Research Paper

Inequitable allocation of deep community wells for reducing arsenic exposure in Bangladesh

A. van Geen, K. M. Ahmed, E. B. Ahmed, I. Choudhury, M. R. Mozumder, B. C. Bostick and B. J. Mailloux

ABSTRACT

Community wells that extend deeper than most private wells are crucial for reducing exposure to groundwater arsenic (As) in rural Bangladesh. This study evaluates the impact on access to safe drinking water of 915 such intermediate (90–150 m) and deep (>150 m) wells across a 180 km^2 area where a total of 48,790 tubewells were tested with field kits in 2012–13. Half the shallow private wells meet the Bangladesh standard of 50 μg/L for As in drinking water, whereas 92% of the intermediate and deep wells meet the more restrictive World Health Organization guideline for As in drinking water of 10 μg/L. As a proxy for water access, distance calculations show that 29% of shallow wells with >50 μg/L As are located within walking distance (100 m) of at least one of the 915 intermediate or deep wells. Similar calculations for a hypothetical more even distribution of deep wells show that 74% of shallow wells with >50 μg/L As could have been located within 100 m of the same number of deep wells. These observations and well-usage data suggest that community wells in Araihazar, and probably elsewhere in Bangladesh, were not optimally allocated by the government because of elite capture.

Key words | arsenic, Bangladesh, groundwater quality, public water supply allocations

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INTRODUCTION

Although the realization that shallow groundwater contained elevated levels of arsenic (As) dates to the late 1990s in Bangladesh, the population exposed in 2009 to levels above the World Health Organization guideline of 10 μg/L for drinking water was still estimated to be 52 million, almost half of whom were drinking water that did not meet the less restrictive Bangladesh standard of 50 μg/L (BBS/UNICEF 2011). Deep tubewells defined as >150 m deep by the government's Department of Public Health Engineering (DPHE) have become the mainstay of efforts to reduce exposure by providing public water points that are low in As (Johnston *et al.* 2014; Ravenscroft *et al.* 2014). One reason is that deep tubewells can supply drinking water that generally is of acceptable chemical and microbial quality for many years (van Geen *et al.* 2003, 2007; Howard *et al.* 2006; DPHE/JICA 2009; McArthur *et al.* 2010). A single deep tubewell located in a widely accessible public location can meet the needs of several hundred villagers (van Geen *et al.* 2003). Another reason for the popularity of deep wells is that although their cost of ~$850 (Ravenscroft *et al.* 2014) is beyond the reach of most individual households in Bangladesh, they require little maintenance compared to the pond-sand filters and hand-dug wells that were initially given precedence in As-affected areas under the government's arsenic-mitigation policy (Johnston *et al.* 2014). These factors help explain why a growing share of government and donor funding has been used to install deep wells, almost 200,000 as of 2007 and many more since (DPHE/JICA 2009; Ravenscroft *et al.* 2014). The present contribution was motivated by the fact that few studies have

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evaluated the extent to which this massive intervention has had the intended impact of increasing access to safe drinking water.

The installation of several hundred thousand deep wells throughout the country is a positive development but has not fully addressed the still serious public-health issue of As exposure (Flanagan *et al.* 2012; Johnston *et al.* 2014). At the regional scale, one reason is that over half the deep wells have been installed in areas where the proportion of shallow high-As wells is modest and low-As water can often be accessed by sharing existing wells (DPHE/JICA 2009). Millions of households in more affected areas still live beyond 100–150 m from a deep well, which is the distance previous studies have shown to be the maximum most villagers in rural Bangladesh are willing to walk to fetch water (van Geen *et al.* 2003; Opar *et al.* 2007). Another reason for concern is that the proportion of untested shallow private wells in Bangladesh has grown significantly and households therefore often do not realize that their well is high in As (Ahmed *et al.* 2006; WASH 2008; DPHE/JICA 2009; George *et al.* 2012). Finally, even when households know that their well is high in As and a deep well is within walking distance, the perceived health benefits are not always sufficient to motivate fetching water from it several times a day because of social and other factors (Chen *et al.* 2007; Madajewicz *et al.* 2007; Mosler *et al.* 2010; Inauen *et al.* 2013; Johnston *et al.* 2014; van Geen *et al.* 2014).

