these systems require more in terms of upkeep in order to function properly and therefore have a higher likelihood of falling into disrepair should this upkeep not happen.

This highlights the importance of understanding effective management practices for filter-based community water systems. Field observations and discussion with the local DPHE officials indicated that PSFs were low in popularity[24] and rarely considered as an option for new systems today. This led us to choose to focus our study on the AIRP and DWSF systems. While selecting cases, we first identified systems that were operational and did not require substantial capital upgrades (defined as >BDT 5,000) to keep functioning, since such capital costs tended to be a roadblock for communities to initiate change themselves. Following this, a series of field visits and meetings were conducted to identify systems that had a user expressed need for better management. This led to selection of two AIRP and two DWSF systems.

An important component in the selection process, was the explicit clarification that the research team would not provide any financial support, but rather would offer technical assessments, troubleshooting help, and organizational support to facilitate changes. This explicit clarification was repeated several times since rural communities often see external parties like our project team as donors of financial capital.

At a later point (February 2018) a fifth system was also included that did require infrastructural improvement to the tune of BDT 20,000 but whose user community expressed interest in mobilizing this capital themselves.

4.2.2 Monitoring of systems

Each system was monitored by a trained technical staff member of AAN. This included a physical inspection of the filter every 2-3 weeks, noting the condition of various parts, and interviews of the designated caretaker to document maintenance steps that were performed. In addition, a detailed record of all income and expenditures for the system was maintained (self-reported by designated collector and caretaker respectively).Every 3-4 months, a summary of information was prepared, and the user community was encouraged to call for meeting to review and plan ahead.

4.2.3 Ethics

The study protocol was approved by the University of Michigan Institutional Review Board (HUM00133042). In addition, we obtained approval from Asia Arsenic Network and the Sharsha Upazilla Nirbhaya Officer and Goga Union Chairman. Verbal consent was obtained from all study participants or, in the case of respondents under 18 years of age, their legal guardians.

4.3 Results

Each of the five selected communities, their safe water systems, and user committees were unique. Two of the five systems flourished and developed into robust well-managed and sustainable systems. Both systems were Arsenic and Iron Removal Plants (AIRPs) located in the Goga Bazaar area. They can be identified by the respective landowners, Arshed Ali and Motaleb Ali. These two systems serve as examples of user-driven positive change in the management of community infrastructure. We documented these two case studies in the form of a video. The video was shown to user committees in both Phulsara and Goga unions and continues to be used by AAN in their mitigation efforts. The video can be accessed at the following links: http://hdl.handle.net/2027.42/153331 or shorturl.at/atO39.

4.4 Conclusions

The two case studies documented in the video present very encouraging results in better management of safe water devices. Both systems are living examples in their communities of how a safe water device can be managed sustainably. The case of the Arshed Ali AIRP system through their large base of ~55 households 3 shopkeepers was able to make several significant improvements in a relatively short amount of time. The case of the Motaleb Ali AIRP system was particularly encouraging because it has a user committee that took complete financial responsibility of making much needed capital upgrades to their water infrastructure. There are several such systems across Bangladesh and this process offers an alternative solution to the highly aid-dependent structures currently prevalent in rural water infrastructure. Through this video we hope to share the story of these two systems with other user communities across Bangladesh in order to inform and motivate them to improve their water infrastructure.

Chapter 5: Evaluation of Arsenic Field Test Kits for Drinking Water: Recommendations for Improvement and Implications for Arsenic Affected Regions such as Bangladesh

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5.1 Highlights

- Portable color scanners were used for a tester-independent evaluation of test kits
- Kit performance ranged from under-estimating arsenic to over-estimating arsenic
- Recalibration can improve accuracy but not precision of field kits
- Manufacturers can improve field kit design and facilitate quality assurance testing
- Stakeholders are urged to review their use of field kits for arsenic testing

5.2 Abstract

Arsenic field test kits are widely used to measure arsenic levels in drinking water sources, especially in countries like Bangladesh, where water supply is highly decentralized and water quality testing infrastructure is limited. From a public health perspective, the ability of a measurement technique to distinguish samples above and below relevant and actionable drinking water standards is paramount. In this study, the performance of eight commercially available field

test kits was assessed by comparing kit estimates to hydride generation atomic absorption spectroscopy (HG-AAS) analyses. The results of tests that control for user-dependent color matching errors showed that two kits (LaMotte and Quick II kits) provided accurate and precise estimates of arsenic, three kits (Econo-Quick, Quick, Wagtech and Merck kits) were either accurate or precise, but not both, and two kits (Hach and Econo-Quick II kits) were neither accurate nor precise. Tests were performed for arsenic concentration ranges commonly found in natural waters and treated waters (such as community drinking water filter systems), and also on laboratory generated arsenic standards in DI water. For those kits that did not perform well, test strips often produced colors too light compared to manufacturer-provided arsenic color calibration charts. Based on these results, we recommend stakeholders carefully re-consider the use of poorly performing field test kits until better quality control of components of these kits is implemented. In addition, we recommend that field test kit manufacturers provide suitable internal standards in every kit box for users to verify the veracity of manufacturer provided color charts.

5.3 Graphical Abstract

5.4 Keywords

Test kit; field kit; arsenic; Bangladesh; color matching

5.5. Introduction

Due to unsafe levels of arsenic in drinking water, more than 100 million people worldwide, including an estimated 35 to 77 million in Bangladesh, face serious risks of developing skin lesions and various types of cancer [11–13,15], adverse pregnancy outcomes and infant mortality [2], and cardiovascular disease [3]. Testing water quality and sharing the results with affected users has been one of the most effective interventions for reducing the number of households consuming arsenic-contaminated water [24]. In the early 2000s, over five million wells were tested for arsenic as part of concerted well screening programs in Bangladesh [23,27,48,49]. Since that time, several million new wells have been installed, although many have not yet been tested [10,23,24]. Given that performance of arsenic removing filters is variable and that arsenic in shallow tube wells can change over time [29], more frequent water testing in affected geographies is of paramount importance [27]. The most recent Multiple Index Cluster Survey report [14] indicates that 25% of the populace in Bangladesh is drinking water that tested above the World Health Organization drinking water guideline for arsenic (10 µg/L) and over 12% of households are drinking water containing more than the Bangladesh national arsenic drinking water standard of 50 µg/L.

Although many arsenic measurement methods exist, in rural low income communities easy-to-use and low-cost colorimetry-based arsenic field test kits are the most popular [33,50–53]. However, the accuracy of these kits, especially when used to classify water samples based on relevant drinking water safety standards has been questioned [31,54]. The last systematic reviews of arsenic field test kits were done over a decade ago [55,56], and recent literature lacks studies evaluating kit performance in field tests of groundwater and surface water samples [57]. Given the prevalence of simple arsenic test kits use in countries such as Bangladesh, an updated analysis of their accuracy, precision, and other potential shortcomings for field applications is urgently needed.

This study examined eight commercially available arsenic field test kits on both laboratory-generated arsenic water standards and actual well water samples in Bangladesh. Each kit was assessed by comparing the field kit results to arsenic measured by hydride generation atomic absorption spectroscopy (HG-AAS). Sources of possible measurement error, including kit-based and human-based error, were evaluated. A qualitative comparison of ease of use was also conducted. Critical assessment of these factors enables stakeholders to select suitable field test kits for their needs. It also provides insights to manufacturers for improving field test kit accuracy, reliability, and ease of use.

The performance of Hach EZ kit was of particular interest to this study since it is widely used in Bangladesh where no other arsenic field test kits are currently readily available on the market. Some previous studies have found the Hach EZ kit to significantly underestimate arsenic concentrations [31,55]. In contrast, a different study [53] reported better kit performance and recommended its continued use for screening of wells. The same study also reported that increasing the reaction time from 20-40 minutes significantly improves the accuracy of the kit, particularly in the 50-100 µg/L region. Subsequent studies [23,58] using this modified reaction time protocol also reported good results. However, a more detailed investigation of the Hach kit [59] found it necessary to further increase the reaction time above 40 minutes or increase reaction temperature to 35°C to obtain similar color to the printed reference chart color blocks for equivalent arsenic concentrations. This later study also found that a reaction time of 24 hours produced better results for concentrations around 10 µg/L but noted color fading for higher concentrations over longer test durations, making it unclear whether the extended reaction times will always be beneficial. While increased reaction time may improve accuracy, we only evaluated the Hach kit using the 20-minute reaction time as this remains the manufacturer's recommendation and the modified protocol reported in literature is not likely to be used in the field.

Similarly, the performance of the Econo-Quick kit was of interest in this study, given its comparatively low price and recent evidence indicating it is accurate and precise [23,60], especially in the concentration range needed to classify samples according to the Bangladesh drinking water standard. Further, this kit was used in the most recent Multiple Indicator Cluster Survey [14] that tested arsenic in ~13,000 households across the country.

5.6. Materials and Methods

5.6.1 Field Test Kits

The eight field test kits included in this study (Table 1 and SI: Tables S5-3 to S5-10) cover a range of arsenic concentrations (0-1,000 µg/L) and costs (0.63-4.67 USD per test). Each can be purchased on the international market but at the time of this study only the Hach EZ kit could be purchased in Bangladesh. Arsenic detection for all kits in this study is based on the Gutzeit method[61,62]. Specifically, aqueous arsenic species are converted to gaseous arsenic hydride through the addition of chemical reducing agents in a reaction bottle. The resulting arsenic hydride gas reacts with a mercuric bromide test-strip located in the headspace of the reactor bottle, forming a colored complex that shifts from yellow to orange to brown with increasing arsenic concentrations. The final color is compared against a concentration calibrated color chart provided by the manufacturer to determine the water's arsenic concentration. Some manufacturers offer color scanners (e.g., Arsenator, Palintest (Gateshead, UK) and Quick Scan, Industrial Testing System (Rock Hill, South Carolina, USA)) with pre-loaded color-concentration calibrations, which enable a digital read out of test results. Color scanners reduce the potential error and variability associated with a manual color matching, and interpolation allows for more accurate results with field kits as has been reported for the Wagtech kit [63]. Recent studies have utilized mobile phone camera images [64], digital camera images [65], and a flatbed office scanned images [66] for this purpose. Generic color scanners (e.g., X-Rite (Grand Rapids, Michigan, USA)) can also be used for color matching with any of the kits [59].

