Targeting low-arsenic groundwater with mobile-phone technology

in Araihazar, Bangladesh

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Abstract

The Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP) has compiled field-kit measurements of the arsenic content of groundwater for nearly 5 millions wells. By comparing the spatial distribution of arsenic inferred from these field-kit measurements with geo-referenced laboratory data in a portion of Araihazar upazila, we show here that BAMWSP data could be used to target safe aquifers for the installation of community wells in many villages of Bangladesh. We also describe our recent experiences using mobile-phone technology to access and update BAMWSP data in the field. We show that the technology, without guaranteeing success, could optimize interventions by guiding the choice of the drilling method that is likely to reach a safe aquifer and identifying those villages where exploratory drilling is needed.
Introduction

Elevated concentrations of arsenic (As) in Bangladesh groundwater were first reported in 1993 (BGS/DPHE, 2001). Broader-scale sampling and laboratory testing subsequently established the regional extent of the problem (Dhar et al., 1997; BGS/DPHE, 2001). These surveys, drawn from a small fraction (~0.1%) of existing wells, guided the selection of a subset of 269 out of 490 upazilas where a blanket survey of millions tube wells was coordinated under the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP) and carried out by various organizations including UNICEF. For logistical reasons, these blanket surveys have relied on field kits rather than laboratory measurements. The nearly 5 million field-kit results compiled by BAMWSP as of May 2005 provide the most extensive and detailed representation of the spatial distribution of As in Bangladesh groundwater to date (Fig. 1a). Maps drawn on the basis of the BAMWSP data to show the proportion of unsafe wells in each surveyed upazila are broadly consistent with previous surveys (we refer in this paper to the status of a well relative to the Bangladesh standard of 50 ug/L As in drinking water, unless the World Health Organization (WHO) guideline value of 10 ug/L is specified). The purpose of the present study is to show that the large quantity of field-kit data compiled by the National Arsenic Mitigation Information Center (NAMIC; http://www.bamwsp.org/search.htm) and disseminated by BAMWSP could be used to target those aquifers that are low in As when examined at the village level. The paper also describes how BAMWSP data can be accessed and updated from the field using mobile phone technology that is readily available in Bangladesh.

In spite of its scale, the impact of the blanket-testing campaign is not well know because household responses to well testing have rarely been quantified. Response surveys that were
conducted in Columbia University’s study area of Araihazar upazila indicate that blanket testing led roughly half the affected households to switch their water consumption away from those wells that were identified as unsafe (van Geen et al., 2002; Madajewicz et al., in review; Opar et al.; in press; Schoenfeld et al., in preparation). While this represents a very significant benefit of well testing, the same observations also show that a significant number of households did not stop drinking water from their well after learning that it was unsafe. The premise of this study is that the installation of one or several safe community wells in the most affected villages holds particular promise to reach those remaining households. Our experiences in Araihazar suggest that the benefit of such installations can be direct, in the sense that safe water is provided to households living within walking distance of a community well, but also indirect because a successful installation serves as a guide to the installation of safe private wells to the same depth that are likely to follow (van Geen et al., 2003a; Opar et al., in press).

Safe community wells could over time be connected to rural piped-water supply systems, although we believe that priority should be give to providing point-sources of safe water throughout the country. We do not claim that alternative approaches to arsenic mitigation such as shallow dugwells, arsenic removal from groundwater, surface water treatment, or rainwater collection, have no role to play in Bangladesh (e.g. BRAC, 2000; Ahmed, 2002). We merely point out that these alternatives are a more radical departure from the current household practice of relying primarily on shallow tube wells to obtain drinking water, compared to switching to a deeper community well.
An argument against continued reliance on tube wells of any sort is that concentrations of As in groundwater could increase over time. Various mechanisms that could lead to such an increase have been proposed but have not been substantiated by systematic observations (Burgess et al., 2000; Chakraborti et al., 2001; Harvey et al., 2002). The most troubling evidence of increases in As concentrations over time comes from West Bengal where a same set of wells were sampled 5 years apart (Chakraborti et al., 2001; Sengupta et al., 2004). By and large, however, published results indicate that if As concentrations change over time, they probably affect only a minority of wells in Bangladesh (BGS/DPHE, 2001; van Geen et al., 2005; Cheng et al., 2005; Cheng et al., in press). Volumetric considerations also suggest that increases in As concentration in deeper aquifers in response to increased withdrawals with hand-pumps is unlikely (Zheng et al., in press). Contamination of deeper aquifers with shallow groundwater elevated in As could occur if mechanized pumping of much larger volumes of water for irrigation were to tap deeper aquifers. More likely than the large-scale contamination of deep aquifers appears to be local contamination due to a faulty pipe connection that leads to entrainment of shallow groundwater elevated in As (Aggarwal et al., 2000; Cheng et al., 2005). Faulty construction may partly explain scattered but significant trends showing an increase in As concentration with well age (BGS/DPHE, 2001; van Geen et al., 2003c; McArthur et al., 2004; Rosenboom, 2004). It is principally for this reason that all wells from which water is regularly drawn for drinking or cooking should be tested periodically for As.