This paper addresses a different reason why deep wells have yet to reach their full potential in terms of providing safe drinking water: insufficient attention paid to where deep wells are installed and how this selection affects public access. We take advantage of a recently completed blanket survey during which all wells within a 180 km^2 rural area of Bangladesh with a population of 380,000 were tested with field kits and well-depth information was recorded (van Geen *et al.* 2014). The data are used to calculate distances from each shallow high-As well to the nearest deep low-As well as a proxy for impact on health. This measure has previously been shown to be an important factor affecting where households fetch their water in Bangladesh. Response surveys conducted in As-affected villages have shown that a majority of households living within 100 m of a community well switch to it and that this proportion drops off at greater distances (van Geen *et al.* 2003; Opar *et al.* 2007). Such responses have been confirmed by a particularly pronounced decline in urinary As levels for households that switch to a low-As community well (Chen *et al.* 2007). The distance calculations show that deep wells in Araihazar were not installed in a way that maximizes access to safe drinking water. After exploring possible reasons for the suboptimal allocation of this public good, the study concludes by suggesting that greater transparency and public discussions at the local level might increase the impact of future of deep-well installations.

METHODS

Well status

The present study covers all 290 villages of Araihazar upazila where a total of 48,790 tubewells were tested for As with the ITS Econo-Quick field-kit as part of a blanket survey conducted from February 2012 to September 2013. As previously described for a subset of 61 villages from Araihazar (van Geen *et al.* 2014), metal placards were placed on each well according to the kit result: blue for As $\leq$10 μg/L, green for 10< As $\leq$50 μg/L, and red for As >50 μg/L, while monitoring the quality of the testing over the course of the intervention. Laboratory measurements carried out for a random subset of 503 samples indicate that 16% of these wells were incorrectly labeled but that exchanges in category were all across the blue-green transition at 10 μg/L or the green-red transition at 50 μg/L (van Geen *et al.* 2014). In other words, not a single well within the set of samples re-analyzed in the laboratory that was labeled with a blue placard on the basis of the field kit should have been labeled with a red placard, and not a single well labeled red should have been labeled blue. The exchanges were largely limited to concentrations just above or below the two transitions and were balanced in terms of over- vs. under-estimates. Throughout the testing campaign, a small fraction of randomly selected wells were also independently re-tested by the field supervisor for verification.

Well depth

Well depths (Figure 1(b)) were recorded on the basis of the recollection of the installation by the owner or local