Table 5. 1 Description of the eight commercially available arsenic field test kits evaluated

A. Hach EZ (2822800)	Hach, Loveland, USA	0, 10, 25, 50, 250, 500	21	70	100	0.70
B. LaMotte (4053-02)	LaMotte, Chestertown, USA	<4, 4, 8, 10, 12, 14, 16, 20, 25, 30, 50, 85, 100, 150, 175, 200, 300, 400	15	208	50	4.16
C. Econo-Quick (481298)	Industrial Test Systems, Rock Hill, USA	0, 10, 25, 50, 100, 200, 300, 500, 1000	15	189	300	0.63
D. Econo-Quick II (481304)	Industrial Test Systems, Rock Hill, USA	<2, 4, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 100, >150, >300	15	158	50	3.15
E. Quick (481396)	Industrial Test Systems, Rock Hill, USA	0, 5, 10, 20, 30, 40, 50, 60, 80, 100, 150, 200, 250, 300, 400, 500, >500	15	179	100	1.79
F. Quick II (481303)	Industrial Test Systems, Rock Hill, USA	< 1, 2, 3, 4, 5, 6, 7, 8, 10, 13, 20, 25, 30, 40, >50, >80, >120, >160	15	231	50	4.62

G. Wagtech (PTH10605)	Palintest, Gateshead, UK	<10, 20-40, 50, 60-80, 100, 100-200, 200-300, 300-400, 400-500	21	272	200	1.36
H. Merck (117917)	Merck, Darmstadt, Germany	5, 10, 25, 50, 100, 250, 500	21	202	100	2.02

[1]These reaction time estimates do not include sample collection, field test kit materials preparation, or clean up after the test, which can vary depending on several factors. The reaction time is based on following manufacturer instructions from when a test is ‘started’ (after adding first reagent) until the test strip can be read. Hence, it reflects the minimum time required per test.

[2]These costs are for single orders and do not include additional import/customs duties that are levied by individual countries. Such costs can be significant (up to 100% of the retail price in our experience in Bangladesh) if no established distribution network exists for a field test kit in the country. Additionally, through bulk ordering it is possible to lower costs below the list prices shown above but that applies to all the kits and was not considered within the scope of the current study.

5.6.2 Field Test Kit Evaluation

The measurement of arsenic by each kit was carried out in accordance with the corresponding manufacturer’s instructions. An optional sulfide interference mitigation step was followed for all kits except for the Wagtech (G) kit (which does not list the step as being optional) and the Merck (H) kit (which does not have a specific procedural step for sulfide mitigation). For the Hach (A) kit, additional tests were performed with and without the sulfide removal step to assess possible effects on test accuracy. Four kits, LaMotte (B), Econo-Quick II (D), Quick (E) and Quick II (F), recommend in their procedures that samples testing above 30 µg/L, 30 µg/L, 50 µg/L and 10 µg/L respectively, should be diluted and re-tested for the most accurate results. The dilution step time was infeasible with our study design and therefore all field test results presented are based on undiluted samples. To reduce errors caused by procedural inaccuracies and variance among testers, three experienced analysts performed all tests. All water sample were tested in triplicate. For each reacted test strip, the color was recorded using a portable digital color scanner, X-Rite RM200qc (Grand Rapids, Michigan, USA), in D65 daylight mode.

For a subset of water samples, the completed test strips were also presented to a five-person panel consisting of government and NGO employees who regularly use arsenic field test kits. The panel was asked to evaluate whether the test result indicated an arsenic concentration above or below 50 µg/L by comparing the color of the test strip to the manufacturer provided color chart. Panelists were not allowed to view other panel members' responses or review previous determinations when recording an answer. Each water sample was tested in triplicate and presented to panelists in a randomized order. All test strips were scanned and evaluated by the panel within two minutes of test completion as recommended by field test kit manufacturers. The study protocol involving evaluation of test results by a panel of field test kit users was approved by the University of Michigan Institutional Review Board.

5.6.3 Water Samples

Field kit tests were run on water samples from shallow and deep aquifer wells, surface waters and rural drinking water infrastructure in Phulsara Union in the southwest of Bangladesh (see SI Table S5-2 for details on water samples characteristics used in this study). To ensure that a single water sample could be used for all field test kits, a large volume (3-5 L) was collected directly into a container from the water source. Immediately after collection, subsamples were aliquoted into 250 or 500 ml plastic bottles filled to the brim, ensuring no headspace, and then sealed with an airtight cap to minimize oxidation of redox sensitive elements such as iron [1,67]. Plastic sample bottles were pre-washed with 10% v/v hydrochloric acid (Merck, Darmstadt, Germany) and then rinsed thrice with the source water before sample collection. All field tests were completed within three hours of sample collection. One sample aliquot was acidified up to 2% v/v hydrochloric acid (Merck, Darmstadt, Germany) for subsequent laboratory HG-AAS analysis [36].

In addition, dilutions of laboratory arsenic standards with distilled water were also tested. A primary arsenic (III) standard in nitric acid (Sigma Aldrich, St. Louis, USA) was used to prepare such laboratory dilutions for all kits except the Hach kit for which a standard in sodium hydroxide (Hach, Loveland, USA) was used per the manufacturer's recommendation. pH adjustments were made to the diluted solutions as needed before testing using sodium hydroxide (Merck, Darmstadt, Germany) and/or hydrochloric acid (Merck, Darmstadt, Germany) to fall within the pH 5-7 range that some manufacturers recommend.

5.6.4 Processing Color Data

For all samples, the arsenic-reacted test strips were scanned in triplicate using the X-Rite scanner, which records color information in three dimensions: light (L), chroma (C), and hue (H). Each completed test strip was scanned three times and the average L, C, and H values were used for calculations. The color difference metric CMC 2:1 from the Color Measurement Committee [68,69] was used to determine closest match to the manufacturer provided color chart (see SI: Section S5-1 for more details).

5.6.5 Laboratory-generated color charts

Laboratory-generated color charts were generated by reproducing the colors recorded by the color scanner and pairing with HG-AAS measurements of the sample. The web application at http://colorizer.org/ was used to generate color tiles from the Lab color values recorded by the scanner. These laboratory-generated charts enabled assessment of the accuracy of manufacturer provided color charts.

5.6.6 Analytical Methods

A portion of each water sample was preserved by adding 2% v/v of 6M HCl (Merck, Darmstadt, Germany) for later laboratory testing of arsenic concentration by HG-AAS (Shimadzu Scientific Instruments, Kyoto, Japan) [36]. The temperature and pH of water samples (shown in Table S5-2 of the supplementary information) were measured using a standard probe (DKK-TOA, Japan) and adjusted as needed to fall within the appropriate ranges specified in the instructions of a given field test kit.

A subset of preserved samples was sent to a commercial laboratory (Bangladesh Council of Scientific and Industrial Research-BCSIR, Dhaka) for an ICP-MS measurement for cross verification.

5.6.7 Ease of use

Informational interviews with broad range of field test kit users (n=15) in Bangladesh were conducted to define desirable attributes that made a field kit easy to use. Each kit was rated by the authors against these metrics to generate an “Ease of Use” comparison (SI Table S5-1).

5.7 Results

5.7.1 Quality control and quality assurance

The detection limit of the laboratory reference method using HG-AAS for arsenic was determined as 0.7 µg/L. A six point calibration curve of standards between 1-12 µg/L was generated daily and if the internal standard (run every ten samples to check for instrumental drift) varied by more than 10%, the system was recalibrated. Recoveries of 10-100 µg/L standard additions to distilled water and groundwater sample matrices showed recoveries between 120±20%.

A set of six samples between 40 µg/L and 170 µg/L were sent to a commercial laboratory at BCSIR for cross laboratory verification and showed consistent results with RSD between the sets at <9%.

5.7.2 Comparison of field kit and laboratory HG-AAS results

A total of 314 arsenic field test kit measurements were run across 21 water samples and 14 different field test kit boxes of the eight commercial products. Arsenic concentrations ranged from 1 to 200 µg/L in water samples of various background matrices, including laboratory arsenic standards in DI water and well water samples. A panel of five experienced field kit users in Bangladesh were asked to determine if the samples were above or below 50 µg/L by color matching of the test strips to standard colors on the reference charts provided by the manufacturers. Their evaluation was then compared to the HG-AAS verified arsenic concentrations of the same samples (Figure 5.1). Thus, the errors in the kit measurements could include both user-based errors (manual color matching) and kit-based errors (based on test strip colors coming out too light or too dark compared to color chart points corresponding to HG-AAS verified arsenic concentrations).

Based on the results shown in Figure 5.1, the kits were ranked based on three factors. First, the highest overall percentage of user responses in agreement with the HG-AAS measurements led to the following ranking with % agreement value in parenthesis: Econo-Quick (C) [86%] = LaMotte (B) [86%] > Quick II (F) [79%] > Merck (H) [77%] > Quick (E) [76%] > Econo-Quick II (D) [61%] = Wagtech (G) [61%] > Hach (A) [59%]. Second, the overall lowest percentage of user responses indicating a sample was < 50 µg/L when the HG-AAS measurements indicated it was >

50 µg/L (False Positives) led to the following ranking with % false positives in parenthesis: Merck (H) [0%] > Econo-Quick (C) [1%] > Quick (E) [4%] > LaMotte (B) [6%] > Quick II (F) [12%] > Econo-Quick II (D) [39%] = Wagtech (G) [39%] > Hach (A) [40%]. Third, the overall lowest percentage of user responses indicating a sample was > 50 µg/L when the HG-AAS measurements indicated it was <50 µg/L (False Negatives) led to the following ranking with % false negatives in parenthesis: Hach (A) [0%] = Econo-Quick II (D) [0%] = Wagtech (G) [0%] > LaMotte (B) [9%] = Quick II (F) [9%] > Econo-Quick (C) [13%] > Quick (E) [20%] > Merck (H) [23%]. From the overall percentage of responses in agreement with AAS, and considering that False Positives (underestimating arsenic) are far worse than False Negatives (overestimating arsenic) for making decisions about well water safety according to the Bangladesh national standard, it is apparent that the Hach (A), Wagtech (G), and Econo-Quick II (D) were the three most poorly performing kits.