Since a case can be made for continued reliance on groundwater in Bangladesh, how could BAMWSP data be used more effectively to install safe wells? This is demonstrated in this paper by first reviewing the sample collection and analysis procedures followed in Araihaazar by
Columbia University and the University of Dhaka (CU/UD), as well as BAMWSP. Technical aspects of down- and uploading well data using mobile phones are also reviewed. The results section starts by comparing the spatial distribution of As in groundwater inferred from BAMWSP field-kit measurements and geo-referenced laboratory data in 10 villages of Araihazar. Predictions based on a simple algorithm developed by Gelman et al. (2004) to identify the likely transition to a safe aquifer are shown to compare favorably with the actual depths of 23 community wells installed in the area. The discussion expands the analysis by considering BAMWSP data for the ~300 villages in the entire upazila. Examples drawn from the BAMWSP data are then used to show how existing mobile phone technology can be used to guide the installation of safe wells.

**Methods**

*Well-water collection and analysis:* A total of 6500 tube well samples were collected from 60 villages distributed over a 25 km² area in 2000-2001 by CU/UD. The location of each sampled well was determined with handheld GPS receivers; well depth was estimated on the basis of the number of PVC pipes that went into the construction of the well, as recalled by the owner. Details of the quality control procedures that were followed for analysis by graphite-furnace atomic absorption of dissolved As are provided by van Geen et al. (2003c). Placards reporting the results were posted on the wells a first time in 2001 and a second time in 2004 (Opar et al., in press).

Approximately 30,000 tube wells were tested throughout Araihazar with the Hach kit by teams of NGO workers hired by BAMWSP in 2002-2003. The spout of each well was painted red or
green for test results corresponding to an As concentration $\leq 50$ and $>50$ ug/L, respectively. In addition to test results reported as one of several ranges of As concentrations, the depth of each well and the name of the village and higher administrative units was recorded on paper forms and manually entered in a database in Dhaka.

The quality of As measurements obtained with field-kits has been challenged by Rahman et al. (2002) but this is no longer a major issue. Of the nearly 5 million tests compiled by BAMWSP, roughly half were conducted using the Hach field kit that became available in 2001. Intercalibration with laboratory measurements has shown that field workers hired by BAMWSP correctly identified the status of the vast majority of wells relative to the Bangladesh standard of 50 ug/L for As in drinking water with the Hach kit in Araihazar (van Geen et al., 2005). The reliability of previous measurements conducted with other kits may have been lower (Rahman et al., 2002), but as we show in this paper, the impact of occasionally poor measurements is limited when trying to identify spatial patterns for the installation of community wells.

**Installation of community wells:** Between January 2002 and October 2003, 23 community wells were installed in 8 of the 10 villages for which complete coverage with both laboratory and field-kit data is available (An additional 27 community wells were installed in surrounding villages.). All but 3 of these wells are less than 230 ft (69 m) deep and were installed by a local drilling team using the entirely manual “hand-flapper” method. The three community wells ranging in depth from 340 to 490 ft (102-147 m) were installed by an outside team of drillers using a hydraulic “dunkin” pump and a tall bamboo rig. In most cases, drilling continued until orange-brown aquifer material typically associated with low As concentrations was reached (Horneman
et al., 2004; Zheng et al., in press). Immediately after installation, the community wells were tested for As with the Hach kit and later in the laboratory by high-resolution inductively coupled plasma mass spectrometry (HR ICP-MS), a method that is considerably more accurate than GFAA at low As concentrations (Cheng et al., 2004).

