Arsenic: Risk, Exposure, Policy and Management

Nadia Binte Jamil

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Arsenic: Risk, Exposure, Policy and Management

A DISSERTATION

Submitted to the Faculty of
Montclair State University in partial fulfillment
of the requirements
for the degree of Doctor of Philosophy

by
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DEDICATION

To my parents Nilufar and Jamil, my husband Rajib and my son Zayaan
and
To the people who are suffering from arsenic contamination all over the world
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CHAPTER 1
SUMMARIZING REPORT

1. Preface

Arsenic (As) is a naturally occurring metalloid ubiquitously present in the environment (water, soil, and air). Organic and inorganic As compounds are colorless, odorless and tasteless. Inorganic As is more toxic than organic As, the former is infamously known as ‘the king of poisons’. Humans can be exposed to As by drinking contaminated water, eating contaminated food (rice, seafood), or breathing air containing As (sawdust or smoke from As-treated wood). Arsenic in drinking water is a global issue and has been considered as ‘the largest mass poisoning’ in the human history (Smith et al., 2000). About 150 million people from 70 countries in the world are at risk to health hazards associated with As contamination (Ravenscroft et al., 2009). Arsenic exposure from drinking water can affect various systems in human body (skin, nervous, respiratory, kidneys, and gastrointestinal systems). Long term exposure to As can cause dermatological toxicity (cancerous skin lesions), losses of limbs, mortality due to cardio-vascular and gastroenterological diseases and lung, liver, kidney and bladder cancers (Chakraborti and Saha, 1987; Smith et al., 2000; Chen et al., 2011; Chakraborty et al., 2015). Arsenic debilitates motor action in children, lowers IQ and causes infant mortality. Some evidence suggests that As exposure in the womb and early childhood may increase early mortality in young people (Wasserman et al., 2004; Rahman et al., 2010).

2. Arsenic Contamination in Bangladesh

Arsenic in drinking water well is a widespread concern, particularly in South and Southeast Asian countries. Bangladesh is one of the worst affected countries suffering from drinking water As contamination. Arsenic was first detected in Bangladesh tube well water in 1993 (Dhar et al., 1997). After that, significant testing programs were conducted with the help of
government and non-government organizations. These programs revealed extensive distribution of As in shallow groundwater (< 30 m), highly variable spatial distribution of As and fair stability of As in tube well water over time (van Geen et al., 2006; Balasubramanya and Horbulyk, 2017).

The drinking water system in Bangladesh is largely dependent on groundwater, which is contaminated with 100-500 ug L⁻¹ of geogenic As (Meharg and Rahman, 2003). Anthropogenic activities, predominantly groundwater pumping have exacerbated this situation. In Bangladesh, As contaminated groundwater is extensively used for drinking as well as irrigation purposes. Therefore, As exposure increases with groundwater irrigation, soil loading of As from groundwater and transfer of As from soil to plants or crops. Irrigation with contaminated groundwater gradually accumulates As in agricultural soil, which causes toxicity to crops, reduces crop yield and threatens sustainable agriculture. Researchers have warned that only a few decades of irrigation pumping will exceed the high end of As level in soil (Meharg and Rahman, 2003; Hossain, 2006; Dittmar et al., 2007; Dittmar et al., 2010).

Most of the research on As contamination have been conducted in Bangladesh. The reason behind this is probably because Bangladesh is suffering the most from groundwater As contamination, both in terms of extent and severity. Also, the broad geological and geochemical conditions of the aquifers are similar in Bangladesh and West Bengal, Nepal, the Ganga Plains, Cambodia, Vietnam and Taiwan (McArthur et al., 2001, 2004; Gurung et al., 2005; Acharyya and Shah, 2006; Liu et al., 2006a,b; Buschmann et al., 2007; Postma et al., 2007). Therefore, the results of this research can easily be applicable to other South and Southeast Asian countries. It is worth to mention that the learning from this study might not be easily transferable to other countries (i.e., USA), which do not have similar geological and geochemical conditions like
Bangladesh, and differ significantly in spatial pattern, well use as well as cultural and social values.

3. **Mitigation Measures**

Many mitigation options have been proposed and promoted in Bangladesh in the last decade. However, not all of those measures have been proved effective or favorable. The following four mitigation measures are practiced in different areas depending on the degree of As contamination, economic viability, popularity, or other socioeconomic reasons.

3.1 **Well Testing & Switching (T&S)**

The immediate response to drinking water As contamination was well testing and therefore switching to surrounding safe well/s if the tested well was found unsafe. The first testing effort to identify As concentration in tube well water was conducted by the British Geological Survey (BGS) and Bangladesh Department of Public Health Engineering (DPHE), which tested ~ 3,500 wells nationwide. The project identified about one-third of the wells as unsafe according to Bangladesh standard (>50 µg L\(^{-1}\)) and about two-thirds of the wells as unsafe exceeding the WHO standard of 10 µg L\(^{-1}\) (BGS-DPHE, 2001). The largest As testing and labeling project was the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP), funded by the World Bank, which tested ~5 million tube wells across the country in 1999-2005. Testing of the wells was totally free of charge for general public. One of the most important outcomes of this project was painting of well spouts with red or green color according to Bangladesh drinking water As standard (50 µg L\(^{-1}\)). People were advised to use the green safe wells (As < 50 µg L\(^{-1}\)) for drinking purpose only and limit the use of unsafe red wells (As > 50 µg L\(^{-1}\)) for other uses. In addition, people were also strongly encouraged to share their safe wells with their neighbors.
Well-switching has high potential for the management of safe drinking water in Bangladesh and by far the most effective form of mitigation in the country (van Geen et al., 2002; MF Ahmed, 2006; van Geen et al., 2014). According to BGS-DPHE (2001), Bangladesh has about 10 million hand tube wells. This high coverage of tube wells (one tube well for each 10-15 people) is higher than the health perspectives (one tube well for 100 people). Most of these tube wells (90%) are managed by private owners. Although the WHO limit for As safe water is 10 µg L\(^{-1}\), a significant portion of these shallow tube wells are safe below 50 µg L\(^{-1}\) Bangladesh standard of As safe water. Therefore, well-switching seems to be the cheapest and quickest option when one safe well is not far from a contaminated well. Moreover, well-switching has been already practiced by a large number of people in Bangladesh. However, well-switching has the following problems: (i) water supply from adjacent safe wells may not be controlled by the owners of polluted wells. In addition, the family of the owner of polluted wells may spend extra time for carrying water, which may reduce their water use, (ii) exclusion of a disadvantage group may happen due to social power and kinship within a specific group, which implies a social cost on well-switching, (iii) increased amount of water withdrawal from safe tube wells may expose to early contamination of the wells, (iv) Well-switching is the most effective in least As contaminated areas and therefore need more public awareness campaigns in those areas.

One solution of the problems of well-switching can be community wells. Community wells are deeper safe wells managed and owned by community. Van Geen et al. (2003) found that one community well is capable of supplying As safe water for 500 people living within 150 m radius of the well. In addition, six community well in a densely populated area supplied 2200L water each day and 4L water /person was available to carry away to home. Although, theoretically more possible, it is very hard to predict which well will be contaminated in reality.
This probability mainly depends on local geology. Places where local aquifer is well protected by low permeable and high attenuated capacity of aquitard, wells are likely to be safe for a long time (years/decades). However, some generalized criteria can be rationally assumed: with increased pumping from a safe well, the number and proximity of contaminated well increases the probability of becoming contaminated for a safe well (Ravenscroft, 2007). It may explain the rationale behind the well-switching conflict, which can be overlooked for community wells.

3.2 Deep Tube Well (DTW)

Deep aquifers are generally defined by BGS-DPHE (2001) as those wells that are installed >150 m below ground level. There is a systematic relationship between groundwater As concentration and well depth in Bangladesh. The depth to low-As aquifers varies locally based on geology, but the regional pattern suggests a deeper threshold of 150 m depth may work for most of the areas of Bangladesh.

By and large, groundwater from deep wells is low in arsenic, iron, and manganese concentrations and devoid of microbial contamination. The deep aquifer is comparatively low in As because of the presence of a thick clay/silty clay layer (~10 m) between deep and intermediate/shallow aquifer preventing downward As mobilization. In most cases, As concentration in deep aquifer is below the WHO As guideline of 10 µg L⁻¹. Only 2% of the wells tested under the National Hydrochemical Survey were found to exceed the national standard of 50 µg L⁻¹ limit. Subsequent studies, such as DANIDA-DPHE, DPHE, BAMWSP, also confirmed that deep tube wells over most of the country are low in As. In coastal areas of Bangladesh, only 2 deep wells exceeded 50 µg L⁻¹ of As out of ~300 wells (DPHE-MMI-BGS, 1999). Although those wells were installed at deeper depth to avoid high salinity, most of the wells were turned out to be As-safe. A recent publication by Ravenscroft et al. (2014) further confirms that...
groundwater composition of deep wells has remained stable for decades, therefore exploitation of the deep aquifers should be encouraged.

In addition to high chemical and microbial quality, DTWs also have little maintenance requirements compared to the shallow wells. Hand pumped deep wells require less operational maintenance after installation. The physical failure rate (e.g., due to broken PVC pipe) of deep community wells in Bangladesh is very rare. However, drilling of deep wells to greater depth may not be possible by local drillers hand percussion drilling technique and in some areas drilling to deeper depth is difficult due to the presence of geologic formations containing hard pebble/cobbles in the subsurface.

Because of their low maintenance and higher water quality, DTWs are the most popular As mitigation option in rural Bangladesh, albeit the high cost (US$1000) that is beyond the reach of most individual households. Widespread installation of private deep wells is only feasible if households could share the cost. Currently, only a small fraction (1-2%) of the tens of millions of hand-pumps are deep. A single DTW located in a widely accessible public location can also meet the needs of several hundred villagers (van Geen et al., 2003). Therefore, installation of deep wells in Bangladesh has been viewed as the most effective form of mitigation to date (APSU, 2005; Ravenscroft et al., 2003).

The numbers of deep tube wells have increased significantly over the last few years. Funding from DPHE and various donors has been used to install public deep wells to reduce As exposure in Bangladesh under various projects (DPHE-JICA, 2009; Ravenscroft et al., 2014; DPHE-JICA, 2015). Unfortunately, the full success of the government installed DTWs has not been achieved yet due to uneven distribution of the wells. This happened because of the privatization of the wells by powerful and wealthy people providing 10% of the installation cost.
As a result, DTWs are failing to reduce As exposure to its full potential (van Geen et al., 2016).

There are also uncertainties about mitigating As crisis by installing deep wells. The age of groundwater in the deep aquifer is typically >12,000 year (Aggarwal et al., 2000), which indicates that, the recharged water was not recycled since the last glacial maxima. In other words, the residence time of groundwater in deep aquifer is long. If the deep aquifer is overexploited everywhere by pumping groundwater for irrigation, for example, the aquifer may not get adequate recharge to replenish. Regional scale modeling also suggests that if deep wells are exploited it would drawdown high As water from the shallow aquifers and contaminate deep aquifer resources (Michael and Voss, 2008). In the coastal areas this may intensify saline water intrusion in deep aquifer. But recent findings in the coastal areas (Khulta district) of Bangladesh have shown that even after exploitation, the deep aquifer remained safe in terms of salinity as well as As concentration (DPHE-MMI-BGS, 1999).

It is worth to note that, the National Policy for Arsenic Mitigation emphasized the use of dug/ring well, rainwater and surface water (ponds) sources that had been used as main sources of drinking water before the promotion of the tube wells (GoB, 2004). DTWs were advised to be installed only where other options were not feasible. However, in reality, this has not been practiced since then (Ravenscroft et al., 2014).

### 3.3 Piped Water Supply System (PWSS)

Piped Water Supply System (PWSS) was oftentimes advocated as a long-term solution to the As contamination problem in Bangladesh. However, the high capital and maintenance costs of the system barred the potential for the implementation, particularly across the large rural areas of the country (Ahmed et al., 2006). Therefore, PWSS was considered to be suitable for areas where no other options are successful (DPHE-JICA, 2009).
Bangladesh government, with the help of World Bank and other donors, took several initiatives to promote PWSS in rural Bangladesh in the past. Prior to the discovery of As contamination in tube well water, most rural water supply schemes had been undertaken by communities with limited roles for the government. The first piped water supply model, the Build-Operate Transfer (BOT) model introduced in 2003, involved a limited role for the government while expediting delivery through an enhanced role for the private sector. The BOT model was seen as a mechanism to address the As issue in rural Bangladesh. Given the limited success of community management models in rural water supply at that time, the BOT approach appeared to be the best option for mitigating the impact of large scale As contamination. It was also thought that a private operator model could cope with the costs and technical issues associated with construction and operation of the DTWs and piped distribution systems providing safe water to rural households.

A 2003 Water and Sanitation Program willingness-to-pay (WTP) study found that customers might be willing and able to pay for such services if safe water could be delivered. Following that, two World Bank supported projects tested a BOT design that covered capital costs with 40% private equity contributions, 10% community contributions, and 50% Output Based Aid subsidies. User tariffs were expected to fully cover operation and maintenance costs and allow private operators to recover their investments in 15 years. These projects were the Bangladesh Arsenic Mitigation Water Supply Project/BAMWSP (1998-2006) and the Social Investment Program Project/SIPP-1 (2003-2007). Because As contamination affected a significant proportion of the country, the real value of the model was expected to be its capacity for scaling up service delivery. Two larger projects, Bangladesh Water Supply Program Project/BWSPP (2005-2009), and the Bangladesh rural Water Supply and Sanitation Project/BRWSSP
(20012-2017), attempted to use the model in setting up hundreds of private operator schemes. Both projects carried out a variety of activities in the water sector beyond piped water supply to deliver improved services, which also contributed to improve non-piped water systems. But the efforts to roll out the BOT model in support of piped water supply were less successful, leading to significant funding and target reductions after mid-term project reviews. In consequence, BWSPP reduced its BOT target from 300 schemes to 21 and BRWSSP from 125 to 35. A 2015 Water and Sanitation Program monitoring report on the 21 schemes set up under BWSSP found ten to be non-functioning or badly mismanaged, and only four of the functioning schemes with any likelihood of recovering private investment by the end of their contract terms (GOB, 2015).