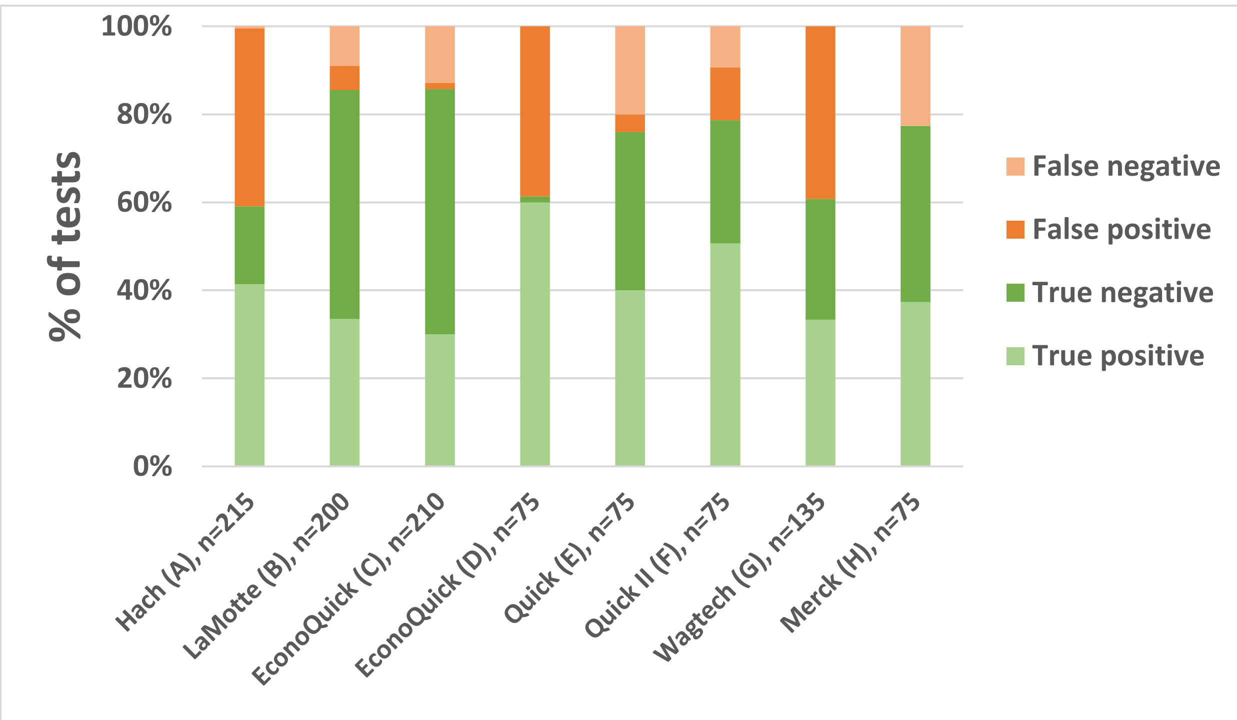

Figure 5. 1. Classification of responses by a panel of five people using field test kits in comparison to laboratory HG-AAS measurements. The panel was asked whether a water sample contained arsenic at a concentration below or above 50 µg/L by color matching of the test strips to standard colors on manufacturer-provided reference charts. Responses in light green show a correct judgement of a sample that was below 50 µg/L (True Positive), while those in dark green indicate a correct judgement of a sample that was above 50 µg/L (True Negative). Responses in light orange indicate an incorrect judgement of a sample below 50 µg/L (False Negative), while those in dark orange indicate an incorrect judgement of a sample that was above 50 µg/L (False Positive). See SI: Figure S5-7 for a logic chart that depicts this convention. The x-axis label includes the total number of panelist observations for each kit represented in the chart.

Figure 5.2 shows arsenic concentrations estimated by the X-Rite color scanner of field test kit results (y-axis) versus the arsenic concentrations measured using HG-AAS (x-axis). Human-based color matching errors were effectively eliminated with the use of a color scanner. Thus, the differences between the X-Rite color scanner results and the HG-AAS results are solely attributable to kit-based errors. Without kit-based errors, results would have an intercept of 0 and a slope equal to 1 (see 'ideal kit' in top left panel). Linear fits to the data in Figure 5.2 show the degree to which a field test kit conformed to this error-free ideal. A slope greater than 1 indicates a positive bias (i.e., the field test kit estimates a higher concentration than the HG-AAS-measured value), while a value less than 1 indicates a negative bias (i.e., the field test kit underestimates the concentration). A lack of linearity and slopes greater than or less than 1 indicate kit-based sources of error in the field test kit measurement. This analysis is similar to the one used in an earlier study for evaluating the relative accuracy and precision of three arsenic field test kits including the Hach kit [23].

As shown in Figure 5.2, the LaMotte (B), Quick (E), and Quick II (F) kits had slopes closest to 1 (1.2-1.3) indicating they were relatively accurate, but with a slight positive bias (tendency to overestimate). The Merck (H) kit had a slope of 0.73 indicating that it was fairly accurate but had a slight negative bias (tendency to underestimate). The Econo-Quick (C) kit had a slope much greater than 1 (~2.0) indicating a large positive bias. The remaining three kits, Hach (A), Econo-Quick II (D), and Wagtech (G) had much lower slopes (0.20-0.41) indicating a substantial negative bias. A high degree of precision was found in case of Econo-Quick (C) (R^2=0.94), LaMotte (B) (R^2=0.88), Wagtech (G) (R^2=0.86), and Quick II (F) (R^2=0.82) kits, implying consistency in measurements across a range of concentrations. In contrast, the linearity was poor for the Quick (E) (R^2=0.63), Merck (H) (R^2=0.54), Hach (A) (R^2=0.47), and Econo-Quick II (D) (R^2=0.33) kits, indicating high variability in field test kit response across several samples.

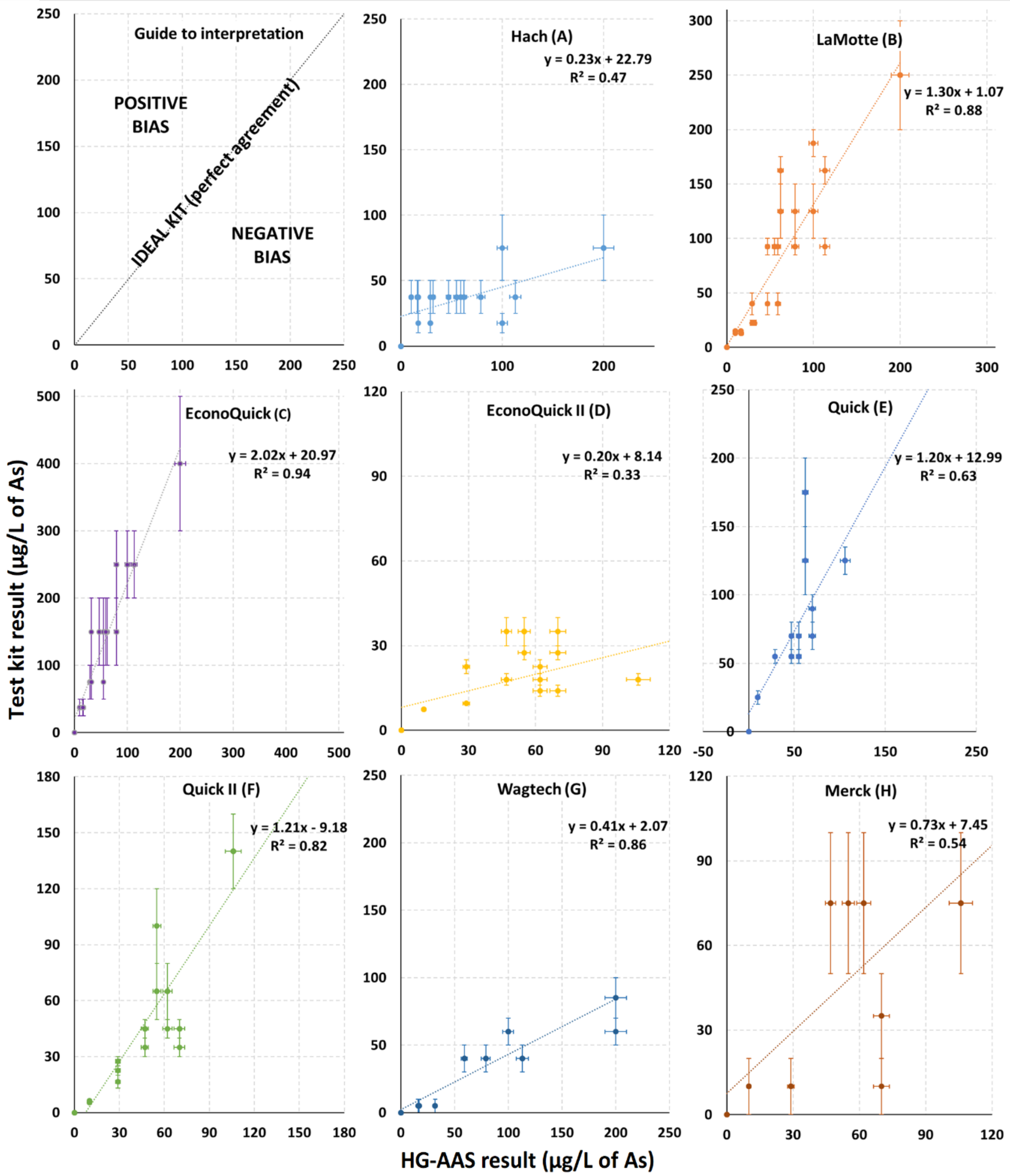

Figure 5. 2. Arsenic concentrations determined by field test kits versus HG-AAS measurements for the same well water samples. The field test kit concentrations are reported as the averages of the two closest color block concentrations on the color chart using the X-Rite color scanner. The field test kit range bars indicate the difference between the two closest blocks. The HG-AAS results are the averages of three replicates with the error bars indicating the standard deviation. The top left panel provides a guide to interpretation. Axes are scaled differently for each field test kit depending on the range of values measured by each kit.

Based on the slope and linearity analyses, the Lamotte (B) and the Quick II (F) kits performed best in terms of accuracy and precision. The Econo-Quick (C), Quick (E), and Merck (H) kits were either accurate or precise but not both. Interestingly, while the Econo-Quick kit showed a high positive bias (tendency to overestimate), it did so in a very consistent manner (R^2=0.94) suggesting that a re-calibrated color chart with darker color blocks would result in better accuracy.