**Algorithm for estimating safe-depth thresholds:** Gelman et al. (2004) developed a search algorithm for estimating safe-depth thresholds for spatial clusters of ~75 wells. In this paper, we replace the previous terminology with the expression “start depth”, to emphasize the possibility of having to drill deeper before a safe aquifer is reached. The algorithm starts from the deepest wells and identifies a start depth below which one can be reasonably confident of the presence of groundwater that is low in As. A single aberration or outlier, which could reflect an incorrect depth or As entry, is accommodated by the algorithm. To estimate the probability that a well drilled below the start depth is safe, the algorithm follows an approximate Bayesian approach that takes into account the number of safe wells below the start depth as well as occasional unsafe wells (Gelman et al., 2004). For those clusters of wells where no start depth can be identified, the algorithm produces a minimum depth below which the start depth still needs to be determined. In the present study, the same search algorithm was used to analyze clusters of wells defined by village name rather than geographic position.

**Mobile phone and server technology:** The first technology that was tested in Bangladesh relied on client software that was purposely developed and required a Java-enabled mobile phone. Such phones are available in Bangladesh but are not widely used because they, as well as the access to the Internet that these phones provide, are relatively expensive. The technology
was modified in November 2005 to allow users to download and update BAMWSP data through the Short Message Service (SMS) offered by local providers. SMS is popular throughout Bangladesh and works on less expensive phones. SMS is also more reliable than the Internet protocol and less expensive. In the present configuration, a mobile phone is connected to a laptop acting as a server. SMS requests are handled by jSMSEngine and mySQL, a robust open software model database server. The software queries the database, runs a search algorithm programmed in R that estimates the start depth, and sends the response back to the mobile phone via SMS. In remote areas, mobile phone service is sometimes unavailable. In that situation, users can save the message and resend when the network becomes available.

Results

**Comparison of laboratory and field-kit data:** The depth distribution of As inferred from the two data sets is compared for 10 villages containing 20-400 wells each that were covered in their entirety by both surveys (Fig. 2a). The CU/UD and BAMWSP surveys inventoried a total of 2205 wells in 2000-2001 and 2396 wells in 2002-2003 in these villages, respectively. The increase in number of wells is consistent with previous observations (Opar et al., in press). The generally higher proportion of unsafe wells reported by the CU/UD surveys, higher by 12±9% on average (Fig. 3b), also matches the observation that most inconsistencies between the two methods reflect an under-reporting of unsafe wells by the BAMWSP survey for wells containing 50-100 ug/L As (van Geen et al., 2005).

The depth distribution of As inferred from the two surveys is broadly consistent, taking into account that new wells were installed after the CU/UD survey (Fig. 4). In the relatively small
village of Kadamdi, for instance, both surveys indicate a predominance of unsafe wells and shallow wells (<80 ft (24 m)). Both surveys indicate a predominance of shallow wells also in the small villages of Narindi and Chhota Manohardi, although with a somewhat higher proportion of safe wells. These distributions contrast sharply with the larger village of Bara Manohardi where, for instance, both surveys show unsafe wells extending to ~100 ft (30 m) and 20-30 wells beyond this depth that are mostly safe. The situation is analogous in the relatively large villages of Edbardi or Ujan Gobindi. Significantly, the BAMWSP survey indicates that a number of the deeper, safe wells were installed after the first survey was completed in these three villages, as well as Binair Char and Laskardi (Fig. 4).

**Start depths and community wells:** It is instructive to compare the depth of the installed community wells with the start depths even if the drilling was conducted before the algorithm became available. In Laskardi village, for instance, the 2000-2001 survey could identify only a minimum depth of 190 ft (57 m) for the start depth (Fig. 4a). Three community wells meeting the WHO guideline of 10 ug/L for As were subsequently installed at depths ranging from 185-230 ft (56-69 m; Table 2). These are probably some of the recent and deeper wells that were subsequently tested by BAMWSP in the same village, even if the reported depths do not exactly match (Fig. 4a). On the basis of these new wells, a revised start depth of 165 ft (50 m) with a probability of 0.84 is estimated by the algorithm (Table 1). This is a situation where the installation of a few wells can change the perception of the options available to households by indicating that a safe aquifer is readily accessible using the local “hand-flapper” drilling method. The situation evolved in a similar fashion between the two surveys for Edbardi (Fig. 4b) and Bara Manohardi (Fig. 4a) villages, although in those cases the algorithm could already identify a
start depth ranging from 120-200 ft (36-60 m) on the basis of the data collected in 2000-2001. In several cases, the exclusion of an occasional outlier by the algorithm was justified by subsequent installations.