Recently, PWSS has been recommended by the Sector Development Plan (2015-25) as a source of safe water in and outside the As affected areas of the country. DPHE evaluated 120 rural PWSS installed at different parts of the country within 2001-2008. These units were installed with the support of various organizations and the maximum number (79) was developed in 2004. The source of water for these schemes is deep groundwater (111), shallow groundwater (2) and surface water (7). At the time of the evaluation, 48%, 13% and 39% were found fully operational, partially operational and nonfunctional respectively (DPHE-JICA, 2009).

4. Materials and Methods

4.1 Study area

Araihazar Upazila is located in Narayanganj District of Dhaka Division, Bangladesh (23.7917°N, 90.6500°E) (Figure 1). Araihazar is about 25 km from the capital city Dhaka with an aerial extent of 183 km² (69.91 mile²). It lies beside Meghna River and consists of plain and low lands with an elevation of 3-6 m. There are 2 municipalities (Araihazar and Gopaldi), 10 unions, 108 wards, 184 mauzas or mahallas, 316 villages and 52,963 households in Araihazar.
According to the 2011 Bangladesh census, Araihazar has a population of 376,550 with 51.75% males and 48.25% females. The literacy rate is 32%. Economy is dependent on agriculture, aquaculture, small and medium industries, i.e., spinning mills and fabrics. Araihazar is one of the most severely affected As contaminated areas in Bangladesh, where As concentration varies from 0.1 and 864 µg L⁻¹ (Ahsan et al., 2006). Numerous studies were carried out in Araihazar for more than a decade to characterize the hydrogeological and geochemical factors, mobilization, and spatial distribution of As in water, aquifer sediments and soil.

4.2 Data processing and analysis

Three datasets were used in this study (Figure 1, Table 1). The first dataset comes from a survey conducted in 2000-2001 comprising 80 villages and ~5,500 wells in northwest Araihazar (Heath Effects of Arsenic Longitudinal Study/HEALS area) (Figure 2a). The second dataset is a subset of BAMWSP blanket testing (Bangladesh Arsenic Mitigation and Water Supply Program), which took place in 2002-2003 and encompasses ~180 villages and ~20,000 wells (Figure 2b). The third dataset belongs to a blanket survey of ~50,000 wells in 2012-2013 covering ~300 villages of the entire Araihazar Upazila (Figure 2c). BAMWSP data were tested with Hach EZ Arsenic kit. However, the other two datasets (2001-2003 and 2012-2013) were tested with ITS Arsenic Econo-Quick field kit and then analyzed and re-analyzed by Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) and High-Resolution Inductively-Coupled Plasma Mass Spectrometry (HR ICP-MS) for quality control (van Geen et al., 2003, 2005; 2014). Data processing and analysis was conducted by R, ArcGIS 10.4, and JMP Pro 2011 software programs.

4.3 Organization of the dissertation

The chapters in this dissertation are laid out in the following sequence with emphasis on
ARSENIC: RISK, EXPOSURE, POLICY AND MANAGEMENT

Chapter 1. Summarizing Report - This chapter is an overview of this dissertation and provides a summary of the research and recommendations for future investigations.

Chapter 2. Arsenic Contamination in Groundwater, Sediment and Soil in Araihazar, Bangladesh - This chapter has been published in Trace Metals: Evolution, Environmental and Ecological Significance (eds Mildred McCarthy), NOVA science Publishers, Hauppauge, New York in January 2017. All available data on water wells, sediments, and soils in Araihazar were compiled and summarized to give an overview of the As contamination scenario in this severely affected area of Bangladesh. We believe that the knowledge from this study will increase our understanding of pollution control, provide support for contamination management and help planners and managers in the local government and regulatory authorities to assess, plan, respond and implement new and existing policies. In addition, the results from this study can also be transferable to other areas of Bangladesh and other South and Southeast Asian countries where groundwater As contamination is a major threat.

Chapter 3. Effectiveness of Different Approaches to Arsenic Mitigation over 18 Years in Araihazar, Bangladesh: Implications for National Policy - This chapter has been published in Environmental Science & Technology (Policy Analysis) in April 2019. Four major As mitigation options (testing and switching, deep tube wells, intermediate wells, piped water supply system) were compared and contrasted from cost-benefit perspectives. Our analysis showed that testing is the cheapest of all mitigation measures and reduced exposure of about 130,000 people by identifying low As wells that could be shared at a cost of <US$1 per person. Testing also had a longer-term impact, as 60,000 people lowered their exposure by installing new wells in intermediate aquifer (45–90 m). In contrast, the installation of deep wells (>150 m) and a single
piped-water supply system by the government reduced exposure of about 7000 inhabitants at a cost of US$150 per person. The findings make a strong case for a long-term, large scale and free well testing program with piped water or groundwater treatment only as a last option.

Chapter 4. Prioritizing Interventions to Reduce Exposure from Arsenic Contaminated Drinking Water in Bangladesh - This chapter is ready for submission to ACS ES&T Water Special Issue “Water Challenges and Solution Opportunities in South Asia, a Rapidly Developing Region of the World.” In this study, we ranked contaminated villages based on weighted exposure (mean As concentration x number of wells), unsafe proportion (number of unsafe wells/total number of wells in a village*100) and village score (average score of each village calculated by the site scoring algorithm developed in this study). Our novel approach (weighted exposure) addressed twice as much as exposure compared to the conventional approach (proportion unsafe) adopted by the local government. We also explored areas where low-cost intermediate wells (45-90 m) are a promising alternate for safe drinking water instead of expensive deep wells. Finally, we introduced a free android mobile phone application (site scoring app “Nolkup”) that can help users to identify As safe well around them or install a new well that is likely to be safe.

5. Objectives

5.1 Objective 1

- Summarize available data to get an overview of the As contamination scenario in Araihazar

5.2 Objective 2

- Obtain previous levels of support for various forms of As mitigation when the government coordinated funding from the World Bank, UNICEF and other
international and non-governmental organizations

- Reallocate government funding for rural water supply improvement to the forms of As mitigation that have proved to be the most effective in the past

5.3 Objective 3

- Review As mitigation approaches to increase village level exposure reduction and allocate funding to the effective mitigation approaches
- Explore areas where low-cost intermediate wells are a potential safe alternative to expensive deep wells
- Identify suitable location for safe water wells using a smartphone application that is quick, easy and reliable to use

6. Results and Discussion

6.1 Cost comparison and prioritizing intervention

Well testing is the cheapest form of As mitigation with a cost of $2.50/well. This cost includes test kits, stainless-steel placard, electronic data collection, supervision, quality control and labor cost (van Geen et al., 2014). According to 2012-13 blanket survey data, the total number of wells in Araihazar is ~48,800, among which 27,500 (~56%) wells are unsafe and 21,300 (~44%) wells are safe at 50 µg L\(^{-1}\) standard. Based on these data, T&S in Araihazar cost ~US$3/person, and therefore reduced exposure to 41,100 villagers. This cost can even be halved (US$1.50/ person) if households get to know the test results and its implications (Jamil et al., 2019).

In our study area, the mean and median As concentrations of deep aquifer are 6.7 and 1.8 µg L\(^{-1}\) respectively. 916 DTWs were identified and tested as part of the 2012-13 blanket survey in Araihazar (van Geen et al., 2016). The cost of this form of As mitigation was about US$230
per well/$61 per person whose exposure was reduced. By ensuring truly public access as well as optimized deep well locations, the cost of DTW installation to the government could be reduced to $120 per well/US$24 per person (Jamil et al., 2019).

From the data of an experimental PWSS operating in Araihazar, the installation cost of this approach to mitigation was $114/person whose exposure was reduced, plus a monthly payment of US$2.50 per month per connection over a ten years period, which increments to $43/person per household (Jamil et al., 2019).

From the above discussion, intervention that is associated with the lowest cost of exposure reduction is testing and switching ($3 per person), followed by intermediate wells ($41 per person), piped water supply system ($43 per person), and deep tube well, the most expensive form of mitigation ($231 per person). These calculations are based on actual mitigation activities conducted in Araihazar over a decade and a half, which show that household responses to BAMWSP testing, by switching to neighboring wells and installing new intermediate wells, reduced the exposure of approximately 94,000 out of a total of 137,000 exposed. The total cost of these two interventions amounted to $122,000 to an outside funder (in this case the US National Institute of Health), with in additional US$1,690,000 in private household contributions. In contrast, the installation of PWSS and DTWs over the same period of time lowered the exposure of only 5,350 villagers and that is at a cost of U$983,000 to the Bangladesh Government (Table 2). Future mitigation efforts should focus more to optimize the impact of testing and private household responses as opposed to heavy infrastructure installation such as deep tube wells and piped water supply systems.

6.2 Screening new wells/National testing program

There has been no national screening of wells, particularly at village level domestic wells
since BAMWSP. The number of domestic hand tube wells keeps changing almost every day as new wells are being installed mainly by private initiatives along with DPHE and NGOs. A large number of new wells have been installed after BAMWSP and there are estimated >30% (~10 million) untested tube wells throughout the country. Therefore, the status of the vast majority of wells in Bangladesh is unknown (~62%) because they were installed later and thus never been tested (van Geen et al., 2014). In addition, a number of new As patients have been registered by DGHS from areas outside major screening where no data on As contamination exists. This clearly demonstrates the need of a new As testing program, which should promote local capacity building to establish a sustainable As testing program built on public-private partnership (DPHE-JICA, 2015).

6.3 Potential of intermediate tube wells (ITWs)

DTWs (> 150 m) are extremely popular in rural Bangladesh for their high-water quality and low maintenance cost. However, the downside of DT is cost (~ $800/well). If the villagers have a choice to get the advantages of a DT without the disadvantage, ITWs (90-150 m) seem promising at that aspect. Araihazar has ~8,450 wells at 45-90 m range, of which ~7,600 are safe (90%) in terms of Bangladesh As standard of 50 µg L⁻¹. The cost of installing these ITWs was significantly lower than deep wells, on average $41/person whose exposure was reduced. This cost could even be halved to $20/person or less if neighboring households can share their well (Jamil et al., 2019).

We explored ITWs of Araihazar at three depth intervals: 45-60m, 60-75m, and 75-90m. Our goal was to identify areas where low-cost hand-flapper method can be used to install intermediate depth wells and where expensive DTWs needed to be installed otherwise. We assumed that for each village i) at least 3 safe/unsafe ITWs are present, and ii) two-thirds (75%)
of the wells are safe/unsafe at 50 µg L\(^{-1}\) As standard. We were curious to see the impacts of a stringer standard towards mitigation, therefore we repeated the same procedure for 10 µg L\(^{-1}\) threshold (Figure 3). Our results showed that the central part of Araihazar has a high potential for safe ITWs. We could also see that a large portion of the area did not meet our condition (less than 3 ITWs) and are not fully explored (central and north eastern Araihazar). We, therefore, assume that some areas might be difficult for developing As safe water options or existing technologies are not suitable. Moreover, there might be a lack of motivation in the community for embracing unfamiliar options. This problem can be minimized by educating local drillers, who works privately with individual households to install large number of tube wells (DPHE-JICA, 2015).

6.4 Identifying effective mitigation approaches

Villages are the lowest and smallest administrative units in rural Bangladesh. Thus, any village level incentives will have more impact on reducing As exposure in high As contaminated areas. Here, we attempted to identify high priority villages using three approaches – proportion unsafe, weighted exposure and village score.

6.4.1 Proportion unsafe

Department of Public Health Engineering (DPHE) is the national agency of Bangladesh which oversees drinking water supply and is responsible for planning, designing, implementing and monitoring water supply and sanitation projects. DPHE prioritize areas as very high, high, medium and low priority based on ‘proportion of unsafe wells’ (number of unsafe wells/total number of wells*100). Thus, any mitigation measures, i.e., allocation of DTWs is based on As contamination and current number of safe water options (SWOs) in a village (DPHE-JICA, 2015). The criteria used by DPHE (proportion of unsafe well) oftentimes under or overestimates As concentration of the wells and their numbers, therefore, overlooks the villages mitigation is
the most needed (Figure 4).

6.4.2 Weighted exposure

We proposed a new criterion to identify high priority areas, which is simply the result of mean As concentration multiplied by total number of wells in a village. Using our new criteria (mean As concentration x number of wells), we ranked 292 villages in Araihazar from the highest weighted exposure to the lowest. We also ranked villages according to DPHE advocated ‘proportion of unsafe wells’ for both 10 and 50 µg L\(^{-1}\) As standards. Our result shows that weighted exposure can address twice as much as exposure compared to other criteria. Surprisingly, WHO As standard of 10 µg L\(^{-1}\) actually addresses the lowest amount of exposure for almost all the villages (Figure 4).

6.4.3 Village score

We developed an algorithm that provides a priority score for any location by calculating number of unsafe wells and existing DTWs within 100 m radius of that location. We applied this algorithm for individual villages in R and calculated average score for each 292 villages. We then ranked the villages from the highest score to the lowest and plotted against ‘weighted exposure’. The plot shows that if mitigation is partial, weighted exposure has the most impact, then village score. We were surprised to see that different thresholds show little difference in terms of exposure reduction in Araihazar (Figure 4).