The other three kits, Hach (A), Econo-Quick II (D), and Wagtech (G), performed poorly, primarily due to the high degree of underestimation in their measurements. As a result, samples with concentrations higher than 100 µg/L were assessed by these kits to be below 50 µg/L. Since the result showed poor linearity, a re-calibrated color chart with lighter color blocks is unlikely to fully address these kits' poor accuracy. Furthermore, these results suggest the false-positives in panelist responses (i.e., misclassification of water samples above the drinking water standard as meeting the standard) were largely due to kit-based errors.

The poor performance of the Hach kit is especially concerning given it is currently the most widely used and only readily available kit on the market in Bangladesh. Based on the poor results discussed above, four additional lots of the Hach kit were acquired and tested in Bangladesh between January 2017 and February 2018. The potential interference caused by the optional sulfide removal step in the procedure was also investigated in these additional tests. The results (SI: Section S5-3) confirmed the initial finding that the Hach kit substantially underestimates the concentration of arsenic.

5.7.3 Laboratory-generated color charts

With reference to Figure 5.3, all colors were regenerated from X-rite scans of the test strips or manufacturer charts respectively as described in the methods section. For the manufacturer calibrations, we represented only four points from their respective color charts (0, 25, 50, 100) as these were points that overlapped for all color charts. The authors note that the eye test for the reproduced manufacturer color charts shows some variability (most notably in case of the "zero" values). Scanning artifacts may arise based on the quality of the color chart image and the material on which it is printed. While a reasonable zero value white color blocks resulted from the scans of the paper-based charts for kits B, C, D, E, F, G, scans of the charts of kits A and H produced noticeably darker "off-white" colors compared to unreacted test strips. This problem was particularly acute for the Hach (A) kit, where a laminated color chart affixed to a curved box surface, resulted in a rather dark gray zero concentration block. To overcome this limitation, the Hach "manufacturer calibration" shown in Figure 5.3 (and the analysis based on it in Figure 5.2) was re-generated from a color scan of a re-printed digital image of the Hach (A) color chart from the manufacturer, rather using the color scan of the chart affixed to the kit box. (See Section S5-2 of the supplementary information for a further discussion and resolution of this issue).

As shown in Figure 5.3, laboratory-generated color charts differ substantially from the manufacturer-provided color charts for several kits. The greatest color difference between the manufacturer's and laboratory-generated color charts occurred with the Hach (A) and Econo-Quick II (D) kits, which showed considerable negative bias in Figure 5.2, as well as the Econo-Quick (C) kit, which showed substantial positive bias. These results imply that kit-based calibration errors could be addressed through laboratory calibration of field test kits using known standards, especially when the actual kit performance led to darker color blocks than the manufacturer provided color chart. For all field test kits and samples analyzed, the laboratory color blocks generated from arsenic standards prepared in DI water closely resemble the colors generated from field samples at near equivalent concentrations. This indicates water sample matrix effects are unlikely to have played a significant role in poor kit performance observed in our studies.

Figure 5.3 also illustrates the variability that arises when the same sample is tested multiple times. This variability of color difference among triplicates in Figure 5.3 is a measure of precision. A lack of color reproducibility is seen most clearly with the Hach (A), Econo-Quick II (D), and Merck (H) kits. These kits also showed low R^2 values in Figure 5.2, another indication of non-calibration kit-based precision error. As mentioned previously, laboratory calibration does not address this error. It should be noted that we were unable to generate similar color charts in Figure 5.3 with the LaMotte (B) and Wagtech (G) kits due to logistical challenges obtaining sufficient test strips of these two kits for the additional tests.

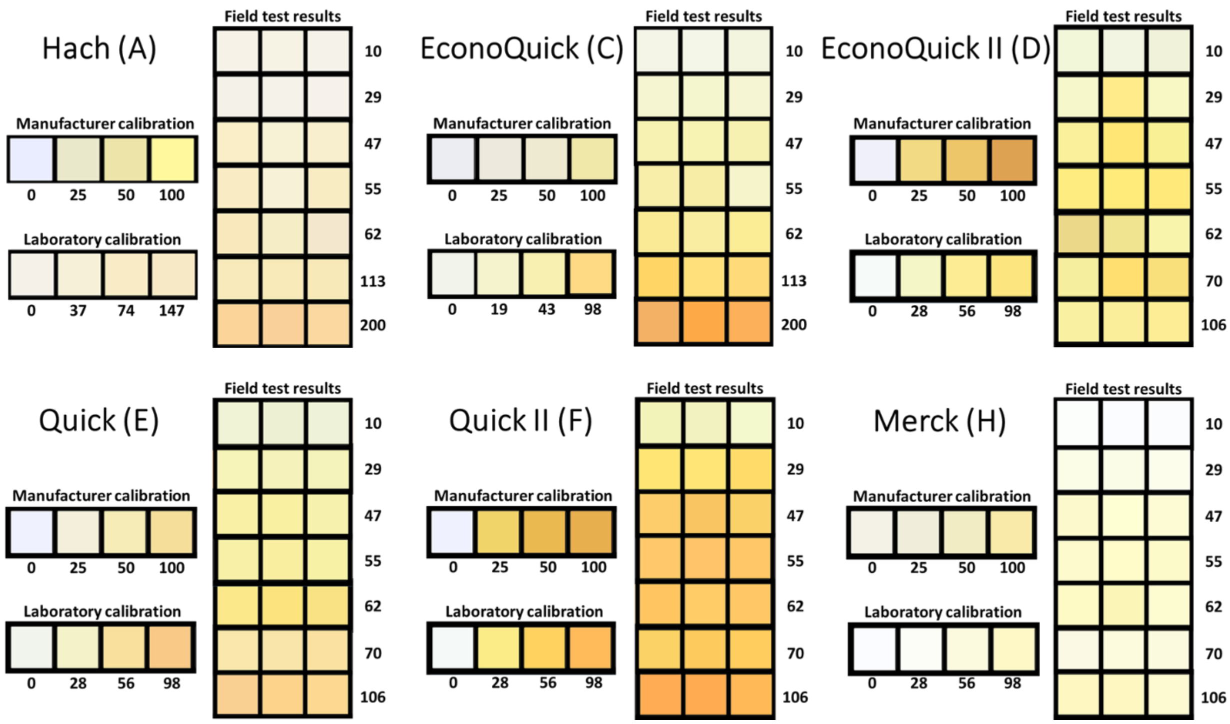

Figure 5. 3. Comparison of manufacturers' color charts (top row left) to laboratory generated color charts from arsenic standards (bottom row left) for each tested kit, with each color tile for the laboratory calibration charts representing the average of triplicate tests. The color tiles from the field test results are provided on the right of calibration charts to show which calibration chart better matches the concentration of the color tiles from the field tests of a given sample by each field test kit. The numbers below the laboratory calibrations color tiles (bottom row left) and numbers given to the right of the field test results color tiles represent actual sample concentrations measured by HG-AAS. All numbers given are µg/L of arsenic.

5.8. Discussion

5.8.1 Implications

In Bangladesh, it is common practice to make decisions on which water sources are safe to use based on a single field test kit result and whether the value is above or below the Bangladesh standard of 50 µg/L [31]. Therefore, it is imperative that the field test kits perform accurately enough for the purpose of classifying samples against the relevant drinking water standards. Furthermore, stakeholders who use these field test kits must understand the potential shortcomings of a kit including its tendency to overestimate or underestimate arsenic concentrations, and the magnitude of precision and accuracy errors.

In this study, the Hach (A), Econo-Quick II (D), and Wagtech (G) tended to underestimate arsenic concentrations leading to false positive assessments as noted previously. A recent study also reported significant underestimation by the Hach (A) kit and the "Quick Econo II" kit [70], but samples were acidified for later kit analysis instead of being tested right away, which could have contributed to the poor results. In the case of Econo-Quick II (D), the recommended diluting and re-testing samples that test above 30 µg/L was not implemented, also a possible source of suboptimal performance. The Hach (A) kit was used in the government-backed well screening program, which tested over five million water access points between 2000-2004. The accuracy of the Hach kit was questioned by a study in 2002 [31]. A subsequent study [53]reported good agreement between Hach kit results and laboratory graphite furnace atomic absorption spectroscopy (GF-AAS) measurements improved accuracy when the reaction time was increased to 40 minutes. Others have found improved performance for the Hach kit with increasing the reaction time as well [23,45,58,59]. Despite these findings, manufacturer-provided instructions continue to state a 20-minute reaction time should be used for the Hach kit, and based on our observations, this is still the procedure followed by government and NGO field test kit users in Bangladesh. Given that the Hach (A) kit is the only readily available field kit on the market in Bangladesh at the time of writing this article, these findings should be cause for concern to NGOs and government employees who use this kit for discerning acceptable water quality.

The LaMotte (B) and Quick II (F) kits performed best, but at more than 4 USD per test, they are also the most expensive (Table 1), and not significantly cheaper than instrument-based laboratory methods (6-30 USD per test), which are more accurate. These performance findings are consistent with previous studies [55,71]. The Quick (E) kit offers slightly lower accuracy at less than half the cost (1.8 USD per test), a finding also consistent with a previous study [72]. It should also be noted that the LaMotte (B), Quick (E) and Quick II (F) kits recommend diluting and re-analyzing samples that test above 30 µg/L, 50 µg/L and 10 µg/L respectively, but this additional step was not performed. It is possible that implementing this step would have further improved the performance of these three kits.