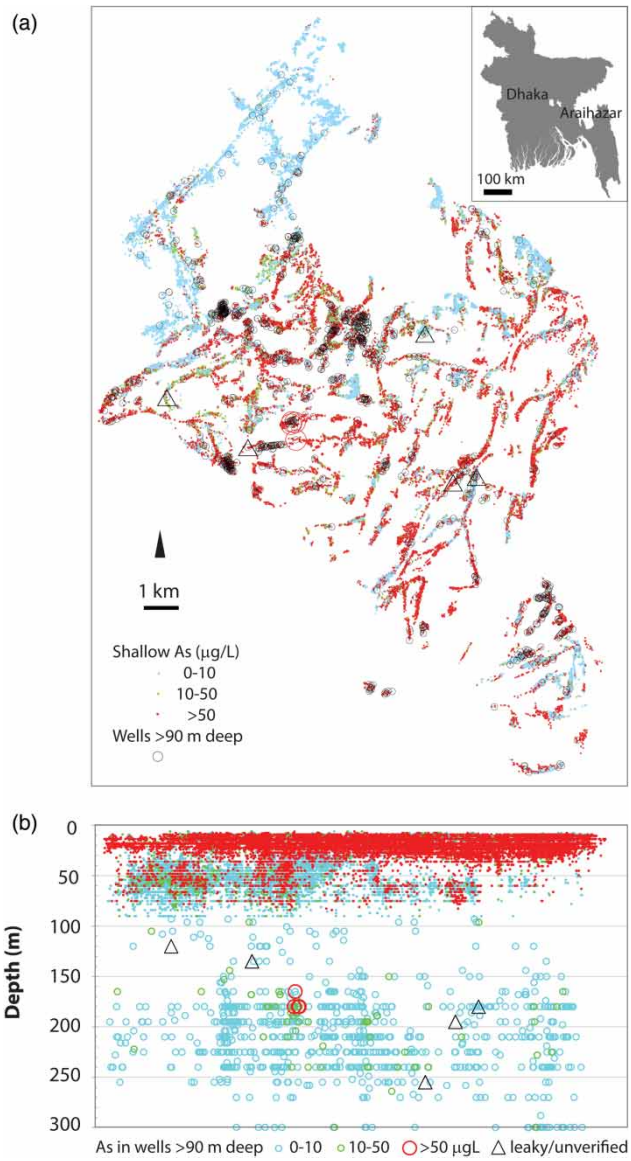

Figure 1 | (a) Map of Araihazar upazila with colored dots used to show the status of 48,790 wells tested with a field-kit in 2012–13 with respect to As. The inset shows in white the area covered by Metropolitan Dhaka and Araihazar within a map of Bangladesh. Shown as thin black circles with a radius of 100 m are the locations of 915 intermediate and deep (>90 m) wells. Black triangles indicate the location and depth of five deep wells with >50 µg/L As with leaky casings. Larger circles identify the location and four wells with >50 µg/L As that showed no indication of a shallow leak. (b) East-west depth section of the same data showing, in addition, the As content of deep wells according to the same color scale. Please refer to the online version of this paper to see this figure in colour.

users. On the basis of this information, the blanket survey identified a total of 927 intermediate (77) and deep (850) wells distributed across the study area. We refer here to wells in the 90–150 m depth as intermediate and wells >150 m as deep. We use a depth of 90 m (300 ft) to distinguish shallow private wells installed within a day by a handful of drillers using the manual hand percussion (or 'hand-flapper') method from intermediate wells in the 90–150 m depth range, which require a larger team working for several days using a manual rotary drilling-direct circulation method with a double-acting ('donkey') pump (Ali 2003). Following the DPHE definition, we characterize wells >150 m deep only as 'deep' even though they are installed by exactly the same method as intermediate wells. Owing to the limits of the technology, there is no reason to believe that wells installed by the hand-flapper and reported to be <90 m deep could be deeper. On the other hand, the actual depth of donkey-pump wells could potentially be shallower than reported because the driller could reduce his costs without informing the contracting party.

From a subset of wells, the pump head was removed and the depth checked with a metering cable weighted at the bottom. Twenty-five out of 927 intermediate and deep wells identified in 2012–13 contained >50 µg/L according to the original set of field tests. Among the 25 high-As wells, 11 turned out to be <90 m deep after verification. The depth of an additional well could not be checked because the owner did not give permission. The total number of intermediate and deep wells considered in this analysis is therefore 915, i.e., 927 minus the 12 wells whose depth turned out to be shallow or could not be verified.

Among the remaining 13 intermediate and deep wells identified in 2012–13 containing >50 µg/L according to the original set of field tests, four wells contained less than 50 µg/L As when re-tested with the field kit. Five of the remaining nine deep wells showed a clear indication of a leak of shallow water into the tubewell that could account for elevated As. The leaks were identified with a salt spiking method (Stahl *et al.* 2014) and a conductivity profiler (TLC Meter, Model 107, Solinst Canada Ltd, Georgetown, Ontario, Canada). Of the remaining four wells verified to contain As >50 µg/L and >90 m in depth, three contained 100–300 µg/L As and were located within the same village (Figure 2(a)). The fourth outlier contained 100 µg/L As and was located in a neighboring village at a distance of only 400 m.