The situation is not as clear-cut for several other villages. In Maruadi, for instance, the installation of 3 community wells shallower than 200 ft (60 m) was successful. Yet, the algorithm yields a start depth of 200 ft (60 m) with a probability of 0.79 on the basis of the subsequent BAMWSP survey (Fig 4a). The reason is the presence of a significant number of unsafe wells in the 100-200 ft (30-60 m) range reported by both surveys. This could be due to errors in data collection and entry or, more likely, significant variability in the subsurface geology of this particular village. This may be the case also in Binair Char and Ujan Gobindi villages (Fig. 4b). In each of these villages, at least one safe community well was successfully installed at a depth that was consistent with the start depth identified by the 2000-2001 data. But for one other location in each of these villages, drilling had to be extended beyond 300 ft (90 m) by a drilling team using a “dunkin” pump to reach the orange-brown aquifer material associated with low As concentrations in groundwater. The variability of the subsurface geology therefore appears to be particularly complex in these two villages.

A different situation was encountered in Balia Para. In that village, four community wells that were installed in the 180—220 ft (54-66 m) depth range initially all met the WHO guideline for As of 10 ug/L (Fig. 4a). Then, one of these community wells started to produce groundwater with a very high As concentration and had to be shut down. It is not clear at this point why this happened, but a similar situation was documented for another community well in the area and
attributed to a faulty shallow pipe connection (Cheng et al., 2005). A community well was reinstalled to the same depth and at the same location in Balia Para and currently produces groundwater that meets the Bangladesh standard for As but not the WHO guideline (Table 2).

**Accessing and updating safe-depth thresholds in the field:** For access to the BAMWSP database, the unique geocode of a specific village must first be determined. This is accomplished through a series of short queries sent by SMS that must include at least three sequential letters in the upazila, union, mouza, or village name. The system responds to the query, typically within a few seconds, with the possible names from which the correct administrative units can be selected. The information that is returned for each of these queries can be retained for the next step by replying with the edited text of the previous response. Some flexibility in transliteration of village names from Bangla to Roman letters is allowed because the user can test various combinations of letters. Global Position System (GPS) coordinates can be entered as an alternative to the name-based search. Once the geocode of a village has been received by SMS, it is sent to the server with a simple command to obtain a summary description of the local test data. The summaries, illustrated in Fig. 4, include the number of wells tested, the proportion of unsafe wells and, when available, the start depth together with an estimate of the probability that the estimate is correct. Additional information in the form of a summary of the test data in various depth intervals is also provided. The server automatically adapts the depth intervals of this display to the depth-distribution of the results available for that particular village.
The technology also allows users to report to the server results for newly-tested wells from the field, together with well location and well depth. The grey or orange color of sandy aquifer material encountered during drilling to install a well, which provides a valuable geological context, can be uploaded. Whereas the goal is to provide access to the latest start depth estimate for anyone using SMS, only certified users provided with a password can upload new test results or geological information.

**Discussion**

*Other constituents of potential health concern:* Arsenic is not the only constituent of groundwater that should be considered when installing new wells. The BGS/DPHE (2001) survey showed that 35% of the 3534 samples of well water from across the country that were tested exceeded the WHO guideline value for Mn of 0.5 mg/L at the time. The WHO guideline value for Mn has since then been reduced slightly to 0.4 mg/L ([http://www.who.int/water_sanitation_health/dwq/chemicals/manganese.pdf](http://www.who.int/water_sanitation_health/dwq/chemicals/manganese.pdf)). Exposure to Mn via inhalation is known to be neurotoxic, but little is known about possible consequences of exposure via drinking water. A recent study conducted in Araihazar has shown a significant reduction in children’s intellectual function at Mn concentrations >1.0 mg/L compared to children drinking groundwater with <0.2 mg/L (Wasserman et al., in press). The study built on previous work in Araihazar demonstrating that children’s intellectual functions were also measurably reduced by drinking groundwater containing >10 ug/L As (Wasserman et al., 2004). Although both As and Mn are naturally released by aquifer particles under reducing conditions, there is no simple relation between their concentrations in Bangladesh groundwater. Many groundwater samples containing little As are enriched in Mn, and vice-versa (BGS/DPHE, 2001;
Cheng et al., 2004). Unfortunately, deeper aquifers that are low in As can still contain significant levels of Mn. Among the 23 community wells that were installed in 10 villages of Araihazar, for instance, a total of 7 wells exceed the new WHO guideline of 0.4 mg/L by up to a factor of nearly 3, counting only once the site where a well had to be re-installed (Table 2). The 7 wells elevated in Mn were less than 230 ft (69 m) deep, however. The implication is that, at least in Araihazar, drilling to a depth of >230 ft increases the chances of reaching groundwater that with both As and Mn concentrations that are sufficiently low.