The Econo-Quick (C), Merck (H) and Quick (E) kits were either accurate or precise (but not both) in our study. A prior study using the Merck (H) [33] kit reported good performance and a low rate of misclassification of the true arsenic concentration based on color matching to the manufacturer provided color charts. The Econo-Quick (C) kit is the cheapest kit (0.6 USD per test) among the group we tested. A study by [55] reported average performance of the kit with a negative bias in the limited samples tested. More recent and extensive studies with the kit have indicated good performance [23,60] but with a positive bias at higher concentrations. Another study [57] indicates that the Econo-Quick kit showed high agreement (97%) with laboratory methods when used on groundwater samples but lower agreement (68%) when used on surface waters suggesting the potential of matrix affects with surface water. A very recent study [73] reports that the kit tends to overestimate by a factor of two the arsenic concentrations above 50 µg/L, with a very low rate of false positives (samples that were actually higher than the drinking water standard being classified as meeting standard). In our study we saw this tendency to overestimate by a factor of two across the entire range of arsenic concentrations tested (10-200 µg/L for this kit). However, we acknowledge that our sample size in this concentration range is limited. The most recent Multiple Index Cluster Survey report [14] utilized the Econo-Quick (C) kit. This kit has the potential to offer a more reliable alternative to the Hach kit in Bangladesh, at a similar cost per test. The substantial but consistent positive bias we observed with this kit could be corrected by recalibration. Even without recalibration, it is a superior alternative as the health implications of overestimating arsenic concentration are far less severe than those associated with underestimating it.

Given that our study did not investigate variability between multiple lots of a kit, except for the Hach kit, it is possible that the findings for other kits may not be representative of performance averaged over multiple lots. Repeating these tests over several different lots of each kit would build a stronger body of evidence of the relative performance of each kit as reported here, and whether quality control is a general concern from one kit to the next.

5.8.2 Ease of use

User preference and ability to perform field test kit procedures accurately can be influenced by the ease of use of a field test kit [74]. Field test kits were assessed based on the ease of use considering several factors that were identified through interviews of field test kit users. These included a) Procedure (number of active steps, number of reagents), b) Packaging (reagent packaging, bottle/cap/overall packaging), c) Color chart (range of concentrations, type of color chart (eg. paper, paper with a viewing aperture in the middle of color tile, printed on bottle etc), number of color tiles around 10 µg/L, number of color tiles around 50 µg/L) and d) Instruction manual (language, instruction clarity). The authors also subjectively ranked the kits against each parameter (see SI, Table S5-1).

The procedures and packaging for Hach (A), Wagtech (G), and Merck (H) kits were rated highly (e.g., the procedures were easy to follow, and the reagent packaging made it simple to use). However, their color charts and instruction manuals did not rate as well when compared to others. The LaMotte (B), Econo-Quick (C), Econo-Quick II (D), Quick (E), and Quick II (F) procedures ranked lower, but their color charts and the clarity of instruction manuals generally rated higher.

5.9 Conclusions

The findings of this study raise concerns with the performance of several of the kits tested, especially those that underestimate arsenic concentration and result in false positives. The findings were similar across a range of field samples (including engineered and natural water sources) and laboratory standards, which demonstrates poor results across a broad range of sample matrices and concentrations.

One way of addressing kit-based errors due to manufacturer calibration chart bias is to use custom calibrations - color scanner generated color blocks of verified arsenic standard solutions for a given kit. This offers a promising option for making the Econo-Quick (C) kit, which showed a consistent positive bias, more accurate. However, this approach does not address all errors associated with poorly performing kits, such as the Hach (A) and Econo-Quick II (D) kits, which in addition to high inaccuracy in the 10-100 µg/L range, also exhibited poor reproducibility and low color intensity making color matching unreliable. For the Hach kit, in particular, the manufacturer should consider the results of a number of studies cited in this work that indicate the current kit with a reaction time of 20 minutes is inadequate, and either modify the kit chemical component amounts or the procedures including reaction time accordingly so that the color chart provided is more representative of the kit's actual performance in the field.

More broadly, the results of this study suggest that field test kit results should be viewed only as a preliminary indication of potential arsenic contamination. Stakeholders should carefully consider whether the benefits of using periodic field test kit results outweigh the risks of an inaccurate assessment and a false positive result versus conducting a more accurate and expensive laboratory instrumental analysis of water samples. At a minimum, re-testing samples found to be close to the relevant drinking water standard (e.g., 10 or 50 µg/L) would be prudent to reduce the number of misclassified drinking water sources as safe (or below the national arsenic standard) when they are not. Before use, manufacturers and users of arsenic field test kits would benefit by being able to evaluate each kit against a verified arsenic standard in order to confirm that the calibration chart provided by a manufacturer accurately reflects the colors produced by the kit. The Industrial Testing Systems (ITS) kits (Econo-Quick (C), Econo-Quick II (D), Quick (E) and Quick II (F)) recommend testing a diluted inorganic standard for familiarization with the kit while the Merck (H) kit procedure suggests it as a quality assurance protocol, but neither kit provides a standard which leads us to believe that this would rarely happen in practice. Manufacturers should consider producing certified standards in the concentrations of interest for high volume test kit users to purchase for quality assurance. If challenges of safety and stability can be ensured, providing aliquots of a verified arsenic standard in each kit would allow users to test whether the kit is performing consistently with the color chart provided in the concentration range of interest.

5.10 Associated Content

5.10.1 Supporting Information

Supplemental information is provided on the color theory used for instrumental color matching; additional Hach (A) kit tests with and without the optional sulfide removal step; comparing methods for analysis of Hach (A) color data; logic chart depicting convention of terminology used while discussing test kit results; ease of use ranking table; water sample source and characteristics; tables with specifications of the various field test kits used in the study including date of expiry and lot number.

5.10.2 Declaration of interests

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

5.11 Acknowledgements

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5.12 Supporting Information:

Section S5-1: Instrumental color matching

A color metric (ΔE) was used to find the closest match between the color of the sample test strip and the standard colors representing concentrations on the reference chart, based on the relationship among the lightness (L), color (C), and hue (H) values, and (ΔE) as shown in Equation 1 below. The metric CMC Color Difference Formula shown in Equation 1 is based on a lightness:chroma (l:c) ratio of 2:1, a ratio considered optimal for perceiving color differences by the human eye.

$$\Delta E = \sqrt{\left(\frac{\Delta L}{l S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{c S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H}\right)^2} \qquad \text{Eq. 1}$$

where:

$$S_L = \begin{cases} \dfrac{0.040975 L^*_S}{(1 + 0.01765 L^*_S}, & if\ L^*_S \geq 16 \\ 0.511, & if\ L^*_S < 16 \end{cases}$$

$$S_C = \frac{0.638 + 0.0638 C^*_{ab,S}}{\left(1 + 0.01315 C^*_{ab,S}\right)}$$

$$S_H = S_C(TF + 1 - F)$$

$$F = \sqrt{\frac{\left(C_{ab,S}\right)^4}{\left(\left(C_{ab,S}\right)^4 + 1900\right)}}$$

$$T = \begin{cases} 0.36 + \left|0.4\cos\left(h_{ab,S} + 35\right)\right|, & if\ h_{ab,S} \leq 164\ or\ h_{ab,S} \geq 345 \\ 0.56 + \left|0.2\cos\left(h_{ab,S} + 168\right)\right|, & if\ 164 < h_{ab,S} < 345 \end{cases}$$

ΔL is the difference between L value (lightness) of the test strip color and the reference color,

ΔC^*_{ab} is the difference between C value (chroma) of the test strip color and the reference color,

ΔH^*_{ab} is the difference between H value (hue) of the test strip color and the reference color, and

$h_{ab,S}$ is the H value (hue) of the reference color.

l = 2, c =1 for optimal perception of color differences by the human eye.

To find the closest color match of the test strip to the reference chart's standard colors, each X-Rite sample scan was compared to X-Rite scans of the reference chart colors, and then ΔE for each comparison was calculated. The smallest ΔE represents the "least distance" or closest match between the sample and one of the provided reference color chart concentration values. The second closest match was then used to define a concentration color chart range within which the sample concentration was estimated. These X-Rite scan results were also used to answer the question of whether the sample concentration was below or above 50 µg/L and compared to the user panel's response. This allowed the differentiation between a user's ability to make accurate color comparisons compared to the scanner, and thereby to assess color matching errors made by the users. The ΔE metric was also used to evaluate the suitability of the manufacturer provided color chart for identifying water samples falling below or above relevant drinking water standards. A trained eye can perceive ΔE differences above 1, while a difference of greater than 3 can be perceived by most people.

Section S5-2: Analyses of Hach (A) kit color data

As discussed in the paper, the eye test for reproduced manufacturers color charts from scanner data showed some variation from the actual color charts. While we expect there to be artefacts of scanning and reproducing colors this difference was particularly acute in case of the Hach (A) kit (see Figure S5-4 and S5-5). We believe this was due to the difficulty in scanning of a curved surface and the poor quality of the Hach (A) color chart (see Figure S5-1 and S5-3) on the kit boxes that we used. We were able to obtain a digital copy of the color chart from Hach (Figure S5-2 and S5-3) which enabled us to analyze data in three different ways. This section discusses the three approaches that were used to analyze the Hach kit data.

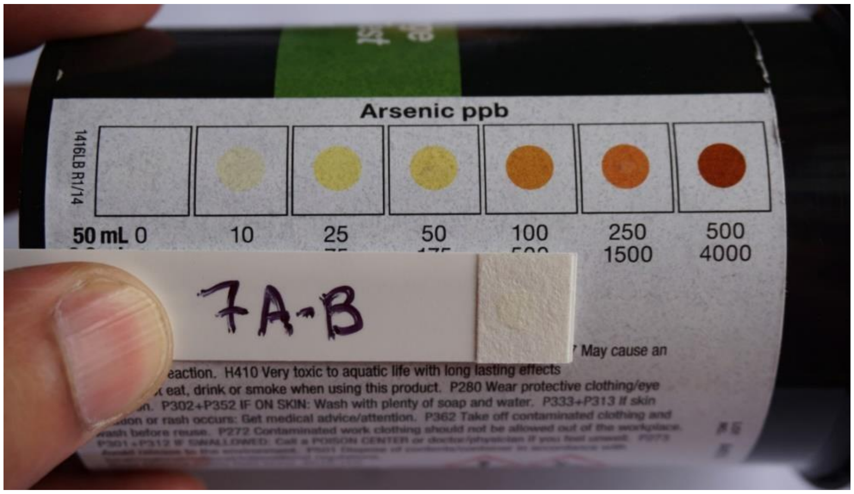

Figure S5- 1. Picture of a Hach (A) test strip and the manufacture provided color chart that is pasted into the kit box. The color tiles are grainy and appear slightly greyish. As an aside, the concentration of arsenic in the sample 7A-B was 79±4 µg/L of arsenic, and the test kit result pictured above is one example of the severe underestimation that we observed when using the Hach (A) kit.