6.5 Allocation of DTWs

DTWs are extremely popular in rural Bangladesh. Because of their high water quality and low maintenance cost, they are one of the most effective As mitigation measures in Bangladesh. We plotted cumulative number of DTWs against cumulative exposure assuming that 1 DTW can supply As safe water to 25 wells (Figure 5). Our results show that ‘proportion unsafe’ can
address more exposure than ‘weighted exposure’, probably because larger villages do not have
the largest proportion of unsafe wells and vice versa. Strikingly, 100 is better in reducing
exposure than 10 $\mu$g L$^{-1}$ threshold because it points out hot spot areas, which needs immediate
attention.

6.6 Identification of well location

A unique criterion to identify and install safe well in rural Bangladesh is not present. We
introduced a smart phone site scoring application ‘Nolkup’ (means ‘tube well’ in Bengali) in this
study (Figure 6). The code for the app was developed in R and can easily be used for mobile
phone query. The high popularity and accessibility of mobile phones in rural Bangladesh for
installing safe wells have been successful before (van Geen et al., 2006). Currently, Nolkup
covers only a limited number of wells (50,000) in Araihaazar that were tested in 2012-13. After
the new well testing campaign is launched by Bangladesh government, Nolkup will have access
to millions of wells all over the country.

7. Summary and Recommendations

The most important agenda for a widespread As contaminated country like Bangladesh
should be exposure reduction. We show here that our proposed criteria ‘weighted exposure’ does
not depend on As standard and is more effective in identifying hot-spot areas and thus reducing
As exposure significantly. We also show here that, from the cost-benefit viewpoint,
intermediate wells are promising As safe water option. In addition, a site scoring app like
Nolkup can help to identify suitable location for a new safe well.

There is no alternative of a robust testing program. A strategic intervention plan and an
effective maintenance and monitoring system is therefore required to decrease As exposure that
can better use limited resources in a limited amount of time. It is worth to note that some kind
of institutional linkage between drillers and DPHE LGIs would be very helpful to disseminate the message regarding safe drinking water and effective mitigation perspectives (DPHE-JICA, 2015). Moreover, government should take proper planning, implementation, and management initiatives for the allocation of resources in targeted areas, specifically areas where the risk of As contamination is relatively high and water coverage is relatively low. This includes water quality monitoring and surveillance activities, quality control in executing and monitoring projects, public awareness and motivation through campaigns stressing the dangers of As exposure. Any population-level reduction in As exposure will decrease As-related morbidity and mortality, likewise, any failure to sustain As mitigation progress will result in deaths that could have been prevented well ahead of time, particularly to children yet to be born (Flanagan, 2012). Therefore, government should take immediate and necessary actions to maximize the health risk reduction benefit from the widespread As exposure in Bangladesh.
References


Figure 1: Tube well data collected from three blanket surveys conducted in 2000-2001 (HEALS), 2003 (BAMWSP), and 2012-2013 (ATP) in Araihazar, Bangladesh. The top-right map shows the location of Araihazar Upazila in Bangladesh.
**Figure 2a:** Well As status in Araihasar Upazila in 2000-2001. Data were collected from HEALS survey (Heath Effects of Arsenic Longitudinal Study) conducted by Columbia University. Wells are labeled with the following colors: red & orange (≥50 µg L⁻¹ As), green (10-50 µg L⁻¹ As), and blue (≤10 µg L⁻¹ As).
**Figure 2b:** Well As status in Araihazar in 2002-2003. Data were collected from BAMWSP blanket survey (Bangladesh Arsenic Mitigation and Water Supply Program). Wells are labeled with the following colors: red & orange (≥50 µg L⁻¹ As), green (10-50 µg L⁻¹ As), and blue (≤ 10 µg L⁻¹ As).
Figure 2c: Tube well status in the entire Araihazar Upazila in 2012-2013. Data were collected from ATP blanket survey (Arsenic Testing Plant) conducted by Columbia University. Wells are labeled with the following colors: red & orange (>=50 µg L$^{-1}$ As), green (10-50 µg L$^{-1}$ As), and blue (<= 10 µg L$^{-1}$ As).
Figure 3: Araihazar intermediate wells (45-90 m) at three depth intervals: 45-60 m, 60-75 m and 75-90 m. Both 50 µg L$^{-1}$ (top) and 100 µg L$^{-1}$ (bottom) As standards were considered. The blue shaded areas indicate villages where at least 75% wells are safe. Similarly, the red shaded areas are villages with at least 75% unsafe wells.
Figure 4: Ranking of Araihazar villages for weighted exposure (mean As concentration × number of wells) in µg L⁻¹, village score (average score of each village calculated by the site scoring method used in this study), and proportion unsafe (number of unsafe wells/ total number of wells) at 10, 50 and 100 µg L⁻¹ As standards. We see that weighted exposure can address two times more exposure compared to site scoring and proportion unsafe criteria. However, different thresholds have little impact on exposure reduction.
Figure 5: Cumulative exposure vs cumulated number of DTWs needed for village level exposure reduction in Araihazar. Here, proportion unsafe at 10, 50 and 100 µg L$^{-1}$ thresholds almost always reduced more exposure than weighted exposure. The reason behind this is probably village size: big villages do not have the highest proportion of unsafe wells and vice versa, as shown in the enlarged versions of the graph to the right.
Figure 6: Site scoring application Nolkup screenshots: 1) Site score calculated from total number of unsafe wells (11) and number of DTWs (2) within 100 m radius of the search location. The solid line represents 100 m radius, whereas the broken line represents 200 m radius. Wells are shown in three color labels: red (>50 µg L\(^{-1}\)), green (10-50 µg L\(^{-1}\)), and blue (<= 10 µg L\(^{-1}\)). 2) Information on the ITWs (30-90 m) and DTWs (>90 m) are accessible by tapping ‘intermediate’ on the righthand corner. The big blue dots are the DTWs. 3) Additional information on a well (i.e., As content, depth) are available by tapping on the specific well. Demo video is available here: [https://youtu.be/Rf-55vY6FuQ](https://youtu.be/Rf-55vY6FuQ)
Tables

Table 1: Three datasets used in this study conducted in Araihazar, Bangladesh

<table>
<thead>
<tr>
<th>Database</th>
<th>Year</th>
<th>Data points</th>
<th>No of villages</th>
<th>Depth (m)</th>
<th>Arsenic content (µg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shallow wells (&lt; 30m)</td>
<td>Intermediate wells (30-90m)</td>
</tr>
<tr>
<td>HEALS*</td>
<td>2001-02</td>
<td>5,560</td>
<td>77</td>
<td>4,689</td>
<td>867</td>
</tr>
<tr>
<td>BAMWSP**</td>
<td>2002-03</td>
<td>29,151</td>
<td>276</td>
<td>23,033</td>
<td>5,936</td>
</tr>
<tr>
<td>ATP***</td>
<td>2012-13</td>
<td>46,969</td>
<td>290</td>
<td>34,705</td>
<td>11,351</td>
</tr>
</tbody>
</table>

* HEALS = Heath Effects of Arsenic Longitudinal Study  
** BAMWASP = Bangladesh Arsenic Mitigation and Water Supply Program  
*** ATP = Arsenic Testing Plant
### Table 2: Comparison of the cost of four arsenic mitigation measures conducted in Araihazar area

<table>
<thead>
<tr>
<th>Mitigation method</th>
<th>Araihazar activity</th>
<th>Exposed population reached</th>
<th>Exposure proportion reduced</th>
<th>Exposed population reduced</th>
<th>Cost ea. Gov’t/NGO (US$)</th>
<th>Total cost Gov’t/NGO (US$)</th>
<th>Cost ea. household (US$)</th>
<th>Total cost household (US$)</th>
<th>Total cost per exposure reduced (US$) actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing and Switching</td>
<td>48,800 wells tested (21,300 safe)</td>
<td>220,000</td>
<td>60%</td>
<td>132,000</td>
<td>2.50</td>
<td>122,000</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Private Intermediate Wells</td>
<td>8,450 intermediate wells installed (7,610 safe)</td>
<td>67,600</td>
<td>90%</td>
<td>60,800</td>
<td></td>
<td></td>
<td>200</td>
<td>1,690,000</td>
<td>28</td>
</tr>
<tr>
<td>Deep Tubewells</td>
<td>916 deep wells installed (907 safe)</td>
<td>51,200</td>
<td>10%</td>
<td>5,120</td>
<td>800</td>
<td>733,000</td>
<td></td>
<td></td>
<td>143</td>
</tr>
<tr>
<td>Piped Water Supply</td>
<td>312 connections installed (all safe)</td>
<td>2,180</td>
<td>100%</td>
<td>2,180</td>
<td>250,000</td>
<td>250,000</td>
<td>300^</td>
<td>93,600</td>
<td>158^</td>
</tr>
</tbody>
</table>

^10 years @ US$2.50/month
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Chapter 2

ARSENIC CONTAMINATION
IN GROUNDWATER, SEDIMENT AND SOIL
IN ARAIHAZAR, BANGLADESH

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ABSTRACT

Arsenic (As) contamination is a severe public health issue for decades. About 150 million people from 70 countries in the world are at risk to health hazards associated with As. Long term exposure to As can cause serious human health issues to both children and adults. Especially, As poisoning is the most threatening to the South and Southeast Asian countries compared to the rest of the world. In Bangladesh, the most severely affected country from As contamination, about 30-35 million people are exposed to elevated (>50 µg L⁻¹) As concentrations in groundwater. Anthropogenic intervention or groundwater pumping has made this scenario even worse. In Bangladesh, As contaminated

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groundwater is heavily used for drinking as well as irrigation purposes. Therefore, As exposure increases with groundwater irrigation, soil loading of As from groundwater and transfer of As from soil to plants and crops. Irrigation with contaminated groundwater gradually accumulates As in agricultural soil, which causes toxicity to crops, reduces crop yield and threatens sustainable agriculture. Researchers have warned that only a few decades of irrigation pumping will exceed the high end of As level in soil. Araihazar Upazila, Bangladesh, is located about 25 km from the capital city Dhaka, and has an aerial extent of 183 km² with a varied groundwater As concentration from 0.1 to 864 μg L⁻¹. Up to date, a significant number of studies have been conducted in Araihazar, to characterize hydrogeological and geochemical factors, mobilization, and spatial distribution of As in water, aquifer sediments and soil. In this study, we compiled As concentration data from water wells, sediments, and soils in Araihazar that were collected from the public sources and government agencies. We summarized all these data to give an overview of the As contamination scenario in this severely affected area of Bangladesh. The knowledge from this study will increase our understanding of pollution control, provide support for contamination management and help planners and managers in the local government and regulatory authorities to assess, plan, respond and implement new and existing policies. In addition, the results from this study can also be applicable to other areas in Bangladesh and other South and Southeast Asian countries where groundwater As contamination is a major threat.

Keywords: Araihazar, arsenic, Bangladesh, contamination, groundwater, soil

1. INTRODUCTION

Arsenic (As), a naturally occurring element, is found in the earth’s crust. Arsenic is oftentimes called ‘the king of poisons’ and As contamination from drinking water has been considered as ‘the largest mass poisoning’ in the human history [43]. About 150 million people from 70 countries in the world are at health hazard risk associated with As contamination [41]. Long term exposure to As causes cancerous skin lesions, losses of limbs [9], increases infant mortality [40], debilitates motor action in children [52], increases
mortality due to cardio-vascular diseases [11] and lung, liver and bladder cancers [10, 43]. As a consequence, about 200,000-270,000 people will face death due to cancer from drinking As contaminated water in Bangladesh. Unfortunately, As contamination is not only limited to drinking contaminated groundwater only. Soil can be contaminated with As, either naturally or anthropogenically from industrial, urban or agricultural sources. In South and Southeast Asian countries (e.g., Bangladesh and India) groundwater is heavily used for irrigating crop fields, especially in the dry seasons. In Bangladesh, 75% of the total cropped area and 83% of the total irrigated area are used for the cultivation of the staple food rice (Oryza sativa L.). Groundwater in Bangladesh is severely contaminated with geogenic As. On an average, As concentration in Bangladesh groundwater ranges from 100-500 µg L\(^{-1}\) [31]. Recent studies found that irrigation with contaminated groundwater gradually and continuously accumulates As in soil, in the amount proportional to the As concentration in irrigation water [15-17, 25, 31]. While the background concentration of As in soil is 4 to 8 mg kg\(^{-1}\), the soil As concentration can reach up to 57-83 mg kg\(^{-1}\) from groundwater irrigation with high As contaminated water. The high As concentration in soil is mostly limited to the uppermost soil layer, which can be about 5 times greater than the As concentration in the rice field irrigated with uncontaminated water [35, 46]. Therefore, only a few decades of irrigation pumping is enough to reach the high end of As levels observed in agricultural soil [15-17].

Excess As in rice field soil has adverse ecological effects on rice plants [1, 2, 7]. Arsenic rich irrigation water decreases rice plant height, filled grain number, yield and weight of rice grain, root biomass and elevates As concentrations in root, straw, and rice husk [1, 2]. Moreover, vegetables (amaranth, red amaranth, arum, coriander, and spinach), rice and wheat from As contaminated areas contain As in their edible parts above the upper permissible limit. Excessive As in rice field soil significantly declines rice yields [7] and a 7-9 to 2-3 ton hectare\(^{-1}\) rice yield decline for one variety of rice (BRRI dhan) was observed [37]. Although, the transfer of As to crops
is low, ranges between 0.1 to 1.8% [26] and any correlation between high As concentration in irrigation water and As concentration in rice was not found, As concentration in rice grains grown in rice fields irrigated with high As groundwater is higher than the normal concentration [53] and this can contribute significantly to the exposure of As with high As contaminated drinking water [31]. Moreover, the daily As intake from 84% of the Bangladeshi rice samples is more likely to exceed daily As intake from water at WHO drinking water standard of 10 µg L⁻¹ [18, 31]. This estimated data of As consumption from only rice and water indicates that As from rice alone can be an important source of exposure. Arsenic exposure in this way can be significant to people who are drinking water with high concentration of As (>50 µg L⁻¹) as well as consuming a large amount of rice daily [46]. In addition, As exposure lowers 6% rice production per year with an economic loss of 3 billion dollars per year and causes 9% loss in household income [38].