Several attempts to install community wells in Araihazar were unsuccessful not because the groundwater contained too much As or Mn, but because it was too salty due to a pocket of old seawater. Drinking water typically tastes salty starting at a Na concentration of ~200 mg/L (i.e. ~2% seawater), which is the case for 6 out of 23 community wells installed in Araihazar (Table 2). Even if the salt content of well water may not be a major health concern, a salty community well will not be used by villagers and therefore will not reduce exposure to As. Because of the complex geological history of Bangladesh, it may therefore take several attempts in certain villages to reach an aquifer with acceptable levels of As, Mn, and salt.

**Extension to an entire upazila:** In this section, we expand the evaluation of potential interventions in the form of community wells to the entire upazila. A closer look at the proportion of unsafe wells in individual villages first reveals that upazila boundaries are arbitrary in terms of the As content of well water. This is because the distribution of As in the subsurface is determined by the variability of local geology over a range of spatial scales (van Geen et al., 2003c; Yu et al., 2003). In Araihazar, for instance, the average proportion of unsafe wells of
32% for the entire upazila obscures the fact that villages in the southwestern half of the upazila are much more affected than in the remaining portion (Fig. 1b). Such patterns also suggest that some villages in the upazilas that were not selected for blanket surveying may contain an elevated proportion of unsafe wells.

How does the entire upazila compared to the 10 villages that were examined in detail? Most villages of Araihazar are relatively small: 115 out of 302 villages (38%) contain <50 wells whereas only 40 villages (13%) contain >200 wells (Fig. 5). Less than one fifth of the wells are unsafe in 99 villages (33%) of Araihazar, while the problem is much more severe in the 35 villages (12%) where over four fifths the wells are unsafe (Fig. 6). In 195 villages of Araihazar (65%), the search algorithm identifies a safe-depth threshold <300 ft and the probability that these safe-depth thresholds are correct ranges from 0.50 to 0.99 (Fig. 7). On the basis of similar conditions encountered in the 10 villages of Araihazar where interventions have already taken place, a local team of drillers using the hand-flapper method should be able to install safe community wells <300 ft deep in most of the 195 villages. Past experience also suggests that the teams should also be prepared to have to drill deeper than the local depth-threshold, however. To maximize the chance of installing a well that meets WHO guidelines for both As and Mn, drilling should generally continue until aquifer material that is orange-brown in color is reached (van Geen et al., 2003c; Horneman et al., 2004). In those cases where such material is not reached, a recently-developed sampling device could be deployed and the groundwater tested before the actual installation of a well (van Geen et al., 2004). The drilling is likely to be disappointing in at least some of the 195 villages identified by the search algorithm, particularly those for which the estimated safe-depth threshold is >200 ft and/or the probability of the
estimate is relatively low (e.g. <0.8). In such cases, a drilling team equipped with a dunkin pump may eventually have to be called in, as was the case in the village of Binair Char.

Two categories of villages were under-represented in the initial set of 10 villages that were studied in detail. These are, on one hand, the 65 (22%) out of 302 villages in Araihazar for which the search algorithm could not identify a safe-depth threshold on the basis of the BAMWSP data. For all but 3 of these villages, the minimum estimated safe-depth of <300 ft probably justifies exploratory drilling using a team of local drillers using the hand-flapper method. The proportion of drilling that turns out to be unsuccessful is likely to be greater than for the previous category of villages for which a safe-depth threshold could be estimated. A third and last category of the classification includes those 42 villages (14%) for which the algorithm has identified a safe depth >300 ft. In such cases, a team with a dunkin pump should probably be called in without incurring the expense of drilling a hole with the hand-flapper method. Exceptions could be made for those villages where little or no data are available from past testing for the 200-300 ft range and where a safe aquifer <300 ft could therefore conceivably be identified.