Figure S5- 2. Digital image of the Hach (A) color chart obtained from the manufacturer.

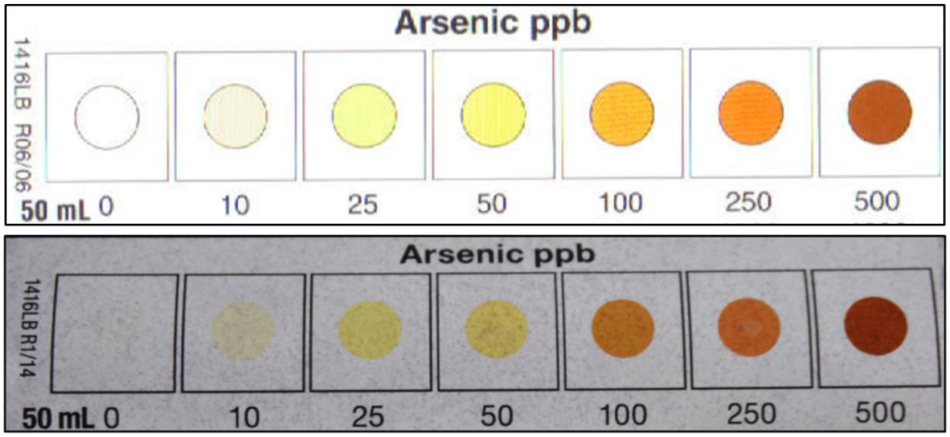

Figure S5- 3 Comparison of the color charts from manufacturer provided digital image (top panel) and a picture of the color chart from a Hach (A) kit box we tested (bottom panel). These images are cropped portions of the images in Figures S5-1 and S5-2.

Method 1 (the standard approach used for all other kits) involved scanning the color chart provided with the kit and reproducing color blocks based on this data in the manner described in the methods section of the main text. As discussed above, the quality of color chart and the fact that it was pasted on a curved box are likely to have impacted the accuracy of this approach and the reproduced color charts using this method looked quite different from the color chart on the kit box(see Figure S5-4). Method 2 involved reading color directly from the digital image using a computer software (in this case the Digital Color Meter application provided with mac OS Catalina) and using this color data for analyses. Method 3 involved printing the digital image of the color chart on paper, scanning the color blocks and using this color data for analyses.

Analyses of data by the three approaches is presented in Figure S5-4. All three approaches indicate poor accuracy and significant underestimation seen in the Hach (A) kit measurements with the slope value ranging from 0.18-0.30. In case of Method I and III the R^2 values of the linear fit were low (0.50 and 0.47 respectively) indicating poor precision. In case of Method II the R^2 value of the linear fit was 0.76, indicating better linearity. Ultimately while we believe the approach in Method III to be most defensible approach for the Hach (A) kit in our study all three methods indicate poor performance. Analysis based on Method III is presented in the main text.

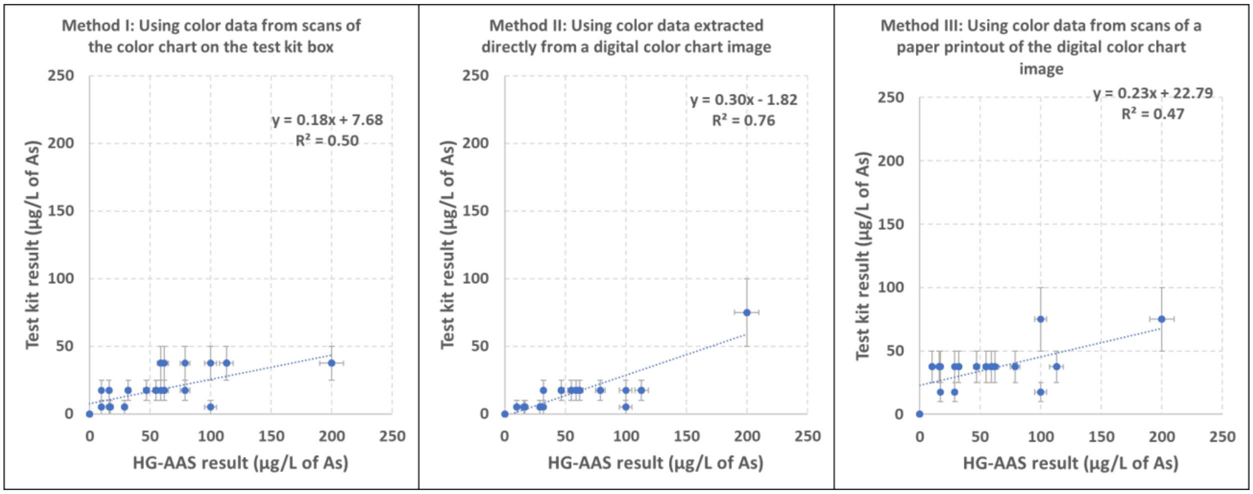

Figure S5- 4 Analyses of Hach field test results using the three methods described above to process data for the reference color chart. This analysis is the equivalent of that presented in Figure 5.2 of the main text.

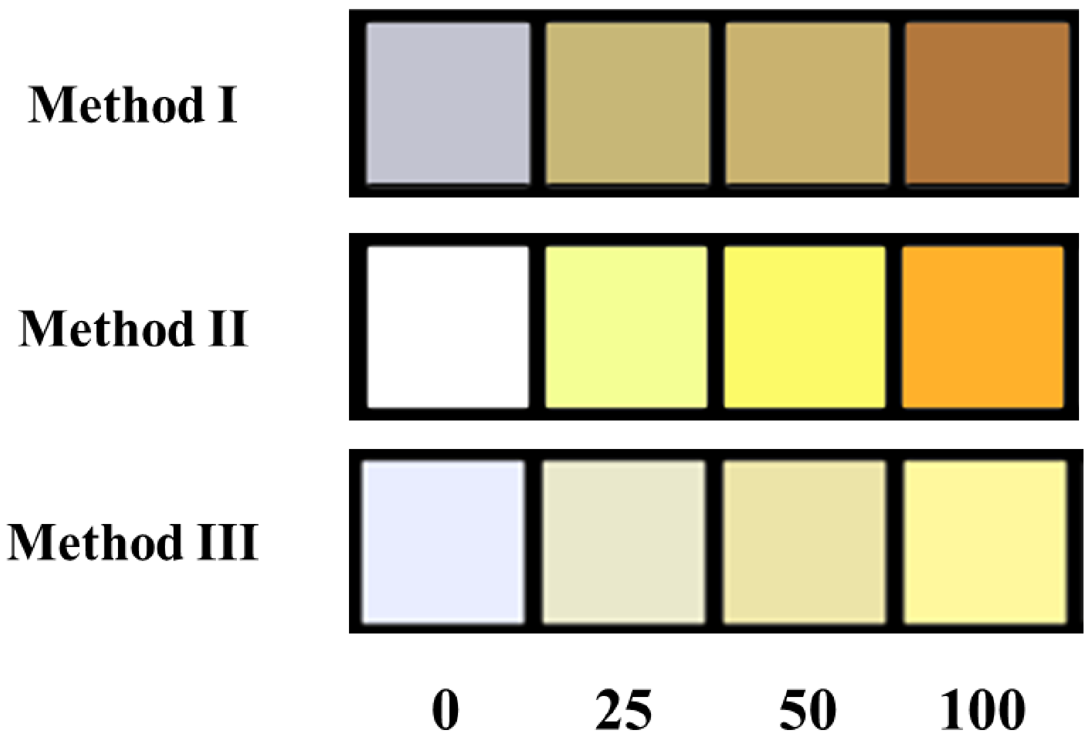

Figure S5- 5 Comparison of reproduced Hach (A) color charts using the three methods described above. The numbers at the bottom row indicate the corresponding arsenic concentration level in µg/L to each color block above. This data is the equivalent of that presented in the top left panels in Figure 5.3 of the main text**.**

Section S5-3: Additional tests with the Hach (A) kit comparing results with and without the optional sulfide removal step

The Hach kit included an optional procedural step for sulfide removal. We didn't expect sulfide in our field or laboratory samples but included this step for all kits that offered it to eliminate the chance of interference and be consistent in evaluations. For the Hach kit this step involved placing a lead acetate-soaked cotton plug at the opening of the reactor bottle lid. Considering the poor performance of the Hach kit the authors of this study wanted to investigate whether this step influenced the arsenic measurement and ran a set of tests with and without the optional step.

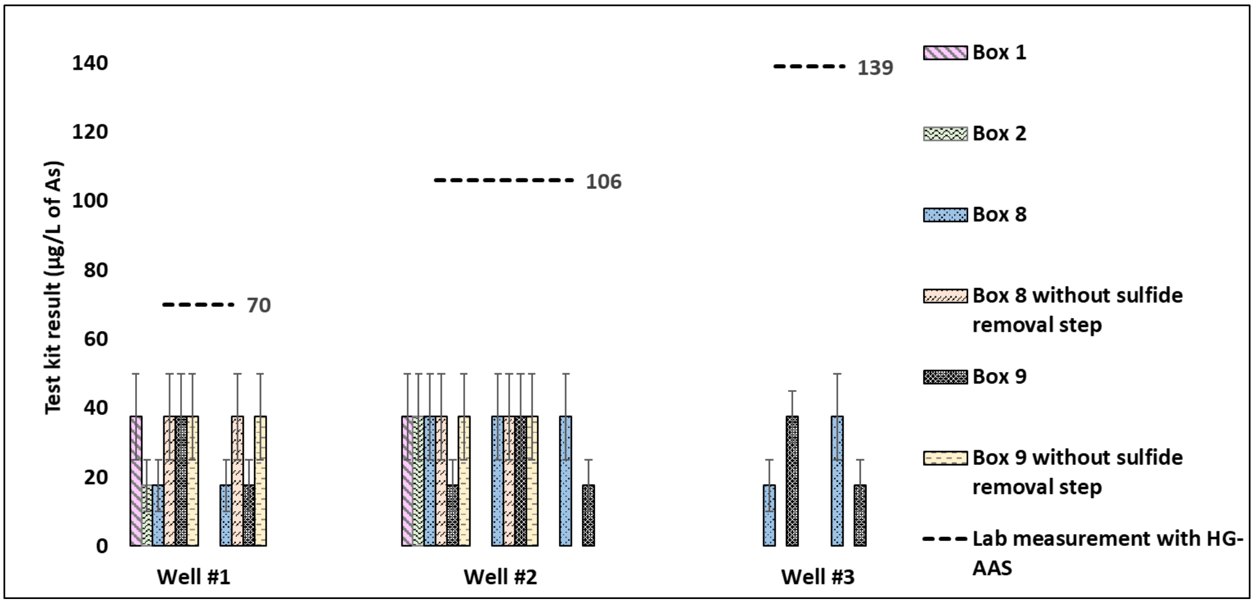

Figure S5- 6 Evaluation of additional Hach kit boxes, including trials with and without the optional sulfide stage. The test kit concentrations are reported as the averages of the two closest color block concentrations on the color chart using the X-Rite color scanner. The range bars indicate the difference between the two closest blocks. Details about the boxes used are given in Table S5-4.