Most of the research on As contamination have been conducted in Bangladesh. The reason behind this is probably because Bangladesh is the most severely affected country from groundwater As contamination. Also, the broad geological and geochemical conditions of the aquifers are similar in Bangladesh and West Bengal [29, 30], Nepal [21], the Ganga Plains [3], Cambodia [8], Vietnam [39] and Taiwan [27, 28]. Therefore, the results of the research done in Bangladesh can be easily applicable to other South and Southeast Asian countries, where groundwater As contamination is a severe problem [7].

In this review paper, we compiled As concentration data from the water wells, sediments, and soils of Araihazar, Bangladesh. These data were collected from various public sources and government agencies. We summarized all data to give an overview of the As contamination scenario in this highly affected area of Bangladesh. We hope that the knowledge from this study will improve our understanding of pollution control, provide support for contamination management and help planners and managers in the local government and regulatory authorities to assess, plan, respond and implement new policies as well as reform existing policies.
2. METHODS

2.1. Study Area

Araihazar Upazila (Figure 1) is located in Narayanganj District of Dhaka Division, Bangladesh (23.7917°N, 90.6500°E). Araihazar is about 25 km from the capital city Dhaka with an aerial extent of 183 km². It is situated beside Meghna River and consists of plain and low lands (elevation 3-6 m). Araihazar has 2 municipalities, namely Araihazar and Gopaldi, 10 unions, 108 wards, 184 mauzas or mahallas, 316 villages and 52,963 households. According to the 2011 Bangladesh census, Araihazar has a population of 376,550 (51.75% males and 48.25% females). The literacy rate is 32%. Economy is dependent on agriculture, aquaculture, small and medium industries (i.e., spinning mills and fabrics). Araihazar is one of the most severely affected, arsenic contaminated areas in Bangladesh. Arsenic concentration in Araihazar varies from 0.1 and 864 μg L⁻¹ [4]. A significant number of studies were carried out here for the past decade to characterize the hydrogeological and geochemical factors, mobilization, and spatial distribution of As in water, aquifer sediments and soil.

2.2. Data Sources and Analysis

Water well or tube well data were collected from various peer-reviewed journals, project reports (Bangladesh Arsenic Mitigation Water Supply Project/ BAMWSP), and government agency sources (British Geological Survey/ BGS) across Araihazar (Figure 2), covering a time period of 1998 to 2013 [6, 12-14, 23, 24, 32- 34, 45-51, 56]. These data have physicochemical parameters, As concentration, depth of wells, installation year, sampling year, etc. We also gathered data on lithology, aquifer sediments, and time series data for water level. Data on agricultural soil and crops for the study area is limited. Therefore, we used soil, soil-water and rice grain As data from van Geen et al. [46]. All these data were processed and analyzed using ArcGIS 10.4, R and JMP Pro 2011 computer softwares.
Figure 1. Map showing location of Araiazar Upazila, Bangladesh. The top right map shows the geographical location of the study area within Bangladesh.
3. RESULTS AND DISCUSSION

3.1. Arsenic in Groundwater

Arsenic concentration in Araihaazar is spatially highly variable (Figure 3). In general, the north-central (Araihaazar-Haizadi-Brahmandi) and the south-western (Khagakanda-Kalapaharia-Paschim Ujan Char) part of the study area have very high As concentration over 50 µg L⁻¹ (Figure 4). As concentration also varies greatly with depth, showing a general declining
trend with increasing depth, which is consistent with the previous findings (Figure 5).

Figure 3. Arsenic concentration in Araihazar showing wells that conform with WHO standard (blue <10 μg L⁻¹) and Bangladesh standard (green <50 μg L⁻¹) for As safe drinking water. The rest of the wells exceed WHO and Bangladesh standard (red >50 μg L⁻¹).
Hydrostratigraphically, the study area has three aquifers. The upper shallow aquifer (0-30 m) has As concentration ranging from 0.879 μg L⁻¹. The mean and median As concentration of the upper aquifer are 114.9 and 68 μg L⁻¹ respectively, based on data from 5771 observations. The intermediate aquifer (30-90 m) has maximum, mean, and median As concentrations of 629.7, 36.5 and 5 μg L⁻¹ respectively, based on 1400 well data. The deep aquifer (>100 m) is comparatively safe, which has mean, median and maximum As concentration of 6.7, 1.8, 103.8 μg L⁻¹ respectively, calculated from 71 data points (Figure 6).

Arsenic concentration in Araihazar shows high degrees of patchiness. Although, the high As concentration in the aquifers do not necessarily follow geology [48], the high local variability or heterogeneity might be caused by local geology and differential groundwater flow [44]. Araihazar is located in between older and uplifted Madhupur terrace (northwest) and the recent floodplain of Meghna River (east). The flat, low lying area has significant spatial variability due to the fluvio-deltaic deposits consisting of fine grained clay, silt and coarse grained sand [20, 44]. The shallow (0-30 m) and intermediate (30-90 m) aquifers are not always separated by fine grained sedimentary layer in the study area. However, the deep aquifer (>100 m) is separated from the shallow and intermediate aquifers by a thick clay layer. The presence of the thick clay layer is more likely to prevent As mobilization from the shallow or intermediate aquifers to deep aquifer.

Arsenic concentration varies with groundwater age and a linear correlation is observed between dissolved As and age of groundwater at very shallow depth (<20 m) [14, 44]. Usually, Pleistocene oxic aquifer (>40 ka) is low in As, whereas the reduced fluvio-deltaic Holocene aquifer (<10 ka) has a high and variable As concentration, that can show a spatial variability of 10 m to 1 km [48, 54, 14]. According to Zheng et al. [55], rapid flushing of organic matter and oxidation of the sediments in the last glacial maxima is responsible for the low As in the deep aquifer. In addition, the linear relationship between groundwater age and As is more likely attributed to the more or less steady As release rate from sediments (20 μg L⁻¹ year⁻¹ for Holocene aquifers) [14].
Figure 4. Arsenic concentration across Araihaazar showing areas that are safe according to WHO (blue <10 µg L⁻¹) and Bangladesh drinking water standard for As (green <50 µg L⁻¹). The rest of the areas are unsafe (red >50 µg L⁻¹).

Arsenic concentration usually remains static over time. However, tube well age can be an important factor for the temporal variation of As [48]. From the regression analysis of As concentration and tube well age, van Geen et. al. [48] found statistically significant increase of As concentration for different depths in 25 km² of Araihaazar, considering 6000 tube well data. A 16 µg L⁻¹ per decade or 2% per year increase of As in old wells were observed. This might be attributed to well pumping, both for domestic use
and irrigation, which withdraw increasing amount of water with time and therefore relocalize As from the shallow aquifers [22]. Although, shallow wells showed seasonal or inter-annual variations due to young age, little seasonality or long term trend is observed in deep wells. The reason behind this is probably the chemical buffering or equilibrium between solute and solid phases and flushing, which slowly depletes As concentration from older sediments.

Figure 5. Variation of As with depth in the study area showing a general decrease in As concentration with depth. The range of As is very high both in the shallow (0-30m) and intermediate (30-90m) aquifers. The colors indicate WHO and Bangladesh drinking water standard for As (blue <10 μg L⁻¹, green <50 μg L⁻¹ and red >50 μg L⁻¹ As) respectively.

3.2. Arsenic in Soil

In paddy fields, As loading in surface soil from As contaminated irrigation water is not uniform, but typically varies with the distance from irrigation well, depth, soil composition and intensity of monsoon flooding. The highest As concentration occurs in the area where water from irrigation
well enters the paddy field. If multiple entry points present along irrigation channel, the fields closest to the irrigation well will gain the highest accumulation of As in soil. This is because irrigation water contains high levels of dissolved iron (Fe) which precipitates on contact with oxygen in the air and strips the irrigation water of its As content [42]. The reversed process, the reductive dissolution of Fe oxides, is responsible for releasing As levels to groundwater in anoxic aquifers [19]. Hussain [25] conducted a study at a shallow tube well (STW) irrigation area in Faridpur, Bangladesh that was irrigated for about 15 years for dry season Boro rice. The total soil As concentration ranged from 61 mg kg⁻¹ nearest to the well to 11 mg kg⁻¹ farthest from the well. At another shallow tube well (STW) irrigation area in Munshiganj, Roberts et al. [42] observed three times decline of As concentration in irrigation water along a 152 m long distribution channel. While working in the same field, Dittmar et al. [16] noticed high topsoil As concentrations (35 mg kg⁻¹) near the field water inlet to 11 mg kg⁻¹ at the end of water inlet. They also reported that topsoil As concentration increased significantly above background levels due to 15 years of irrigation with As contaminated water in the above mentioned site. The topsoil As concentration also varies within fields due to seasonal fluctuation of monsoon flood water. From the same study, Dittmar et al. [16] observed that As concentration declines during monsoon flooding and retained to previous concentration after monsoon. A time series of As concentrations in paddy soil over several years had documented the gradual build-up of contamination, as well as a decline every year during monsoon flooding that only partly resets the system [17]. Rice paddies that are not subjected to monsoon flooding are unlikely to benefit from this partial reset. Therefore, only a few decades of irrigation pumping is enough to reach the high end of As levels in soil by precipitation of As out of irrigation water along with iron oxyhydroxides, if 100-500 μg L⁻¹ range of As concentrations in irrigation wells and the requirement of ~100 cm per season to grow rice under flooded conditions are considered.
Figure 6. Summary of statistical analysis of As concentration in the study area. A) The shallow aquifer has maximum, mean, and median As concentrations of 879, 114.9 and 68 μg L⁻¹ respectively, based on 5771 observations; and B) The intermediate aquifer has maximum, mean, and median As concentrations of 629.7, 36.5 and 5 μg L⁻¹ respectively, as observed from 1400 well data.

From an extensive survey throughout Bangladesh, Meharg and Rahman [31] observed the buildup of As in rice fields from groundwater irrigation and As exposure from rice grains. The survey revealed that As concentration in rice field soil is proportional to the As concentration in irrigation water, tube well depth and age. The highest As concentration was found as 46 μg g⁻¹ dry weight in the highest As contaminated area. Although any correlation
between high As concentration in irrigation water and As concentration in rice was not found, typical As level in rice can contribute significantly to the exposure of As with high As contaminated drinking water. Norra et al. [35] carried out a study in a highly cultivated agricultural land in West Bengal Delta Plain, India where highly irrigated rice and less irrigated wheat were grown. The uppermost soil layer As concentration in the rice field was found to be 38 mg kg\(^{-1}\), which was two folds higher than the As concentration in the wheat field (18 mg kg\(^{-1}\)). The uppermost soil layer As concentration in the rice field was even 5 times greater than the As concentration in the rice field irrigated with uncontaminated water (7 mg kg\(^{-1}\)). Norra et al. [35] also noticed a declining trend in As concentration (11 mg kg\(^{-1}\)) up to 100-110 cm depth in soil profile than the 5–10 mg kg\(^{-1}\) background value of As in the uncontaminated reference area.

Van Geen et al. [46] conducted a survey in four paddy fields in Arahazur. They observed soil and soil-water As concentration during monsoon (when low As surface water is used for irrigation) and dry season (when high As rich groundwater is used for irrigation). The irrigation water they used contained 80–180 μg L\(^{-1}\) As. The As concentration in rice field soil irrigated with As contaminated water was higher than the As concentration in control site soil. They found 13 ± 12 mg kg\(^{-1}\) acid-leachable As and 370 ± 340 μg L\(^{-1}\) dissolved As in the uppermost 5 cm soil of 3 paddy fields and 3 ± 2 mg kg\(^{-1}\) acid leachable As and 18 ± 7 μg L\(^{-1}\) dissolved in the soil of control site.

**CONCLUSION**

The risk and exposure of toxic element As in Arahazur has been discussed in this study. The shallow aquifer is highly contaminated (up to 879 μg L\(^{-1}\) As). Although, groundwater As shows high spatial variability in the study area, As concentration decreases with depth and after 100 m depth wells are mostly safe for drinking and irrigation (<10 μg L\(^{-1}\) As). Arsenic concentration does not vary significantly with time. Also, there is a strong linear correlation between dissolved As concentration and age of shallow
Aquifer. Young (Holocene) aquifer shows high concentration of As in water. Irrigation with As contaminated water contributes to the high As concentration in soil, which has negative impact on crops. We expect that, the results from this study will be useful for pollution control, As contamination management, and assessment, planning and implementation of new and existing policies.

ACKNOWLEDGMENTS

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REFERENCES


CHAPTER 3

EFFECTIVENESS OF DIFFERENT APPROACHES TO ARSENIC MITIGATION
OVER 18 YEARS IN ARAIHAZAR, BANGLADESH: IMPLICATIONS FOR
NATIONAL POLICY

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Approaches to Arsenic Mitigation over 18 Years in Araihaazar, Bangladesh: Implications for National

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Effectiveness of Different Approaches to Arsenic Mitigation over 18 Years in Arahazar, Bangladesh: Implications for National Policy

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Supporting Information

ABSTRACT: About 20 million rural Bangladeshis continue to drink well water containing >50 μg/L arsenic (As). This analysis argues for reprioritizing interventions on the basis of a survey of wells serving a population of 380,000 conducted one decade after a previous round of testing overseen by the government. The available data indicate that testing alone reduced the exposed population in the area in the short term by about 130,000 by identifying the subset of low As wells that could be shared at a total cost of <US$1 per person whose exposure was reduced. Testing also had a longer term impact, as 60,000 exposed inhabitants lowered their exposure by installing new wells to tap intermediate (45–90 m) aquifers that are low in As at their own expense of US$30 per person whose exposure was reduced. In contrast, the installation of over 900 deep (>150 m) wells and a single piped water supply system by the government reduced exposure of little more than 7000 inhabitants at a cost of US$150 per person whose exposure was reduced. The findings make a strong case for long term funding of free well testing on a massive scale with piped water or groundwater treatment only as a last resort.