**Prioritizing interventions:** The goal of interventions in Araihazar is obviously to give access to safe water to the entire population of ~300,000. But even if resources were unlimited, it would be important to target the most affected villages first. In this context, it is worth pointing out that there is no systematic relationship between start depths and the proportion of unsafe wells in a village (Figs. 8, 9). The search algorithm produces a start depth that is either unidentified or >300 ft for many villages with <50% unsafe wells. By the same token, there are many villages
with >50% unsafe wells where the algorithm has identified a start depth <300 ft. The practical implication is that the proportion of unsafe wells as well as the start depth should be considered when prioritizing interventions.

The BAMWSP data allow us to estimate the number of wells that are most urgently needed throughout the upazila, and how they should be installed. We consider only those villages containing more than 10 wells, which eliminates 10 villages that are likely to be very small or thinly populated out of a total of 278 for which complete information is available. We would also propose to restrict interventions at first to those villages with a proportion of unsafe wells 50%. Taking into account the geographic extent of the larger villages documented for the portion of Araihazar studied in detail (Fig. 2), we would propose to install one community well for each unit of 100 wells, or fraction thereof, that has been inventoried in a particular village. We also distinguish villages according to the start depth estimated by the search algorithm. For the 150 villages of Araihazar with an estimated start depth <200 ft (60 m), we propose to limit the intervention at first to the provision of specific advice. The expectation is that, in most cases, households or communities that are not willing to share existing safe wells will be able to install their own relatively shallow but safe well. No emergency subsidy should probably be provided for these installations. The next category includes those 32 villages with a known start depth ranging between 200 and 300 ft (60-90 m) and 54 villages whose start depth is unknown but might be <300 ft (Table 3). Using the criteria listed above to identify the subset of prioritized villages, the installation of 73 community wells should be attempted using the hand-flapper method in this subset of villages. In the prioritized subset of 42 villages where the start depth is
at least 300 ft, instead, a team of drillers equipped with a dunkin pump should be called in to attempt the installation of 27 wells.

**Installing community wells throughout the country:** There is no technical difficulty involved in storing, retrieving, and updating BAMWSP data for additional upazilas now that the mobile phone technology has been developed for one upazila. Doing so for the entire BAMWSP dataset could therefore immediately help the Bangladesh Department of Public Health Engineering (DPHE) optimize its on-going program of well installation throughout the country. How many wells would have to be installed to reach coverage comparable to that estimated above for Araihazar? On the order of 17,000 wells, considering that 50,000 villages distributed over 250 upazilas have been surveyed under BAMWSP and assuming that a distribution of As over the entire area that is broadly similar to that of Araihazar. The process would take over a decade, however, at the current rate of installation of ~1000 wells per year under the current DPHE structure. The possible implication is that DPHE should focus its efforts on installing community wells by contracting teams of drillers using a dunkin pump, while leaving installations by local teams of drillers using the hand-flapper method to a different type of organization. The decentralized structure of a large non-governmental organization such as BRAC might be more suitable for supervising well installations relying on local teams of drillers in those villages where this approach is likely to be successful. If the mobile phone technology could be systematically used by DPHE and NGO workers involved in well installations to upload sand color, well depth, and field-kit results, the national data set would become increasingly valuable over time and reduce the risk of installing unsafe wells.
Conclusion

This analysis of existing data from Araihazar upazila illustrates how BAMWSP data interpreted at the village scale can guide the installation of safe community wells. SMS-based mobile phone technology can provide an inexpensive and convenient means of accessing and, just as importantly, updating the BAMWSP data set from any location. Start depths calculated on the basis of up-to-date information could help choose the drilling technology and the type of organization that is most suited to the installation of safe community wells throughout the country.
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**Table 1** Properties of 10 villages of Araihazar surveyed twice in their entirety by Columbia University and the University of Dhaka (CU/UD) and the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP).

<table>
<thead>
<tr>
<th>Village</th>
<th>CU/UD</th>
<th>BAMWSP</th>
<th></th>
<th>Start depth</th>
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<td>No. wells</td>
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<td>232</td>
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<td>200</td>
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<tr>
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<td>29</td>
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Table 2  Characteristics of 23 community wells installed in 8 villages of Araihazar, including the arsenic (As), manganese (Mn), iron (Fe), and sodium (Na) content of well water. (* re-installed well.)