Well water containing 70 ± 4, 106 ± 6, and 139 ± 7 µg/L of arsenic (concentrations measured by HG-AAS are indicated by the dashed lines in Figure S5-1) resulted in Hach kit estimates of below 50 µg/L with all four boxes. This finding was consistent across trials with and without the sulfide removal stage. As discussed in the main paper, the Hach kit's poor performance results from kit-based errors, viz., test strips with significantly lighter color than the color blocks provided on the manufacturer calibration color charts for equivalent concentration ranges.

Section S5-4. Logic chart depicting convention of terminology used when discussing field kit results

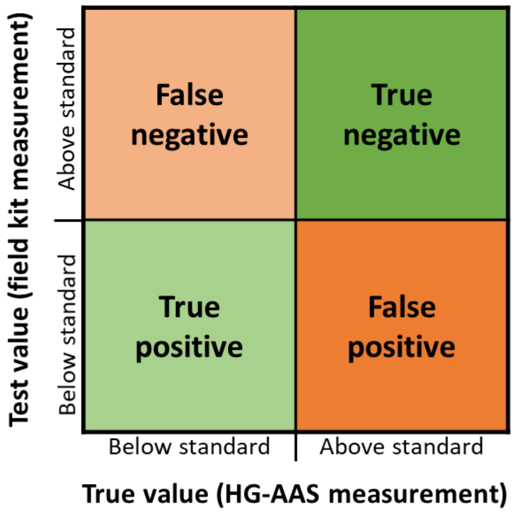

Figure S5- 7 Logic chart depicting convention used in defining False Positives and False Negatives. A True Positive is when a sample whose concentration is below standard is correctly assessed by the test kit as being below standard. A False Positive is when a sample whose concentration is above the standard is incorrectly assessed by the test kit as being below the standard. A False Negative is when a sample whose concentration lies below the standard is incorrectly assessed by the test kit as being above the standard. A True Negative is when a sample whose concentration is above the standard is correctly assessed by the kit as being above the standard.

Section S5-5. Ease of use ratings for each kit

Table S5- 1 Ease of use ratings for each kit included in this study. Ratings done by three of the authors based on parameters identified through kit user interactions.

Rating category	Hach (A)	LaMotte (B)	Econo-Quick (C)	Econo-quick II (D)	Quick (E)	Quick II (F)	Wagtech (G)	Merck (H)
Procedure	4	2	2	2	2	2	4	4
Packaging	4	4	3	4	3	4	4	4
Color chart	1	5	4	4	4	5	3	1
Instruction	2	4	5	5	5	5	3	3
Average	2	3.75	3.5	3.7	3.	4	3.5	3
1 = Poor 2 = Below average 3 = Average 4 = Above average 5 = Excellent								

Section S5-6. Water sample characteristics and field test kit details

Table S5- 2 Water sample source and characteristics

Sample code	Temperature (°C)	pH	Sample collection location	Sample source
W1	28.2	6.04	Asia Arsenic Network laboratory, Jessore	Lab dilution of an arsenic standard
W2	28.4	5.15	Asia Arsenic Network laboratory, Jessore	Lab dilution of an arsenic standard
W3	28.5	7.05	Phulsara union, Jessore	Dug well sand filter (raw water)
W4	29.1	7.95	Phulsara union, Jessore	Arsenic Iron Removal Plant (treated water)
W5	26.7	6.87	Phulsara union, Jessore	Arsenic Iron Removal Plant (raw water)
W6	28.4	7.95	Phulsara union, Jessore	Arsenic Iron Removal Plant (treated water)
W7	29.8	5.39	Asia Arsenic Network laboratory, Jessore	Lab dilution of an arsenic standard
W8	28.3	7.14	Phulsara union, Jessore	Shallow tube well
W9	28.5	7.05	Phulsara union, Jessore	Shallow tube well

W10	21.6	7.09	Phulsara union, Jessore	Dug well sand filter (raw water)
W11	19.1	7.92	Phulsara union, Jessore	Arsenic Iron Removal Plant (treated water)
W12	20.4	7.72	Phulsara union, Jessore	Mixed: Shallow tube well + dug well @1:2
W13	19.7	7.89	Phulsara union, Jessore	Arsenic Iron Removal Plant (treated water)
W14	23.5	7.36	Phulsara union, Jessore	Arsenic Iron Removal Plant (treated water)
W15	21.7	7.32	Phulsara union, Jessore	Mixed: Shallow tube well + dug well @2:3
W16	21.2	7.34	Phulsara union, Jessore	Mixed: Arsenic Iron Removal Plant Raw and Treated water @1:3
W17	23.1	7.20	Phulsara union, Jessore	Arsenic Iron Removal Plant (raw water)
W29	27.4	7.12	Phulsara union, Jessore	Shallow tube well
W30	28.9	7.02	Phulsara union, Jessore	Shallow tube well
W31	27.1	7.13	Phulsara union, Jessore	Shallow tube well
W32	28.4	6.22	Asia Arsenic Network laboratory, Jessore	Lab dilution of an arsenic standard

Table S5- 3 Specifications of Hach (A) test kits used, which were purchased in Bangladesh

Box number		1	2	8	9
Date purchased		June 2016	Jan. 2017	June 2017	June 2017
Box	Lot	A4350	A5143	A51428	NA
	Expiration	NA	NA	NA	NA
Test Strip	Lot	A4275	A5105	A5105	A5105
	Expiration	Oct-19	Oct-19	Oct-19	Oct-19
Reagent 1 (Sulphamic acid)	Lot	A4136	A5072	A5072	A5159
	Expiration	May-19	Mar-20	Mar-20	May-20
Reagent 2 (Zinc)	Lot	A4351	A4352	A4349	A5245
	Expiration	Dec-19	Dec-19	Dec-19	Aug-20
Lead acetate	Lot	A4309	A5068	A5068	A5245
	Expiration	Nov-19	Mar-20	Mar-20	Sep-20

[1] This kit was purchased without a ‘box’ as a 'refill pack'. Hence the Box number has been marked NA.

Table S5- 4 Specifications of LaMotte (B) test kit, which was purchased in Bangladesh

Date purchased		July 2016
Box	Lot	236608
	Expiration	NA
Test Strip	Lot	53213
	Expiration	Jul-18
Reagent 1	Lot	156415
	Expiration	NA
Reagent 2	Lot	216525
	Expiration	NA
Reagent 3	Lot	216526
	Expiration	NA

Table S5- 5 Specifications of Econo-Quick (C) test kits, which were purchased in Bangladesh

Box number		1	2
Date purchased		June 2016	Dec.
Box	Lot	NA	NA
	Expiration	NA	NA
Test Strip	Lot	120214	120214
	Expiration	Dec-17	Dec-17
Reagent 1	Lot	12615	11515
	Expiration	Jan-18	Jan-18
Reagent 2	Lot	0115	0115
	Expiration	Feb-18	Feb-18
Reagent 3	Lot	120214	120214
	Expiration	Feb-18	Feb-18

Table S5- 6 Specifications of Econo-Quick II (D) test kit, which was purchased in the USA

Date purchased		May 2016
Box	Lot	NA
	Expiration	NA
Test Strip	Lot	NA
	Expiration	Apr-18
Reagent 1	Lot	09115
	Expiration	Sep-18
Reagent 2	Lot	UN1759
	Expiration	NA
Reagent 3	Lot	9035
	Expiration	NA

Table S5- 7 Specifications of Quick (E) test kit, which was purchased in the USA

Date purchased		May 2016
Box	Lot	NA
	Expiration	NA
Test Strip	Lot	2216
	Expiration	Jul-18
Reagent 1	Lot	031416
	Expiration	Mar-19
Reagent 2	Lot	UN1759
	Expiration	NA
Reagent 3	Lot	9035
	Expiration	Jul-21

Table S5- 8 Specifications of Quick II (F) test kits, which were purchased in the USA

Date purchased		May 2016	May 2016
Box	Lot	NA	NA
	Expiration	NA	NA
Test Strip	Lot	091115B	31516
	Expiration	Sep-18	Mar-19
Reagent 1	Lot	UN1759	UN1759
	Expiration	NA	NA
Reagent 2	Lot	9035	9035
	Expiration	Jul-21	Jul-21
Reagent 3	Lot	NA	NA
	Expiration	Apr-18	Apr-18

Table S5- 9 Specifications of Wagtech (G) test kit, which was purchased in Bangladesh

Date purchased		Oct. 2015
Box	Lot	NA
	Expiration date	NA
Test Strip	Lot	NA
	Expiration date	NA
A1 powder sachet	Lot	M11B
	Expiration date	Nov-16
Reagent 2	Lot	114319
	Date of manufacture	Jun-12

Table S5- 10 Specifications of Merck (H) test kit, which was purchased in Bangladesh

Date purchased		July 2016
Box	Lot	HC553816
	Expiration	Mar-18
Test Strip	Lot	NA
	Expiration	Mar-18
Reagent 1	Lot	NA
	Expiration	Mar-18
Reagent 2	Lot	NA
	Expiration	Mar-18

Chapter 6: Recommendations for Stakeholders and Policy Makers Involved with Water Supply in Bangladesh

6.1 Introduction

This chapter is intended to provide recommendations for the broad set of stakeholders involved with drinking water supply in Bangladesh. As discussed in Chapter 1, this dissertation was part of an integrated assessment study performed by University of Michigan researchers in collaboration with Asia Arsenic Network, a water focused Bangladeshi NGO. The study aimed to characterize existing barriers to the long-term sustainability of safe water supply in Bangladesh and identify solutions that can address these barriers. We conducted field work in Phulsara and Goga unions in southwest Bangladesh. This chapter summarizes the recommendations to various stakeholders that were derived from the various studies presented in Chapters 2-5. Even though the work was conducted in only two unions in southwest Bangladesh, many of the recommendations are relevant in other arsenic affected parts of rural Bangladesh. The summary and recommendations provided in this chapter are intended to serve as a readily accessible document for the wide range of water supply stakeholders in Bangladesh. The executive summary and recommendations below along with reports and other outputs from the study will also be relayed directly to the specific stakeholder groups.