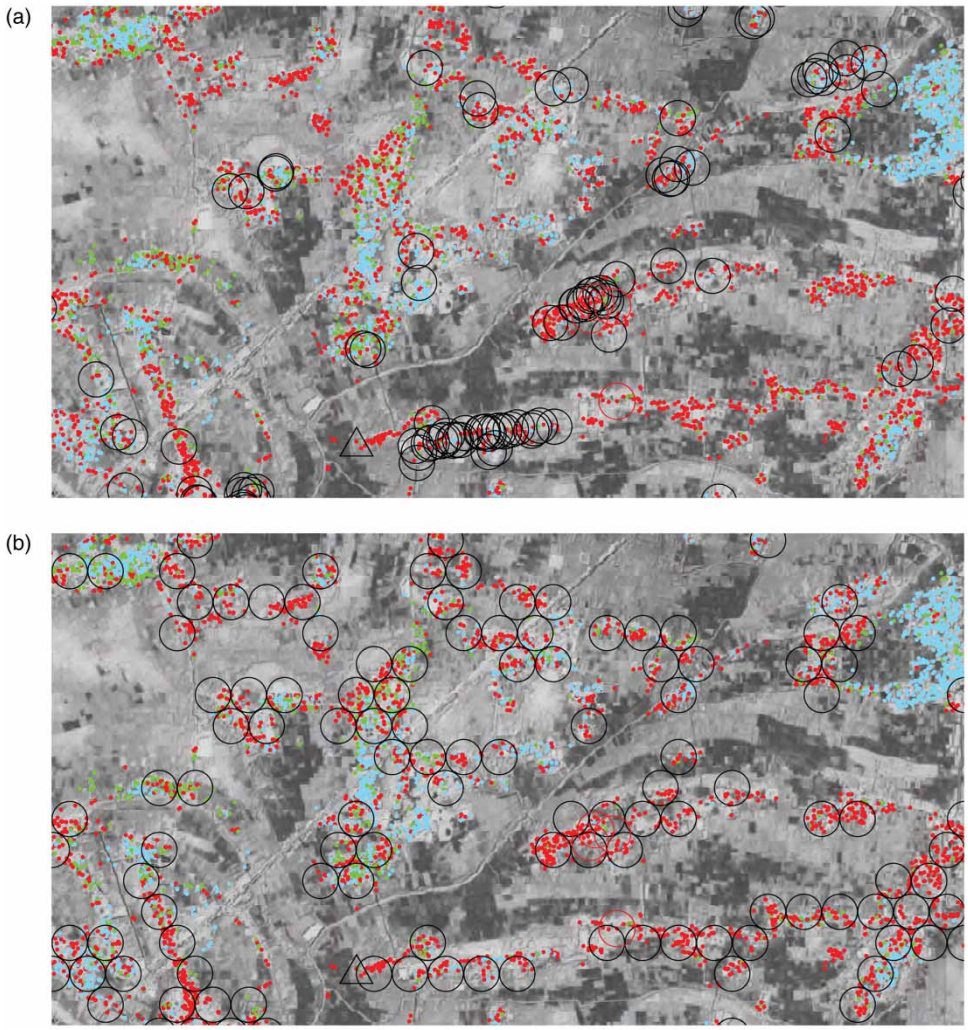

Figure 2 | Close-up map of a portion of Araihazar upazila with a high-resolution IKONOS image in grey-scale showing the status of wells with respect to As using the same symbols and color scale as in Figure 1: (a) the location of a subset of deep (>90 m) wells surveyed in 2012–13 and (b) the optimized location of a subset of the same number of wells selected from a regularly spaced grid. The two villages of Roynadi and Roynadi Kalagachhia contain four deep wells with >50 μg/L As that do not show evidence of a leak and are shown as larger circles. Please refer to the online version of this paper to see this figure in colour.

Well usage

Villagers residing near the intermediate and deep tubewells were interviewed at the pump/platform of 60 wells selected with a random number generator from two lists in order to independently assess the total number of users in October 2014. Thirty of the wells were randomly selected among the 150 wells installed at no charge to the community by Dhaka University in 2001–05 (van Geen *et al.* 2003, 2007) and, following an approximately 10% contribution provided by the local community, the non-governmental organization WaterAid, Bangladesh in 2009–10. These wells, referred to here as DU/WAB wells, were installed after consulting the local community about the location that would maximize the number of users. Thirty other deep wells installed between 2004 and 2013 were selected randomly among the remaining 765 (i.e., 915 minus 150) wells installed in Araihazar by the government's DPHE, typically in response to a local contribution of approximately 10% to the cost of installing a hand-pumped deep well (Ravenscroft *et al.* 2014). In addition, the accessibility of the two groups of 30 deep wells was compared qualitatively on a three-level

scale ranging from low (isolated area inaccessible to non-household members), to medium (limited access provided to neighboring households), and high (public location accessible to any villager).