<table>
<thead>
<tr>
<th>Village</th>
<th>CW ID</th>
<th>Installation</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (ft)</th>
<th>As (ug/L)</th>
<th>Mn (ug/L)</th>
<th>Fe (mg/L)</th>
<th>Na (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balia Para</td>
<td>38</td>
<td>Oct 03</td>
<td>23.7692</td>
<td>90.5851</td>
<td>180</td>
<td>349</td>
<td>0.6</td>
<td>2.2</td>
<td>467</td>
</tr>
<tr>
<td>&quot;</td>
<td>38*</td>
<td>Mar 05</td>
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<td>90.5851</td>
<td>180</td>
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</tr>
<tr>
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<td>23.7740</td>
<td>90.5923</td>
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<td>3</td>
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<td>0.1</td>
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<td>0.6</td>
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<tr>
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</tr>
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<tr>
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<td>332</td>
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<td>23.7736</td>
<td>90.6045</td>
<td>185</td>
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<td>0.5</td>
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<td>0.2</td>
<td>1.9</td>
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</table>
Table 3 Categories of villages in Araihazar and number of community wells that would be required to intervene in all villages containing at least 10 wells and a proportion of unsafe wells $>0.5$. The number of community wells required per village was calculated assuming 1 CW per 100 wells or fraction thereof.

<table>
<thead>
<tr>
<th>No. villages</th>
<th>No. of CWs</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start depth &lt;200 ft</td>
<td>150</td>
<td>32</td>
</tr>
<tr>
<td>Start depth 200-300 ft</td>
<td>32</td>
<td>39</td>
</tr>
<tr>
<td>Start depth &gt;300 ft</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>No start depth but &lt;300 ft</td>
<td>54</td>
<td>34</td>
</tr>
<tr>
<td>No start depth and &gt;300 ft</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>278</td>
<td>132</td>
</tr>
</tbody>
</table>
Figure captions

Figure 1  (a) Map of available BAMWSP results, color-coded according to proportion of unsafe wells at upazila level (http://www.bamwsp.org); (b) expanded view of Araihazar upazila showing the proportion of unsafe wells in 297 villages using the same color scheme. The coordinates of a central location of 109 villages was determined with a handheld GPS receiver. For the remaining villages, a central location of the mouza to which they belong was read from the upazila map. Whenever a mouza contains more than one village whose precise location was not determined, symbols representing each village were lined up vertically below a central mouza location. The rectangle delineates the CU/UD study area enlarged in Fig. 2.

Figure 2  Expanded view of 10 villages in Araihazar surveyed by Columbia and BAMWSP identifying by color (a) the location of wells belonging to the different villages and (b) the arsenic content of well water. The location of community wells is indicated by triangles.

Figure 3  Comparison of (a) number of safe wells for 10 overlapping CU/UD and BAMWSP villages and (b) proportion of safe wells for the same 10 villages. Open symbols show results for wells reported to be installed through 2000; closed symbols show the results for the entire BAMWSP data set.

Figure 4  Comparison of CU/UD and BAMWSP results for 10 individual villages as a function of depth and year of installation, together with the output from the safe depth algorithm. The actual depths selected for the installation of 23 community wells are shown by colored triangles.
**Figure 5** Histogram of the number of wells in the 300 villages of Araihazar based on the BAMWSP survey.

**Figure 6** Histograms of the proportion of safe wells for the ~300 villages of Araihazar based on BAMWSP data.

**Figure 7** Scatter plot comparing start depth and the probabilities that the start depth is correct for those 261 villages where these parameters could be estimated from BAMWSP data.

**Figure 8** Map showing the spatial distribution of start depths and minimum depths to a safe aquifer throughout Araihazar on the basis of BAMWSP data.

**Figure 9** Comparison of start depths and minimum estimates for start depths with the proportion of unsafe wells in the 300 villages of Araihazar. Symbols are the same as in Figure 8.
JHPN Figure 1a,b

Arsenic Contamination in Bangladesh
Update 2018: Combined Result of The National Screening Program

Percentage of Tubewell Contamination:
- Below 0.1 mg/L
- 0.1 - 0.5 mg/L
- 0.5 - 1.0 mg/L
- 1.0 - 5.0 mg/L
- Above 5.0 mg/L

JHPN Figure 1a,b