6.2 Executive summary

Arsenic exposure through using groundwater as a drinking water source remains a major public health concern in Bangladesh, despite considerable mitigation efforts over the past two decades. The most recent Multiple Index Cluster Survey conducted by the Government of Bangladesh and UNICEF in 2012-2013[14] indicated that approximately 20 million people were drinking water with arsenic levels above the national drinking water standard of 50 µg/L and that over 40 million people were using drinking water with arsenic levels above the World Health Organization (WHO) standard of 10 μg/L. Clearly, arsenic mitigation remains an urgent and unmet priority for Bangladesh.

Researchers at the University of Michigan (Ann Arbor, USA) in collaboration with Asia Arsenic Network (Jessore, Bangladesh), a water focused NGO, conducted this study aimed at elucidating barriers to reducing arsenic exposure and identifying opportunities to address these barriers. Field work was conducted in Phulsara and Goga unions, Jessore district in southwest Bangladesh, but findings and recommendations are likely valid across rural Bangladesh. The purpose of this communication is to share findings and recommendations with the broad range of water supply stakeholders in Bangladesh. Some recommendations specific for Phulsara and Goga unions are provided as well.

The key findings of this study are as follows:

- Arsenic monitoring infrastructure in Bangladesh is limited, and the current levels of water quality testing are insufficient.
    - Arsenic field test kits often significantly underestimate arsenic levels in water sources. We studied eight commercially available field kits including the Hach EZ and Econo-Quick kits, which are commonly used in Bangladesh. The Hach EZ kit results were variable but consistently underestimated arsenic levels. The Econo-Quick kit was more consistent but tended to overestimate arsenic levels. While some of the other kits we tested performed well in terms of both accuracy and precision, they were significantly more expensive than the Hach EZ and Econo-Quick kits. The complete report[32] can be accessed free of cost at the following link https://doi.org/10.1016/j.watres.2019.115325.
    - Access to water quality testing is severely limited in arsenic affected areas. Laboratory infrastructure is difficult to access for most rural communities due to the distance and costs involved. Field test kits are commonly available at union parishad or upazilla parishad but, in addition to the concerns with test kit quality mentioned above, this method relies on households collecting and transporting water samples to the test location, which is a significant barrier.

  - Commercial laboratory infrastructure for arsenic measurement in Bangladesh lacks oversight. Only a small fraction of the commercial laboratories offering arsenic analyses are accredited and regularly audited for quality control.
  - Despite being identified as a key priority in the Arsenic Mitigation Policy (2004), Bangladesh lacks a locally manufactured field test kit. Access to a locally produced field test kit has the potential to reduce cost and improve the reliability of supply, which are important factors in improving the monitoring of arsenic in drinking water sources.
  - Awareness of water quality among rural households is poor with only about 40% of households reporting that they knew their drinking water source had tested arsenic safe. Further, arsenic testing takes place infrequently with only 5% of households surveyed indicating their water source had been tested in the preceding 12-month period.
- Existing mitigation strategies do not align well with user behaviors leading to high levels of arsenic exposure. The complete study report can be found in Chapter 2.
  - As many as 75% of households continued to drink shallow tube well water despite knowledge of high levels of arsenic in shallow groundwater and the availability of community safe water infrastructure.
  - About 40% of community safe water infrastructure was not operational, whereas about 20% was operational but provided water with arsenic levels above the Bangladesh drinking water standard. Only about 40% of the community safe water infrastructure was operational and provided water that tested below the Bangladesh drinking water standard.
  - Spatial analyses of water supply points and household locations indicated that only about one quarter of households were within 150 m of a functional safe water point. Further, many of these systems were in close proximity indicating a need for better water supply planning and coordination between implementing agencies and the government.
- A low-cost educational intervention among households consuming arsenic contaminated water can lead to significant reduction in arsenic exposure. The detailed findings behind this conclusion are available in Chapter 3.

  - Through a randomized control trial study, we showed that providing arsenic awareness, household water quality information and a recommendation for improved water quality led to a ~20% reduction in the number of households drinking arsenic contaminated water. However, repeating this intervention did not further reduce exposure.
  - The intervention cost was 750 BDT or 9 USD per household and this cost could have been lowered by 30-40% through the careful use of field test kits instead of laboratory analyses.
  - This informational intervention provides a relatively low-cost approach to reducing the burden of arsenic exposure in high priority areas.

6.3 Recommendations to water supply stakeholders

6.3.1 Recommendations to the Government of Bangladesh

- Arsenic mitigation efforts need a renewed sense of urgency. Since the early 2000s, the issue has faded from the spotlight, but exposure to arsenic and the associated health effects remain a massive public health crisis. Continuing educational programming and regular monitoring of existing community safe water points and private tube wells, which are rapidly growing in numbers, should be an urgent priority.
- Access to water quality monitoring for rural households needs to be improved.
  - Continued blanket well screenings remain beneficial. Additionally, door-step access to testing in rural communities would cater to an existing demand for more frequent water testing.
  - Laboratory testing infrastructure needs to be expanded and requires oversight to ensure quality control.
  - Field test kit use must be carefully scrutinized as results of commonly used kits can often be inaccurate. Given the convenience and relatively low costs of field test kits, expanding their availability, while ensuring their accuracy, deserves attention. Developing locally manufactured field test kits remains an unmet priority.
- Water supply planning must incorporate spatial geographic analyses. Better co-ordination among implementing agencies can improve the effectiveness of mitigation efforts.

6.3.2 Recommendations to the donor community

- Arsenic mitigation efforts should include robust monitoring and evaluation. Several studies indicate that the majority of community safe water points cease to function within three years of installation and a long-term approach is essential to achieve sustainability[19,26].
- Educational programming in rural communities is essential to generate adequate demand for improved water quality and better participation in the management of community owned infrastructure.
- More robust systems of community infrastructure management are needed. This includes:
  - Ensuring strong local expertise to troubleshoot and manage community water supply systems.
  - Incentivizing the role of a designated caretaker or outsourcing this role to a local trained mechanic. Giving the responsibility for the upkeep of community water infrastructure to a volunteer caretaker does not appear to work well.
  - Incorporating a schedule of regular water quality testing and preventive maintenance events.
  - Aiming for financial sustainability. Most user communities have no corpus of funds to fall back on making anything more than a minor repair infeasible to pursue. Encountering such a scenario without the necessary capacity to address leads to a debilitating dependence on external donor driven interventions, the absence of which can lead to the system being abandoned.
- Arsenic testing methods need to be carefully selected. While field kits provide convenience of use and lower cost, they are often inaccurate and prone to various errors in measurement. When field kits are used, we strongly recommend verifying the accuracy of each box against an arsenic reference standard and adopting quality control measures.

6.3.3 Recommendations to implementation partners

- Field test kits have several sources of potential error and must be used carefully.
  - Each box of test kits should be evaluated using a laboratory standard to identify potentially faulty test kit boxes.
  - Test kit procedures should be standardized among testers.

    - Most test strips contain mercury bromide, which is harmful through dermal exposure. Test kit users should handle the strips very carefully to avoid contamination and dispose used test kits carefully and appropriately.

6.3.4 Recommendations to field test kit manufacturers

- Providing an internal standard in each test kit box to verify the accuracy of tests would help users identify faulty kit boxes.
- Individually packaged reagents or smaller aliquots are preferred by users and could help retain regent quality especially for hygroscopic or light sensitive components.
- Color charts printed on paper that resembles the test strip in texture and finish makes for easier evaluation of test results.
- Color charts should be designed with reference color blocks that clearly differentiate concentrations relevant to drinking water standards. For example, in the case of several commonly used kits, the colors corresponding to 10 and 50 μg/l of arsenic are too similar making it very hard to manually assess differences.

6.3.5 Recommendations to the Union Parishad council in Phulsara Union

- Arsenic mitigation needs a renewed sense of urgency. Over 50% of the households in Phulsara Union are drinking arsenic contaminated water. This is largely because over 90% of households in Phulsara union drank water from a shallow tube well. The community safe water infrastructure was in poor condition with only one quarter of the systems operational and providing arsenic safe water.
- Educational messaging on arsenic must be continuously reinforced. This will encourage households with access to improved water quality to make changes to their water use behavior. Further, it will encourage better participation and contributions toward community operated safe water infrastructure.
- Field test kits have several sources of potential error and must be used carefully.
    - Each box of test kits should be tested against a laboratory standard to identify potentially faulty test kit boxes.
    - Test kit procedures should be standardized among testers.
    - Most test strips contain mercury bromide, which is harmful through dermal exposure. Test kit users should handle the strips very carefully to avoid

contamination and store used strips separately after the test is complete until appropriate disposal.

6.3.6 Recommendations to the Union Parishad council in Goga Union

- Arsenic mitigation needs a renewed sense of urgency. Approximately 60% of households in Goga union drank water provided by a shallow tube well, leading to potentially high levels of arsenic exposure. Almost 60% of the community safe water systems were providing arsenic safe water, but about 30% of systems were not operational.
- Educational messaging on arsenic must be continuously reinforced. This will encourage households with access to improved water quality to make changes to their water use behavior. Further it will encourage better participation and contributions toward community operated safe water infrastructure.
- Field test kits have several sources of potential error and must be used carefully.
    - Each box of test kits should be tested against a laboratory standard to identify potentially faulty test kit boxes.
    - Test kit procedures should be standardized among testers.
    - Most test strips contain mercury bromide, which is harmful through dermal exposure. Test kit users should handle the strips very carefully to avoid contamination and store used strips separately after the test is complete until appropriate disposal.

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