Distance calculations

The position of each of the 48,790 wells tested in 2012–13 was determined with hand-held Global Positioning System receivers (Figure 1(a)). Distance calculations between shallow wells with >50 μg/L and the 915 intermediate or deep wells were carried out using the Proximity tool in ArcGIS 10.2.1. The deep well closest to each of the unsafe shallow wells was considered in order to avoid double-counting of red wells located within 100 m of more than one deep well in the cases of deep wells less than 200 m apart (Figure 2(a)). These distances were chosen because 100 m is the distance most villagers in rural Bangladesh are willing to walk to fetch water. The same calculation was performed for a hypothetical distribution of deep wells positioned 200 m apart across the entire study area (Figure 2(b)). For this calculation, the centers of alternating east-west rows of wells were positioned mid-way relative to each other and the rows were separated by 173 m (sin 60 ° × 200 m) in order to obtain the densest possible grid of non-overlapping circles 200 m in diameter. From this grid, the location of the 915 wells with the largest number of high-As wells located within 100 m were then selected for the analysis.

RESULTS

Blanket testing identified a total of 48,790 wells, the status of almost two-thirds of which was unknown with respect to As prior to the 2012–13 testing. The overall proportion of blue (<10 μg/L), green (10–50 μg/L), and red (>50 μg/L) placards attached to each well after testing was 44%, 10%, and 46%, respectively. In agreement with previous findings for a subset of 61 villages in Araihazar (van Geen *et al.* 2014), the vast majority (97%) of well owners or users were correct in their assessment that a well was unsafe relative to 50 μg/L. A smaller proportion (77%) was correct in their assessment that a well was safe. Among the 902 (927 minus 25) deep wells that did meet the national standard of Bangladesh for As in drinking water, the kit gave readings of 0 μg/L for 81% of the tests, 10 μg/L for 13%, 25 μg/L for 5%, and 50 μg/L for 1%.

The follow-up survey for the two random subsets of 30 deep wells indicates considerable differences in usage (Figure 3(a)). Only 5 of the 30 DPHE wells had more than 100 users and averaged 71 ± 14 per users per well (1 standard deviation divided by the square root of the number of wells). In contrast, 23 of the 30 DU/WAB community wells had more than 100 users, with a corresponding average of 229 ± 21 users per well. According to the survey, access was also restricted to only household members for 12 of the DPHE-installed wells and none of the DU/WAB-installed wells (Figure 3(b)). Twenty-four of the 30 (80%) DU/WAB wells fell within the highest public access category. A distance

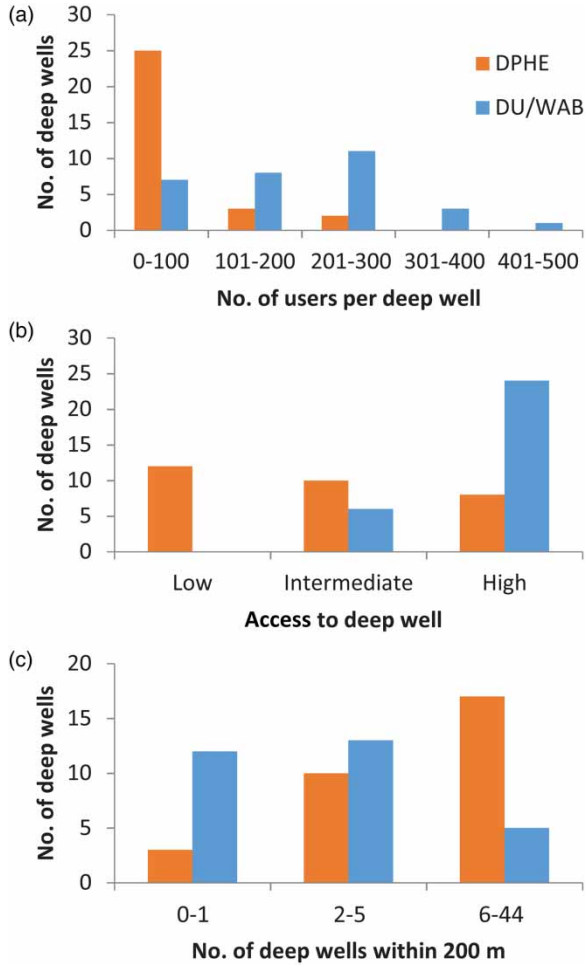

Figure 3 | Histogram of (a) the number of users per well, (b) the level of access to each deep well, and (c) the number of deep wells within 200 m of each deep well based on a survey of 30 randomly selected wells installed by DPHE and another 30 randomly selected wells installed by DU/WAB.