BACKGROUND

The case for addressing the groundwater arsenic (As) issue in Bangladesh is easy to make. Two independent epidemiologic studies have attributed about 6% of total mortality in the country to past chronic exposure to As from drinking well water that contains as much as 10–100 times the World Health Organization (WHO) guideline for As in drinking water. The main cause of excess mortality is cardiovascular disease, rather than the various forms of cancers that have been linked to chronic As exposure elsewhere in the past. Fetal exposure to As has been shown to negatively impact birth outcomes and infant mortality. In addition, motor and intellectual function are diminished in children drinking well water that is elevated in As.

Chronic exposure to As also has significant economic consequences. Pitt et al. estimate that lowering the amount of retained As among adult men in Bangladesh to levels encountered in uncontaminated countries would increase earnings by 9%. Matching households to As data, Carson et al. find that overall household labor supply is 8% smaller due to As exposure. Clearly, there would be significant returns to investments in As mitigation.

Despite mounting evidence of the negative impacts of drinking well water that is elevated in As, only modest progress has been made in addressing the issue. The first representative survey across Bangladesh concluded that a population of 57 million was exposed in 2000 to As levels above the WHO guideline of 10 μg/L. Subsequent drinking water surveys based on geographically representative sampling indicate that the population exposed relative to this guideline declined to 52 million in 2009 and to 40 million in 2013. Relative to the outdated Bangladesh drinking water standard of 50 μg/L As, the corresponding decline in the exposed population over the same period has been from an initial 35 to 22 and 20 million, respectively. In other words, the number of people chronically exposed to elevated levels of As has declined but remains very high and has diminished only slowly if at all in recent years. Part of the reason is that private well installations have continued unabated even if the rural population of Bangladesh has reached a plateau (Figure 1). Most of the millions of wells installed since the last government led blanket testing campaign under the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP) ended in 2005 have never been tested for As.

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reducing their exposure if they do not know the status of their well with respect to As.

This analysis of well As and household decisions concerning As spanning almost two decades from a sizable and fairly representative area of Bangladesh has two goals. The first is to argue for a return to the previous levels of support of various forms of As mitigation when the government coordinated the allocation of tens of millions of dollars obtained through the World Bank, UNICEF, and various international and non-governmental organizations. The second is to reallocate this level of funding, which has already been set aside by the government for improving rural water supply in general, to the forms of As mitigation that have proved to be most effective in the past.

We show here, on the basis of direct observations whenever possible, that currently favored infrastructure projects such as the installation of deep community wells and piped water supply systems have been much less cost effective and reduced the exposure of many fewer people than individual household initiatives such as the sharing of low As wells and the reinstallation of private wells that target low As aquifers. These private initiatives are both heavily dependent on households and local drillers knowing the status of a well and that of neighboring wells. Given that wells are replaced on average once a decade, we argue that the government’s top priority with respect to As mitigation should be establishing a permanent and free well testing service.

MATERIALS AND METHODS

Chronology of Main Surveys. The first well water and household survey used in this analysis is the Health Effects of Arsenic Longitudinal Study (HEALS) baseline testing conducted in Araihazar upazila (subdistrict) of Bangladesh in 2000–2001 (Figure 1). All 6000 wells within a 25 km² portion of Araihazar upazila, one of 491 subdistricts in the country, were sampled by local partners and tested in the laboratory by

Figure 1. Evolution of population and number of tubewells in rural Bangladesh over time. Source: World Bank (https://data.worldbank.org/indicator/SP.RUR.TOTL?locations=BD&view=chart, accessed March 3, 2019) for population. The number of wells was extrapolated from the model of well installation and well replacement presented in ref 18 by assuming that the average number of 11 users per well in the HEALS area recorded in 2000–2002 applies to the entire country. Also shown is the timing of the HEALS baseline testing, the HEALS follow up survey, the BAMWSP testing within Araihazar (2000–2005 for the entire country), and the most recent 2012–2013 Araihazar blanket survey.

Figure 2. Map of Bangladesh showing (a) the proportion of wells meeting the national standard of 50 μg/L for arsenic in drinking water at the administrative level of the union and (b) the number of villages per union with >20% unsafe wells distributed across a subset of 881 unions where a target depth for reaching low As water could be determined on the basis of the available data. The map is based on 4.7 million well tests conducted with a field kit between 2000 and 2005 in 2330 of the total of 4554 unions in the country. The geographic pattern is dominated by the status of shallow (<45 m) wells with respect to As because most wells in Bangladesh are privately installed. Source: NAMIC/BAMWSP.
Columbia University. Field staff did not report any households that declined to have their well tested or respond to a questionnaire. A small but unrecorded proportion of households estimated at <1% were not available, and their wells were therefore not tested. The survey set the stage for recruiting a cohort of 12,000 men and women who were drinking well water spanning a wide range of As concentrations and continue to be followed to this day under HEALS.

In 2002–2004, the same households were asked about the status of the wells they were drinking from with respect to As during a second survey referred to as the HEALS follow up. During the intervening period, test results had been delivered to each household by providing a card showing the result, household level counseling, and a series of neighborhood meetings during which the risk of drinking well water high in As was communicated through skits, songs, and conversation.

The third survey this analysis refers to covers 4.7 million wells throughout the country tested in 2000–2005 under BAMWSP (Figure 2), including 29,000 wells across Araihazar upazila tested in 2003 after the HEALS baseline survey. Wells were tested with the Hach EZ Arsenic kit (part no. 2822800) during this survey. Depending on the outcome of the test relative to the local standard for As in drinking water of 50 μg/L, the spout of each pumphead was painted green or red. The 20 min reaction time recommended by the kit instructions was subsequently shown to underestimate As concentrations in the well water relative to the local standard of 50 μg/L.

The fourth and main survey that this analysis relies on to document the effectiveness of different forms of As mitigation is a blanket survey of Araihazar upazila conducted in 2012–2013 by a team of 10 local women coordinated by Columbia University and the University of Dhaka (Figure 3). Almost 49,000 wells serving a population of about 380,000 (2011 census) were tested with a different field kit. This kit, the ITS Arsenic Econo Quick (part no. 481298), does a much better job distinguishing wells that meet the WHO guideline for As of 10 μg/L from wells that do not meet the national standard of 50 μg/L but still misclassifies some wells in between. Blue (≤10 μg/L As), green (>10–50 μg/L), or red (>50 μg/L) metal placards were attached to all tested pumpheads immediately after each test. The design of the placards and the choice of colors were a compromise reached to avoid conveying information inconsistent with the national standard (as might have been perceived with green, orange, and red placards) while still encouraging households with a “green” well containing 10–50 μg/L to switch to a nearby “blue” well that meets the WHO guideline for As. During the 2012–2013 survey, households were asked the depth of their well and how long ago it had been installed. The owner of a private well typically knows this because a household well is a significant investment and its installation is therefore followed closely.

Cost. The cost of the 2012–2013 testing in Araihazar was previously calculated at US$2.50 per well (at an exchange rate of BDT80/$1), including the cost of the kit, labor, supervision, as well as the $1.00 cost of a metal placard displaying the test result on the pumphead. The cost of blanket testing with a field kit without attaching a placard is therefore about $1.50 per well.

We have contracted numerous well installations in Araihazar over the years, and the cost has remained almost constant in US currency. The cost of installing a standard hand pumped 1.5 in. diameter well in Bangladesh, including PVC and galvanized iron pipe, a handpump, a concrete platform, and labor, is essentially proportional to well depth at a rate of about US$3.30 per meter. Approximately the same rate applies to...
wells up to 90 m deep installed by small teams of local drillers in a single day and to wells up to 300 m deep that require a heavier rig and a crew typically brought in from elsewhere. In this analysis, we refer to wells installed by local teams at 10−45 m depth as shallow, 45−90 m depth as intermediate, and 90−300 m depth as deep, which requires larger rigs. Overall, shallow wells are as likely to be high or low in As in Araihazar (Figure 3a). Intermediate wells, on the other hand, are much more likely to be low in As (Figure 3b), whereas most deep wells in Araihazar are low in As (Figure 3c). Across the country, there are areas where the vast majority of shallow wells are low in As and other areas where most are high in As (Figure 2a). Intermediate aquifers throughout Bangladesh are often but not always low in As. A search algorithm developed for Araihazar was applied to the countrywide BAMWSP data to determine where these measurements indicate an intermediate aquifer that is systematically low in As, along with an estimate of the reliability of this assessment using an approximate Bayesian approach. When applied to 11,173 villages in the BAMWSP data set (see the Supporting Information) with at least 20% of wells containing >50 μg/L As and a minimum of 20 wells, the algorithm indicates a target depth in the 45−90 m depth range with an estimated probability of at least 0.8 that it is correct in a subset of 1558 villages (Figure 2b). Many of these villages are located within the most affected regions of the country (Figure 2a).

The government’s Department of Public Health Engineering defines wells >150 m as deep, but in some parts of the country, even these deep wells are elevated in As. In reality, there are relatively few wells in the 90−150 m depth range because it is beyond the practical range for the local drilling teams, and once an outside rig is brought in through a government contract, the terms are typically to drill beyond 150 m.

The installation cost of the single piped water supply system installed in Araihazar as well as the income generated by monthly payments from users were obtained from the local manager of the facility (Md. Firoz Mia, personal communication, January 2018) and corroborated by DPHE (Md. S. Rahman, Superintending Engineer, Groundwater Circle, personal communication, August 2018). The system fed by two drilling rigs was used to develop for Araihazar was applied to the countrywide BAMWSP survey in 2003 because of under reporting of As concentrations by the field kit that was used. The smaller HEALS subarea within Araihazar provides a better basis for comparing the proportion of wells with >50 μg/L As: 53% in 2000−2002 with 47% in 2012−2013. This modest decline is disappointing, although it should be pointed out that, whereas in 2000−2002 households were drinking from all wells because they could not have known their status with respect to As, only two thirds of wells in the HEALS area perceived as unsafe were actually used for drinking or cooking in 2012−2013.

Response to Well Testing by Switching. The cost of testing all 48,790 wells in Araihazar in 2012−2013 amounted to US$73,200 for the kit, supplies, and labor, with an additional US$48,800 for the placards. Households were asked when their well was installed, and 65% reported that it had been installed after the previous blanket survey conducted under government auspices in 2003. The vast majority of these new wells were therefore never tested, and 62% of households indeed reported that they did not know the status of their well with respect to As. Households were mostly correct when they claimed to know the status of a well when it was high in As but often incorrect when claiming that a well was low in As. It is therefore reasonable to assume, as we do here, that the response to the 2012−2013 survey can be extrapolated to other areas where little or no testing has been conducted and most households therefore do not know if their well is high in As.

RESULTS

Status of Wells Installed over Time. The increase in the total number of wells in Araihazar from 29,000 in 2003 to 49,000 in 2012−2013 is consistent with a previous comparison of the 2012−2013 survey with the first 2000−2001 survey conducted in the HEALS area. The actual number of new wells installed in Araihazar was considerably larger because the average lifetime of a well is on the order of a decade before it is replaced for technical reasons or by choice. A simple model of well installations and well replacement based on well ages in the HEALS area recorded in 2000−2002 and 2012−2013 was used to estimate the number of wells in the entire county (Figure 1). Out of the 48,790 wells tested in Araihazar in 2012−2013, 27,500 (56%) received a red placard because the field kit indicated an As content >50 μg/L. This proportion cannot be related to the 29% of high As wells reported by the BAMWSP survey in 2003 because of under reporting of As concentrations by the field kit that was used. The smaller HEALS subarea within Araihazar provides a better basis for comparing the proportion of wells with >50 μg/L As: 53% in 2000−2002 with 47% in 2012−2013. This modest decline is disappointing, although it should be pointed out that, whereas in 2000−2002 households were drinking from all wells because they could not have known their status with respect to As, only two thirds of wells in the HEALS area perceived as unsafe were actually used for drinking or cooking in 2012−2013.

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The 2012–2013 data show that 96% of the high As wells were located within 100 m of at least one low As well, meaning that in terms of geography the vast majority of households had the option of seeking a low As well.\(^{14,18}\) Using the high end estimate of 60% switching away from unsafe wells in response to testing and the posting of placards and taking into account an average number of 8 users per well (pop. 375,000 divided by 48,790 wells) in 2012–2013, we infer that the most recent testing probably led about 132,000 inhabitants to switch away from their high As well. This remarkable change was obtained at a cost of US$0.90 per person whose exposure was reduced (Table 1). If the testing had been conducted without a placard, the cost would have been lowered from US$2.50 to US$1.50 per tested well, but the response would have been halved to about 30%. The cost of this hypothetical scenario would therefore have been slightly higher at US$1.10 per person who exposure was reduced but, more importantly, would have reached only half as many people.

**Installation of Private Intermediate Wells.** The 2012–2013 survey is used also to gauge the longer term response of households to well testing by looking at the type of wells that were installed in Araihazar since the BAMWSP survey of 2003. The data show that wells installed over the previous decade were overwhelmingly private shallow (<45 m) wells, about half of them containing >50 μg/L As (Figure 4a). Fortunately, households of Araihazar had a much higher health return on their investment from installing new wells tapping the intermediate (45–90 m) aquifer over this period. Their rate of installation remained below that of shallow wells but was strongly dominated by wells that not only meet the national standard but typically also met the WHO guideline of 10 μg/L for As (Figure 4b).

The cost of a total of 8450 intermediate wells installed until 2012–2013 to households was US$1,690,000, based on an average depth of 60 m and the corresponding average cost of US$200 per well. Assuming most of these households installed an intermediate well because their shallow well tested high for As and the fact that 90% of these intermediate wells were low in As, the exposure of 60,800 inhabitants was reduced by this form of mitigation, about half as many as are estimated to have responded by switching after the 2012–2013 testing (Table 1). The corresponding cost of this private initiative therefore averaged US$28 per person whose exposure was reduced.

**Deep Tubewells.** The 2012–2013 blanket survey of Araihazar identified and tested a total of 927 wells reportedly over 90 m deep (Figure 4c).\(^{21}\) Most of these deep wells were installed by the government at a total cost of US$733,000, based on an average cost of US$800 each.\(^{22}\) Only 9 of these deep wells were high in As, 5 of which because of an additional shallow screen or a leak in the casing.\(^{23}\) The potential impact of the remaining 916 deep wells was previously estimated by summing the number of unsafe wells located within a 100 m radius of a deep well, which previous work conducted in Araihazar has shown is about the maximum distance a household member is willing to walk to lower As exposure.\(^{31}\) Unsafe wells located within a 100 m radius of one or several

Table 1. Comparison of the Effectiveness of Various Forms of Arsenic Mitigation Conducted in Araihazar with Their Cost

<table>
<thead>
<tr>
<th>Mitigation Method</th>
<th>Araihazar Activity</th>
<th>Exposed Population Reached (100% as Safe)</th>
<th>Exposure Proportion Reduced</th>
<th>Exposed Population Reduced</th>
<th>Cost/EA (US$)</th>
<th>Total Cost Govt/NGO (US$)</th>
<th>Cost/EA Household (US$)</th>
<th>Total Cost Household (US$)</th>
<th>Total Cost Per Exposure Reduced (US$) Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing and Switching</td>
<td>4,800 wells tested (21,300 safe)</td>
<td>220,000</td>
<td>60%</td>
<td>132,000</td>
<td>2.5</td>
<td>122,000</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Private Intermediate Wells</td>
<td>8,450 intermediate wells installed (7,610 safe)</td>
<td>67,600</td>
<td>90%</td>
<td>60,800</td>
<td>200</td>
<td>1,690,000</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Deep Tubewells</td>
<td>916 deep wells installed (907 safe)</td>
<td>51,200</td>
<td>10%</td>
<td>5120</td>
<td>800</td>
<td>733,000</td>
<td>143</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>Piped Water Supply</td>
<td>312 connections installed (all safe)</td>
<td>2180</td>
<td>100%</td>
<td>2180</td>
<td>250,000</td>
<td>250,000</td>
<td>300</td>
<td>93,600</td>
<td>158</td>
</tr>
</tbody>
</table>

*10 years @ US$2.50/month.*

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**Figure 4.** Time series of the number of wells installed in 2 year intervals according to their status with respect to As for three different depth ranges. Compilation based on a blanket survey conducted in 2012–2013 during which, in addition to testing wells with a field kit for arsenic, owners were asked the depth of their well and when it was installed. Line colors refer to the same As concentrations as the symbol colors in Figure 3.
deep wells were counted only once.\textsuperscript{21} Multiplying the total of 6470 unsafe wells within 100 m of 907 safe deep wells by 8 users per well and assuming the lower rate of 30\% switching, because BAMWSP testing did not use metal placards, indicates that these installations could have lowered the exposure of about 15,500 inhabitants of Araihazar. The number of inhabitants benefiting from this intervention has to be reduced further by a factor of 3 to only 10\% switching (Table 1), however, because deep wells installed by the government were not as publicly accessible as the smaller number of deep wells installed by an NGO.\textsuperscript{21} On the basis of these considerations, the cost of this form of As mitigation, which reached only a fraction of the population benefiting from testing and the installation of intermediate wells, was about US$142 per person whose exposure was reduced.

Piped-Water Supply. As of February 2018, a total of 2180 inhabitants were drawing their water for drinking and cooking from the 312 water points connected to the water tower, based on a reported average of 7 users per connection (Md. Firoz Mia, personal communication, January 2018). Access is limited to three 2 h periods a day when the system is pressurized. The installation cost of this approach to mitigation was therefore $115 per person whose exposure was recently lowered by this intervention. The water points were offered in several high As villages of Araihazar, and given that they cover only a small portion of all households, it is reasonable to assume that households who requested a connection previously all had a high As well. The cost increases to US$158 per person after taking into account a monthly payment of US$2.50 per connection, which over a period of 10 years (also a realistic lifespan for tubewells) amounts to an additional cost to households of $43 per person (Table 1).

\section*{DISCUSSION}

Comparing Interventions. Our measures of effectiveness based mostly on direct observations reveal a startling range in coverage and efficiency of the four main approaches to As mitigation that have been followed in Bangladesh over the past decade and a half. Other options such as sand filtration of pond water, arsenic removal at the household or community level, shallow dug wells, and rainwater harvesting have all proved to be unsustainable for various reasons.\textsuperscript{12,32--35} Well testing, enhanced by the posting of durable placards, clearly comes out at the top, followed by private installation of intermediate low As wells. The estimated total of close to 193,000 inhabitants in Araihazar whose exposure was reduced by these two forms of mitigation alone is over 20 times greater than the 7400 inhabitants who benefited from the installation of deep tubewells and a piped water supply system (Table 1). Moreover, the outside funding required for well testing and intermediate well installation was almost 10 times below that of the cost of installing deep wells and a piped water supply system. Most of the funding for As mitigation in Araihazar was actually born by households that installed an intermediate well.

Our discussions with a successful local driller (Md. Abu Taleb Mia, personal communication, January 2018) indicate that concern about As spurred the installation of intermediate wells in the area. Although we do not have data from a suitable control area, it is hard to imagine a similar number of households would have done so in the absence of testing. The geographic distribution of intermediate wells suggests that their number could have been considerably larger (Figure 3b). Safe intermediate wells are located primarily in the northwest portion of Araihazar, which includes the HEALS area, as well as another group of villages along the banks of the Meghna River to the south. Between these areas, there is a wide swath of villages with very few intermediate wells. The same local driller has told us that there is no geological reason for the lack of intermediate wells in these villages; there was simply no private demand for installing them. This suggests an overlooked opportunity that should be addressed in future mitigation campaigns: a demonstration well installed in a village where testing of existing wells does not provide sufficient evidence of the status of the intermediate aquifer.

Implications beyond the Study Area. To what extent can the findings in Araihazar be extrapolated to other upazilas of Bangladesh? According to BAMWSP data,\textsuperscript{13} the water pumped from 32\% of the 29,000 wells tested in Araihazar in 2003 contained >50 \(\mu\)g/L As. Overall, this proportion was 29\% for the 4.7 million wells in the country that were tested under the same program in 269 out of 491 upazilas selected for blanket testing (Figure 2).\textsuperscript{13} Even if the kit used for the 2003 testing under BAMWSP underestimated the number of high As wells,\textsuperscript{17} the similar proportions using the same kit suggest that the findings concerning mitigation in Araihazar are broadly relevant to other parts of the country. The available data also indicate comparable levels of spatial heterogeneity in the proportion of unsafe wells at the union level across the country (Figure 2) and within Araihazar (Figure 3a). This matters because spatial heterogeneity down to the very local level is key for making it possible to share the subset of low As wells.\textsuperscript{14} Target depths that are likely to be low in As based on village level BAMWSP data can be recombinated to identify larger areas where households are likely to be able to lower exposure by installing an intermediate well. The subset of 1558 villages identified by the search algorithm\textsuperscript{17} covers as many as 691 unions, almost half of the total of 1633 unions encompassing the 11,174 BAMWSP villages with a minimum of 20 wells and at least >20\% high As wells. For villages within each of these 691 unions and possibly others, an intermediate aquifer low in As would probably be identified by a new blanket testing campaign because of the installation of new and somewhat deeper wells.

The selection of Araihazar for this evaluation has some limitations in terms of generalizability. One is proximity to Dhaka and an expanding textile industry within the area, and therefore an economic status above that of more remote areas of the country. Another potential source of bias is that the HEALS cohort of almost 12,000 inhabitants was recruited in a subset of 60 out of the total of 300 villages in Araihazar.\textsuperscript{15} The cohort has since almost tripled in size and expanded to roughly twice as many villages. The presence of a HEALS clinic in the main town of Araihazar probably increased awareness of the As issue as well, possibly beyond the villages where cohort participants reside,\textsuperscript{26} relative to other affected regions in the country. Another limitation is that intermediate or deep aquifers that are low in As in some upazilas may contain groundwater that is too salty to consume or contain particularly high levels of other constituents of potential concern such as Mn.\textsuperscript{9,26}

Despite these limitations, the new findings have significant implications for future As mitigation in Bangladesh, as most of the 242 upazilas affected by elevated As groundwater (Figure 2), unlike Araihazar, were never blanket tested again since the BAMWSP campaign ended in 2005. The cost of mounting a colored metal placard with the test result on a pumphead...
almost doubles the cost of this intervention, but this is more than compensated by more switching. The policy recommendation is therefore that testing should be accompanied by mounting placards and possibly other ways of enhancing household responses. To the best of our knowledge, current plans of the government’s Department of Public Health Engineering, as in the past, are instead to mark the typically rusty, cast iron pumphead with paint in two different colors that will remain visible for a year or two only. 38

**Issues Raised by Well-Switching.** Concerns that well switching is a short term measure and that households will revert to their own high As well over time have proved to be unfounded by repeated household interviews within Araihazar, but outside the HEALS area, conducted in 2005 and 2008. 36 Once an exposed household decides to switch to a nearby low As well, it usually continues to do so for an extended period. Our time series data indicate that this has not prevented a large number of households from installing a new well that taps the intermediate aquifer (Figure 4b).

The reason tube wells are popular in rural Bangladesh is that they provide a source of drinking water that is generally free of microbial contaminants and therefore does not require boiling. One concern is that local hydrological factors render shallow low As wells more prone to fecal contamination than shallow high As wells. This has been confirmed by monitoring of the fecal indicator *E. coli* and seems to have an impact on childhood diarrhea monitored over multiple years in Matlab upazila. 37,38 For reasons that remain unclear, drinking from intermediate wells in Matlab, most of them low in As, is also associated with a higher incidence of diarrheal disease. 38 Switching from a high As household well to a more distant low As well could potentially also increase the chances of water contamination with microbial pathogens during prolonged storage of water in the home. 39 On the other hand, a systematic country wide study has shown that As awareness campaigns and well testing have led to a reduction in diarrhea and mortality among infants because of prolonged breastfeeding. 40 Further study of any potential increase in exposure to microbial pathogens resulting from a change in behavior to reduce As exposure is clearly needed.

**Optimizing Deep Well Allocations.** One aspect of the findings from Araihazar will not necessarily be applicable to all other parts of the country. In some villages, the intermediate aquifer is not low in As and cannot provide households with a ready mitigation option (Figure 2b). This is why the two other more costly approaches, deep hand pumped wells and piped water supply, are needed in some areas as well.

In the case of deep wells, their impact could be significantly increased by optimizing their installation and terms of use. We have previously calculated that 916 optimally sited, safe deep wells could have brought 132,000 inhabitants with an unsafe well within a 100 m radius of a safe source of water. 21 If these sources had been truly public and switching had been increased to 60% with placards posted during the 2003 survey, we estimate that the exposure of as many as 79,000 inhabitants would have been lowered at a cost of only US$9 per person whose exposure would have been reduced. This is even below that of the cost of installing intermediate wells, although this does not take into account the convenience of having a safe well in your own yard. There is an enormous gap between the potential of deep wells to reduce exposure (US$9 per person) and the reality (US$142 per person). Previous work has shown that one way to address this issue is to take into account when allocating deep government wells to the proportion of unsafe wells in a village as well as the presence of existing deep wells. 21 One avenue for improved siting of such deep wells would be to assign their location to local water and sanitation committees that represent all segments of the population. 41 Better allocation may also require dropping the current DPHE requirement for local households to contribute 10% of the cost of a deep well. This requirement could have contributed to, in essence, the privatization of government installed deep wells by households wealthy enough to make this contribution.

The much higher cost of piped water supply systems indicates that this approach should be reserved only for parts of the country where not even hand pumped deep wells can provide low As water. Two examples are the border area between West Bengal, India, and Bangladesh near Jessore and the Sylhet basin. 22 In these areas, even deep aquifers are elevated in As and some form of groundwater treatment at the community level, rather than at the household level, will be required. 42 We would argue, however, that tapping those aquifers that are low in As, not necessarily deep aquifers, should take precedence over any large scale deployment of community level treatment systems, since they require a lot more maintenance than a deep community well.

**Recommendations.** The Bangladesh government’s new ambitious rural water supply program (Md. Saifur Rahman, personal communication, August 2018) presents a unique opportunity to reduce As exposure across the country. Our analysis indicates, however, that spending priorities will need to be drastically changed to achieve this. A shift of funding to disseminate well test results and help households make decisions on the basis of these results will be more than offset by additional reductions in As exposure. The testing should be offered for free because demand has been shown to drop sharply even with a small charge. 43 The large sums already spent by households to install a new well to intermediate depths in Araihazar are a clear indication of the value attached to safe drinking water. The potential of this approach was not fully realized even in Araihazar. Beyond posting test results, the government could therefore guide households wishing to install a new well by presenting As test results aggregated at the village level as a function of depth. Demonstration drilling and well installation should also be considered. Well test results should become the primary criterion for allocating more expensive mitigation options such as the installation of deep wells, which could become very cost effective if their locations are optimized and public access is ensured. At least in the foreseeable future, the installation of piped water supply systems should only be a last resort when all other less expensive avenues are exhausted.