calculation shows that the number of deep wells located within 200 m of each of the randomly selected 60 deep wells is considerably higher for the DPHE wells compared to the DU/WAB wells (Figure 4(c)).

Distance calculations show that 6,471 shallow unsafe wells (29% of the total of 22,280 unsafe wells) were located within 100 m of at least one of the 915 intermediate or deep wells, including 13 high-As wells whose depths were verified (Figure 4). Another set of distance calculations based on the hypothetical grid of evenly distributed deep wells indicates 16,545 shallow unsafe wells (74%) located within 100 m of an equal number of 915 deep wells selected to maximize their impact. Starting from the current distribution of wells, a final set of calculations shows that an additional 1,857 deep wells would be sufficient to bring 90% of all unsafe wells in Araihazar within 100 m of a source of safe drinking water, provided that the additional wells are distributed according to the evenly spaced grid (Figure 4).

DISCUSSION

Insufficient well testing

From 1999 to 2005, a total of 4.7 million (mostly private) wells were tested with field kits across the portion of Bangladesh affected by As, covering about half of the country. The large fraction of wells of unknown status inventoried in Araihazar over a decade later (Figure 2(a)) is a serious public-health concern because it reflects the current situation in other As-affected areas as well (WASH 2008; DPHE/JICA 2009; George *et al.* 2012). The status of the vast majority of these wells was unknown not because households do not remember the test results from previous testing but because the wells were installed after the most recent testing campaign under the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP), which in this area took place in 2003. Subsequently, only limited testing was conducted for public health research until 2012. The large proportion of wells with As >50 μg/L within the set of wells of unknown status not only indicates that numerous households were exposed to As without knowing it but also that their options in terms of switching to a nearby safe well is limited by lack of information. Despite repeated reports over the past decade that households continue to install wells and that most of these wells remain untested, the government of Bangladesh currently does not have a plan to support the testing of private wells at the village level on a long-term basis. UNICEF and the World Bank have supported pilot scale tests of well-testing for a fee but this service has not been implemented at any significant scale, despite evidence that there is considerable private demand for well tests (George *et al.* 2013; van Geen & Singh 2013).

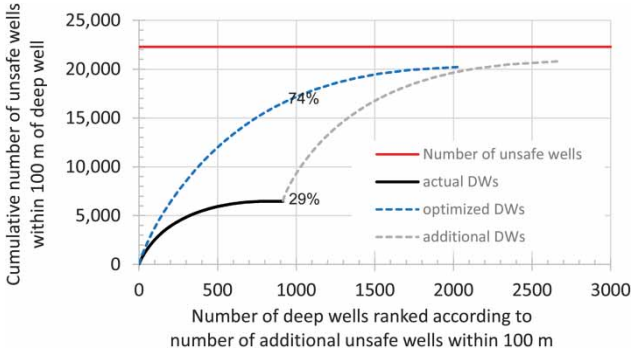

Figure 4 | Spatial calculation of the number of unsafe wells in Araihazar located within 100 m of deep wells according to three different scenarios. (a) The actual location of up to 915 deep wells surveyed in 2012–13. Each unsafe well is counted only once by assigning to the closest deep well, even if circles with a 100 m radius of existing deep wells overlap. (b) The hypothetical location of deep wells positioned on a regular grid and ranked according to the number of unsafe wells within 100 m. (c) The actual location of 915 deep wells and additional deep wells positioned on a regular grid.