**ASSOCIATED CONTENT**

**Supporting Information**
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b01375.

MS Excel file with compilation of BAMWSP data at the village level, including target depths for low As aquifers for a subset of villages (XLSX)

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■ REFERENCES
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CHAPTER 4
Abstract

Arsenic (As) contamination has been a worldwide public health disaster for decades. In Bangladesh, the most severely affected country from groundwater As contamination, about 35 million people are exposed to high concentrations of geogenic As (> 50 ug L\(^{-1}\)). The national standard for drinking water As in Bangladesh is 50 ug L\(^{-1}\), which is 5 times higher than the WHO recommended guideline of 10 ug L\(^{-1}\). Minimization of As exposure is oftentimes challenging for a developing country like Bangladesh due to limited economic, technical and institutional resources. In this study, we reviewed As mitigation options and ranked contaminated villages based on three criteria: i) weighted exposure, which is the product of mean As concentration and number of wells in an area, ii) village score, the average score of a village calculated from number of unsafe wells as well as deep wells within 100 meter radius of each well in that village, iii) unsafe proportion, which is the result of number of unsafe wells divided by total number of wells and multiplied by 100. Our novel approach (weighted exposure) addressed twice as much as exposure compared to the currently practiced approach (proportion unsafe) adopted by the local government. We also explored areas where low-cost intermediate wells (45-90 m) are a promising safe alternative to expensive deep wells. Finally, we used an algorithm for site scoring and developed a smartphone application to identify suitable location for a new safe well. We believe that the knowledge from this research will help local government and regulatory authorities to develop new policies or amend existing ones, as well as optimize resource allocation and management by prioritizing actions. In addition, the results from this study will be transferrable to other areas of Bangladesh and other countries with similar geologic and socio-economic settings, where groundwater As contamination is a serious problem.

Keywords: Arsenic, Exposure, Mitigation, Policy, Standard
1. Introduction

Arsenic (As) is a naturally occurring element found in the earth’s crust. Arsenic is oftentimes called ‘the king of poisons’ and As contamination from drinking water has been considered as ‘the largest mass poisoning’ in the human history (Smith et al., 2000). About 150 million people from 70 countries in the world are at risk to health hazards associated with As contamination (Ravenscroft et al., 2009). Long term exposure to As can cause chronic health issues, such as cancerous skin lesions, losses of limbs (Chakraborti and Saha, 1987), mortality due to cardio-vascular diseases (Chen et al., 2011) and lung, liver and bladder cancers (Smith et al., 2000; Chakraborty et al., 2015). Arsenic also debilitates motor action in children, lowers intelligence quotient (IQ) and causes infant mortality (Wasserman et al., 2004; Rahman et al., 2010).

More people are affected by As poisoning in Asia than in the rest of the world combined. In Bangladesh alone 30-35 million people are exposed to elevated (> 50 ug L$^{-1}$) concentrations of As in groundwater (BGS-DPHE, 2001). Arsenic was first detected in Bangladesh tube well water in early 1990s (Dhar et al., 1997). After that, significant testing programs were conducted with the help of government and non-government organizations. These programs revealed extensive distribution of As in shallow groundwater (< 30 m), highly variable spatial distribution and fair stability of As in tube well water over time (van Geen et al., 2006; Balasubramanya and Horbulyk, 2017). In Bangladesh, the drinking water system is largely dependent on groundwater, which is contaminated with geogenic As ranging from 100-500 ug L$^{-1}$ (Meharg and Rahman, 2003). About 13.4% of the population lives in 466 unions where As contamination level is equal to or greater than 80%. The estimated population, calculated from various surveys conducted in 2000 to 2010, who are chronically exposed to drinking water As is from 20 to 77
million in Bangladesh. Although the number of disease and death instances caused by As depend on different factors, i.e., variations in individual exposure over time and different latency periods between different diseases, it is certain that As is causing premature deaths of millions of people living in rural Bangladesh (GOB, 2002; BBS-UNICEF, 2009; Flanagan, 2012).

Regulating As concentration in drinking water always has been a controversial and protracted process. Arsenic standards or guideline values for drinking water are adopted by the World Health Organization (WHO). These values are not mandatory, rather used as a basis for setting national standards for individual countries. The guideline values are frequently revised based on increased knowledge of the nature, extent and effect of various contaminants as well as improved techniques for the identification and determination of concentrations of the contaminants. The adoption or establishment of national standards based on WHO guidelines should use qualitative and/or quantitative risk-benefit approach. This approach should lead to standards and regulations that can be i) readily implemented and enforced, ii) ensure the use of available national financial, technical and institutional resources for maximum public health benefits, iii) considers local environmental, social and cultural conditions, and iv) potential exposure that is affected by a variety of geographic, socio-economic, dietary and other factors. In countries where both the economic and human resources are scarce or limited, short and medium-term targets should be set in establishing national standards.

Currently, WHO provisional value for As in drinking water is 10 µg L⁻¹ (WHO, 1993). This value has been adopted by a number of countries as their national standard. However, over 21 countries are still using the earlier 50 µg L⁻¹ standard. The probable reasons seem to be lack of sampling program, analytical equipment, and funding to enforce lower standard effectively. It is worth mentioning that many countries are using the previous 50 µg L⁻¹ standard as an interim
target towards lower standard, particularly countries that have significant portion of the population exposed to As concentrations in the range of 10-50 µg L⁻¹ (Smith and Smith, 2004). Surprisingly, reduction in As concentration in drinking water conforming the WHO guideline value (10 µg L⁻¹) does not always ensure reduction in cancer risk. In some cases, the potential cancer risk even remains high (NRC, 2001). This information is particularly useful to the developing countries, who are suffering the most from this issue, because of the large size of exposed rural population, widespread exposure, limited resources, and influence on exposure from multiple sources, i. e., geographic, socio-economic, dietary and other conditions (Smith et al., 2002). Bangladesh is using WHO old standard for drinking water As (50 ug L⁻¹) as national standard. There is a long and still ongoing debate whether or not Bangladesh should lower the As standard for drinking water corresponding to the current WHO standard of 10 µg L⁻¹ As. Bangladesh adopted a National Policy for Arsenic Mitigation and Implementation Plan in 2004. Current safe water coverage in Bangladesh is 88% (JMP, 2012) or 92 people per public water option within ~1.4 million installed public water options countrywide. Each option is a public water point that may be a well with a hand pump or a stand post from a piped water supply system. There is a large gap between the number of installed safe water options (SWO)s and areas urgently in need of SWOs. According to the new national policy, Bangladesh government has targeted 50 people/ water option which will be achieved by three target levels within 2015, 2020 and 2025, respectively. Considering several levels of targets with growing population, the necessary number of SWOs and estimated installation cost are BDT 153,885 ($151.5 million); BDT 96,429 ($95 million); and BDT 278,984 ($274.5 million) by 2015, 2016-2020 and 2021-2025 respectively (DPHE-JICA, 2015).

Proper management of As contaminated water can reduce exposure to tens of millions of
rural people in Bangladesh. The purpose of this work is to assess and evaluate As contaminated areas in Araihazar and identify the highest priority areas, provide guideline for useful mitigation options and point out suitable location for safe well. We strongly believe that this study will help policy makers, planners and researchers of the local government and regulatory authorities in decision making, policy development, resource allocation, management and investments in targeted areas. Moreover, the outcome of this study will be useful to other As contaminated areas of Bangladesh, as well as other South and Southeast Asian countries and regions, because they share similar geological, geochemical, socio-economic and cultural conditions, such as Bangladesh and West Bengal (McArthur et al., 2001, 2004), Nepal (Gurung et al., 2005), the Ganga Plains (Acharyya and Shah, 2006), Cambodia (Buschmann et al., 2007), Vietnam (Postma et al., 2007) and Taiwan (Liu et al., 2006a, b).

2. Materials and Methods

2.1 Study area

Our study area is Araihazar Upazila, located in Narayanganj District of Dhaka Division, Bangladesh (23.7917°N, 90.6500°E) (Figure 1a&b). Araihazar has an aerial extent of 181.07 km² (69.91 mile²). Araihazar is about 25 km southeast from the capital city Dhaka, is situated beside Meghna River and consists of plain and low lands (elevation 3-6 m) formed by the alluvial formations of Shitalakshya, Meghna, Old Brahmaputra, Buriganga, Balu and Dhaleshwari rivers. The annual average temperature ranges from 29.8 °C-17.6 °C with an average annual rainfall of 2376 millimeters. Araihazar has 2 municipalities, 12 unions, 159 mauzas or mahallas, 322 villages and 77,462 households (BBS, 2011). According to the 2011 Bangladesh census, Araihazar has a population of 3,90,895 (1,95,499 males and 1,95,396 females) with a literacy rate of 41%. The economy is dependent on agriculture, aquaculture, and
small and medium industries (i.e., spinning mills and fabrics). Arsenic concentration in Araihazar groundwater ranges from 0.1-864 µg L\(^{-1}\) (Ahsan et al., 2006).

2.2 Data processing and analysis

Araihazar is the place where probably the most detailed information on As has been collected over almost two decades of research by Columbia University, the University of Dhaka, and UChicago Research Bangladesh.

Three datasets were used in this study, which are the followings (Figure 1a&b, Table 1):

i) HEALS (Health Effects of Arsenic Longitudinal Study) – The first dataset comes from a survey conducted in 2000-2001 in HEALS area comprising 80 villages and ~5,500 wells in northwest Araihazar.

ii) BAMWSP (Bangladesh Arsenic Mitigation and Water Supply Program) - The second dataset is a subset of BAMWSP blanket testing, which took place in 2002-2003. ~20,000 wells in ~180 villages in Araihazar were surveyed and tested with Hach EZ Arsenic kit.

iii) ATP (Arsenic Testing Plant) - The third dataset belongs to a blanket survey of ~50,000 wells in 2012-2013 covering ~300 villages of the entire Araihazar Upazila.

HEALS and ATP data were tested with ITS Arsenic Econo-Quick field kit and then analyzed and re-analyzed by Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) and High-Resolution Inductively-Coupled Plasma Mass Spectrometry (HR ICP-MS) for quality control (van Geen et al., 2003, 2005, 2014). All data were processed and analyzed by R using basic packages, including the site scoring algorithm. Maps were produced by R and ArcGIS.
3. Results and Discussion

The first assessment of As mitigation measures in Bangladesh took place in 2005 (National survey 2005). The survey was aimed to identify number of SWOs installed by various government and non-government programs. Eleven different types of water supply options were reported to be used among 972,865 existing water options throughout Bangladesh, within which 692,488 (71.1%) SWOs were found active. The most active SWOs were shallow tube wells, followed by deep tube wells and piped water supply systems. An estimated 45 million (54.4%) people out of 82 million could be served with public SWOs based on the number of users criteria for each type of option and 40 million were estimated to be not receiving public SWOs (DPHE-APSU, 2005). The most recent survey on As contamination and mitigation was undertaken by DPHE-JICA in order to assess As mitigation situation in 2009. In this survey, union wise data have been collected from upazila level DPHE, Health Complexes, NGO offices and related government offices by JICA field staffs with assistance from DPHE Sub-Assistant Engineers. The survey was conducted over 3132 unions in 301 upazilas covering 55 districts within 6 divisions. The estimated population in need of As safe water was calculated to be ~19 million (92 persons/water point), which suggested installation of 0.2 million water points (~53,000 water options/year) considering the population growth rate of 1.5% and yearly rate of de-functioning (~2%) of water points (DPHE-JICA, 2010).

3.1 Prioritization of intervention

We ranked villages for intervention purposes. We used the following three approaches –

3.1.1 Proportion unsafe

Department of Public Health Engineering (DPHE) under the Ministry of Local Government, Rural Development and Co-operatives (MLGRD&C) of Bangladesh Government
is the national agency for drinking water supply, waste management, environmental sanitation and hygiene education in rural Bangladesh. DPHE is responsible for planning, designing, implementing and monitoring water supply and sanitation projects and providing cooperation with the public services organizations, local government institutions (LGIs), private sectors/NGOs and academic and research institutions. DPHE uses ‘proportion of unsafe wells’ (number of unsafe wells/total number of wells*100) as the defining criteria for mitigation measures, i.e., allocation of deep tube wells. Here ‘unsafe’ means wells that exceed 50 µg L$^{-1}$ As, the national As standard for drinking water in Bangladesh. DPHE thus prioritize areas as very high, high, medium and low priority unions based on As contamination conditions and the current number of SWOs (DPHE-JICA, 2015). The criteria used by DPHE (proportion of unsafe well) oftentimes under or overestimates As concentration of the wells and their numbers, therefore, fails to focus or overlooks the areas or villages mitigation is the most needed (Figure 2).

3.1.2 Weighted exposure

In this study, we are proposing a novel criteria (weighted exposure) to identify high priority areas, which is simply the result of mean As concentration multiplied by total number of wells in any given area. Using our new criteria (mean As concentration x number of wells), we ranked 292 villages in Araihazar from the highest weighted exposure to the lowest. We also ranked villages according to DPHE advocated ‘proportion of unsafe wells’ for both 10 and 50 µg L$^{-1}$ As standards. Our result shows that weighted exposure can address twice as much as exposure compared to other criteria. Surprisingly, WHO As standard of 10 µg L$^{-1}$ actually addresses the lowest amount of exposure for almost all the villages (Figure 2). A comparison within two villages might help to explain the impact of two approaches. Let’s assume we have
two hypothetical villages: one with a well with 40 µg L⁻¹ As and 10 users and another with 60 µg L⁻¹ As with 5 users. Weighted exposure for the villages are 400 µg L⁻¹ and 300 µg L⁻¹ respectively. Although, the ‘proportion unsafe’ would prefer the second village with >50 µg L⁻¹ well As, the weighted exposure would suggest the first village with 40 µg L⁻¹ well As. Thus, weighted exposure can quickly identify villages that need attention the most.

3.1.3 Village score

We developed an algorithm that provides a priority score for any location by calculating number of unsafe wells and existing DTWs within 100 m radius of the proposed location. We applied the algorithm for individual villages in R and calculated average score for each 292 villages in Araihazar. We then ranked the villages from the highest score to the lowest and plotted against weighted exposure. The plot shows that if mitigation is partial, weighted exposure has the most impact, then village score. We were surprised to see that different thresholds show little difference in terms of exposure reduction in Araihazar (Figure 2).

3.2 Mitigation options

3.2.1 Deep Tube Wells (DTWs)

Deep Tube Wells are generally defined by BGS-DPHE (2001) as those wells that are >150 m deep below ground level. In general, groundwater from deep wells is low in arsenic, iron, and manganese concentrations and devoid of microbial contamination. In most cases, As concentration in deep aquifer is below the WHO As guideline of 10 µg L⁻¹. In addition to high chemical and microbial quality, DTWs also have little maintenance requirements compared to the shallow wells. Because of their higher water quality and low maintenance, DTWs are the most popular As mitigation option in rural Bangladesh. Therefore, installation of deep wells in Bangladesh has been viewed as the most effective form of mitigation to date (APSU, 2005;
We plotted cumulative number of DTWs against cumulative exposure (Figure 3). We assumed that 1 DTW can supply As safe water to 25 As contaminated well users. We find that thresholds do better job for the allocation of DTWs. The reason behind this is probably village size, i.e., larger villages do not have the largest proportion of unsafe wells and vice versa. Strikingly, 100 is better than 10 µg L\(^{-1}\) threshold.

3.2.2 *Intermediate Tube Wells (ITWs)*

Deep wells (> 150 m) are extremely popular in rural Bangladesh for their high water quality and low maintenance cost. However, the downside of DTW is cost (~ $800/well). If the villagers have a choice to get the advantages of a DTW without the disadvantage, intermediate wells (90-150 m) seem promising at that aspect. Araihazar has ~8,450 wells at 45-90 m range, of which ~7,600 are safe (90%) in terms of Bangladesh As standard of 50 µg L\(^{-1}\). The cost of installing these intermediate wells was significantly lower than deep wells, on average $41/person whose exposure was reduced. This cost could even be halved to $20/person or less if neighboring households can share their well (Jamil et al., 2019).

We identified areas in Araihazar where exploratory drilling using the low-cost hand-flapper method can be used to install intermediate wells and where that is not the case, therefore, high cost deep wells needed to be installed for safe water supply. For each village at three depth intervals (45-60m, 60-75m, 75-90m), our conditions were i) presence of at least 3 safe/unsafe intermediate wells, and ii) two-thirds (75%) of the wells are safe/unsafe at 50 µg L\(^{-1}\) As standard (Figure 4). We then repeated the procedure for 10 µg L\(^{-1}\) threshold to observe the impact of a stricter standard towards mitigation. The result showed high potential of safe intermediate wells in the central part of Araihazar. Although, a large portion of the area did not qualify for our
condition (less than 3 intermediate wells), it is not clear why the intermediate aquifer is not fully explored in the central and northeastern Araihazar (Figure 4). However, we assume that such areas might be very difficult with respect to hydrogeology for developing As safe water options or existing technologies are simply not suitable. Moreover, there might be lack of motivation of the community towards alternative being unfamiliar options. This problem can be minimized by educating local private drillers, who install large number of tube wells contracted by individual households (DPHE-JICA, 2015).

3.3 Identification of well location

There is a tremendous discrepancy between the number of installed SWOs and the areas with high As contamination. Villages are the lowest administrative unit in Bangladesh, preceded by Mouza, Union, Upazila, District and Division respectively. Upazila-wise resource allocation is decided by the central government, therefore, progress on As mitigation or water supply interventions are not monitored beyond union level. Upazila parishad distributes the allocated water options at union level. Sites of the water options are selected by the Site Selection Committee chaired by Union Parishad chairman. In many cases, installation sites are not been selected by demand-driven needs because of the union doesn't have enough manpower, knowledge and/or budget to conduct a meeting with lower-level administrative units to take mutual decisions. Moreover, sometimes influential or elite person influence the site selection process which results in selection of less priority areas. DPHE is trying to increase community participation by supporting NGOs engagement in preparing demand-based plan and involvement of LGIs in site selection process (DPHE-JICA, 2015).

It is extremely difficult to identify safe well location due to highly variable spatial distribution of As, particularly in shallow aquifer. In the villages/unions where there is presence
of As but the average contamination level is less than 5-10%, the existing technology is recommended as STW. In that case, before going for installation of STW, As concentration of 5-10 tube wells within 500 meters of the site is needed to be tested (DPHE-JICA, 2015). Different institutions use different sets of criteria for site selection. The Upazila parishad and LGED install wells using their own criteria and so does the NGOs. In many cases, DPHE or the Upazila Parishad is not aware of the criteria NGOs are using for site selection (DPHE-JICA, 2015).

There is an information gap among the stakeholders lacking a unique criteria to identify and install wells that would be safe. Therefore, a smart phone site scoring application (‘Nolkup’, which means ‘tube well’ in Bengali) is introduced in this study. The code for the app was developed in R and can be easily used for mobile phone query. Use of mobile phones for installing safe wells had been successful before (van Geen et al., 2006). Considering the success of mobile phones and their high popularity and accessibility in rural Bangladesh, site scoring app can be promising to install a safe well in otherwise highly As contaminated areas (Figure 5).

3.3.1 Site Scoring Application ‘Nolkup’

Nolkup is a free android app, which helps to find nearby low As/As safe wells or to install a well that is likely to be safe. This app is already available on ‘Play Store’. Nolkup determines the suitable location of a safe well based on the scoring of surrounding unsafe wells. The app provides a priority score by counting the number of unsafe wells and existing DTWs within 100 meter of any proposed location.

By default, Nolkup opens a map of user’s current location. However, a different location can also be searched from the search box. The app then shows all the wells within 200 m of the selected location. The inner circle shows wells within 100 m and the outer circle shows wells within 200 meters. Wells are colored as blue (<=10 mgL⁻¹), green (10-50 mgL⁻¹) and red (=>50
mgL⁻¹) depending on their As concentration. Additional information (i.e., well depth, As content, image) is also available just by tapping on any well. Wells over 30 meter can be selected by tapping the ‘Intermediate’ button on the upper right-hand corner of screen. It is worth to notice that the bigger blue circles are DTWs, which are generally As safe. Nolkup also shows the net score, number of unsafe wells, and number of unsafe wells that have DTWs around them. The net score means the number of unsafe/red wells which DO NOT have any DTW within 100 m around them. The higher the score, the more useful or important it is to install a new safe well in that location. Thus, by comparing site scores, one can take an informed decision about switching to a safe well or install a new well in your area. To get score for a different area, the user needs to zoom out, then tap and hold the marker and then drag it to a specific area/village of interest (Nolkup app demo video: https://youtu.be/Rf-55vY6FuQ).

Nolkup might face some challenges at first, for example, input of the countrywide data into Nolkup server from the regulatory authorities, acceptability in older population. Hopefully, demand will rise after people will start getting the benefits of the app. Currently, Nolkup covers only a limited number of wells (50,000) in Arailhazar that were tested in 2012-13. After the new well testing campaign is launched by Bangladesh government, Nolkup will have access to millions of wells all over the country.

4. Conclusions and Recommendations

The most important agenda for a widespread As contaminated country like Bangladesh should be immediate exposure reduction. Bangladesh should decrease As exposure as much as possible with limited resources and limited amount of time. Therefore, a strategic intervention plan as well as a maintenance and monitoring system is required. In addition, there is much speculation on lowering drinking water As standard in Bangladesh. Delays in establishing a
maximum contaminant level (MCL) to preserve health increases burden of disease and causes substantial and avoidable loss of life (Fisher et al., 2017). However, this study shows that changing As standard does not affect exposure reduction that much, particularly in high As contaminated areas. According to Jameel et al. (2021), the maximum exposure reduction by well switching was observed at 41 mg L\(^{-1}\) threshold, which is close enough to the current Bangladesh standards of 50 mg L\(^{-1}\). Smith and Smith (2004) pointed out the exclusion of the short-term mitigation options (i.e., dug wells in the range of 10-50 µg L\(^{-1}\) As) in the areas where long term solution is not available yet, if the standard is lowered to 10 µg L\(^{-1}\). On the other hand, the novel criteria ‘weighted exposure’ proposed by this study, which does not depend on As standard, is more effective for identifying hot-spot areas, therefore useful in exposure reduction. From the cost-benefit viewpoint, intermediate wells are promising As safe water options. In addition, site scoring app like Nolkup can help to identify suitable location of a new safe well. It is worth to note that some kind of institutional linkage between drillers and DPHE LGIs would be very helpful to disseminate the message regarding safe drinking water and therefore effective mitigation perspectives (DPHE-JICA, 2015). Moreover, government should take proper planning, implementation, and management initiatives for the allocation of resources in targeted areas, specifically areas where the risk of As contamination is relatively high and water coverage is relatively low. This includes water quality monitoring and surveillance activities, quality control in executing and monitoring projects, public awareness and motivation through campaigns stressing the dangers of As exposure. According to Flanagan (2012), any population-level reduction in As exposure will decrease As-related morbidity and mortality, likewise, any failure to sustain As mitigation progress will result in deaths that could have been prevented well ahead of time, particularly to children yet to be born. Therefore, government should take immediate and necessary actions to maximize the health risk reduction benefit from the
widespread As exposure in Bangladesh.
References


Figure 1a: Well arsenic (As) concentration in Health Effects of Arsenic Longitudinal Study (HEALS) area in Araihazar Upazila from 2001 to 2012 for shallow (<30 m), intermediate (30-90 m) and deep aquifers (>90 m). Color coding shows wells at 10 µg L$^{-1}$ (blue), 10-50 µg L$^{-1}$ (green) and >50 µg L$^{-1}$ (red) As standards. Note that the number of deep tube wells (DTWs) has increased from 2001 to 2012. Only 4 DTWs were present in 2001 in HEALS area.
Figure 1b: Arsenic concentration in well water in the entire Araihazar Upazila (2003-2012) for shallow (<30 m), intermediate (30-90 m) and deep aquifers (>90 m). Color coding shows wells at 10 µg L\(^{-1}\) (blue), 10-50 µg L\(^{-1}\) (green) and >50 µg L\(^{-1}\) (red) standards. The bottom right map shows DTWs with 100 meter radius, the average distance villagers are willing to walk to collect their daily drinking water supply.
Figure 2: Village ranking based on weighted exposure (mean As concentration × number of wells) in µg L⁻¹, village score (average score of each village calculated by the site scoring method used in this study), and proportion unsafe (number of unsafe wells/ total number of wells) at 10, 50 and 100 µg L⁻¹ thresholds. Weighted exposure can address two times more exposure compared to site scoring and proportion unsafe criteria. Surprisingly, different thresholds have little impact on exposure reduction.
Figure 3: Cumulative exposure vs cumulated number of DTWs needed for village level exposure reduction. Here, proportion unsafe at 10, 50 and 100 \( \mu g \) \( L^{-1} \) thresholds almost always reduce more exposure than weighted exposure. The head and tail of the graph is shown in enlarged version on the right. Village size might be the cause behind this flip as big villages do not have the highest proportion of unsafe wells and vice versa.
Figure 4: Intermediate tube wells (ITWs) in Araihazar at three depth intervals (45-90 m) considering 50 µg L$^{-1}$ (top) and 10 µg L$^{-1}$ As standards (bottom). The blue shaded areas indicate villages where at least 75% wells are safe. Similarly, the red shaded areas are villages with at least 75% unsafe wells.
Figure 5: Some screenshots of the site scoring application ‘Nolkup’: 1) Site score calculated from total number of unsafe wells (11) and number of DTWs (2) within 100 m radius of the search location. The solid line represents 100 m radius, whereas the broken line represents 200 m radius. Wells are shown in three color schemes: red (>50 µg L\(^{-1}\)), green (10-50 µg L\(^{-1}\)), and blue (<= 10 µg L\(^{-1}\)). 2) Information on the ITWs (30-90 m) and DTWs (>90 m) are accessible by tapping the righthand corner button. DTWs are shown as big blue dots. 3) Additional information (i.e., As content, depth) on a well are available by tapping on a specific well. Demo video is accessible here: https://youtu.be/Rf-55vY6FuQ
Tables

Table 1: Comparison of the three datasets used in this study collected from Araihazar, Bangladesh

<table>
<thead>
<tr>
<th>Database</th>
<th>Year</th>
<th>Data points</th>
<th>No of villages</th>
<th>Depth (m)</th>
<th>Arsenic content (µg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shallow wells (&lt;30m)</td>
<td>Intermediate wells (30-90m)</td>
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<td>HEALS*</td>
<td>2001-02</td>
<td>5,560</td>
<td>77</td>
<td>4,689</td>
<td>867</td>
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<td>BAMWSP**</td>
<td>2002-03</td>
<td>29,151</td>
<td>276</td>
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<td>5,936</td>
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<td>46,969</td>
<td>290</td>
<td>34,705</td>
<td>11,351</td>
</tr>
</tbody>
</table>

* HEALS = Heath Effects of Arsenic Longitudinal Study

** BAMWASP = Bangladesh Arsenic Mitigation and Water Supply Program

*** ATP = Arsenic Testing Plant