Low arsenic in deep aquifers

The vast majority (>99.5%) of intermediate and deep wells in Araihazar yield groundwater that is very low in As. Some of the exceptions turned out to be wells <90 m deep, an installation problem reported elsewhere in Bangladesh (Ravenscroft *et al.* 2014). Other intermediate or deep wells inventoried in Araihazar may be shallower than reported but this did not increase their As content. Low As concentrations have been widely reported for deeper aquifers of Bangladesh, but there are regional exceptions elsewhere in the country (Hossain *et al.* 2012; Ravenscroft *et al.* 2014). Municipal pumping from the deep aquifer for the city of Dhaka has created a vast cone of depression that extends to Araihazar (Hoque *et al.* 2007) but the

resulting downward flow has evidently not resulted in a widespread increase in As concentrations in deep aquifers. The four wells with >50 μg/L As in two neighboring villages warrant further study and justify periodic re-testing of wells currently low in As throughout the study area.

Unlike coastal and other areas of Bangladesh (Hug *et al.* 2011; Ravenscroft *et al.* 2014), salinity is not a major issue in deep aquifers of Araihazar. On the other hand, previous laboratory testing of a smaller sample of deep wells from the area has shown that a third of intermediate and deep wells exceed the health-based WHO guideline for manganese (Mn) in drinking water of 0.4 mg/L, which was in effect until recently, by a factor of 2–3 (van Geen *et al.* 2007). A smaller fraction of deep wells across the country also contain elevated levels of Mn (Ravenscroft *et al.* 2014). The health implications of chronic exposure to Mn present in groundwater, however, appear to be less severe than for As (Wasserman *et al.* 2006; Hafeman *et al.* 2007). In addition, concentrations of Mn in wells >90 m deep are, on average, considerably lower than in shallower private wells (van Geen *et al.* 2003, 2007). The findings from Araihazar support the argument of Ravenscroft *et al.* (2013) that enough is known about the resilience of deep aquifers with respect to As to justify the installation of tens of thousands of additional deep tubewells throughout the affected regions of Bangladesh.

Uneven distribution of deep wells

The shortage of testing and the suitability of deep aquifers as a drinking-water source in many parts of Bangladesh have been known for close to a decade. The present study concerns instead the spatial distribution of deep wells. The new data clearly show that some villages in Araihazar contain dozens of deep wells whereas others do not contain any, including many villages with very few existing low-As wells (Figure 2(a)). This explains why a more equitable distribution of the same number of deep wells (Figure 2(b)) would have brought almost three times as many exposed households within walking distance of a low-As source (Figure 4). The usage of the 30 DPHE-installed wells in Araihazar is consistent with the average of 97 users per deep tube well determined in a national survey of 349 deep wells (Ravenscroft *et al.* 2014). One reason for the three-fold higher average usage of DU/WAB-installed wells compared to DPHE wells could be that villagers have more deep wells to choose from in the villages that have been favored (Figure 3(c)). The large difference in public access between the two categories of deep wells suggests, instead, that neighbors who are not related to the household that owns the land where the deep well was installed by DPHE are discouraged from using it (Figure 3(b)).

Policy implications

Unless mitigation becomes more effective, continued exposure to As will place an enormous disease burden on Bangladesh, including increased mortality due to cardiovascular disease and cancers of the lung, liver, and bladder in adults, as well as diminished intellectual and motor function in children (Smith *et al.* 2000; Wasserman *et al.* 2004; Flanagan *et al.* 2012).

The government currently allocates funds to the local DPHE office in Araihazar to install 50–100 deep wells each year. The location of these installations is determined on the basis of input from the Upazila Nirbahi Officer (UNO), the senior local government official, the elected Upazila Parishad chairman, and the 12 Union Parishad chairmen. The local member of the national parliament also appears to hold significant sway over how deep wells are allocated. The clustering of deep wells and their frequent installation in areas where access is limited to the household of the land owner may indicate elite capture of a public good ostensibly intended to benefit the entire population (Bardhan & Mookherjee 2006; Hossain 2012). The influence of elected politicians on decisions affecting their constituency that should, in principle, be taken by non-partisan civil servants has been a growing problem in Bangladesh (Sobhan 2004).

A central feature of the current state of As mitigation in Bangladesh appears to be lack of information and transparency. Villagers throughout Bangladesh are aware of the health risks linked to drinking well water elevated in As, but most outside Araihazar do not know the status of their well and have no simple way to have it tested. Similarly, until the recent testing in Araihazar, DPHE headquarters, let alone the local population at large, were not fully aware of the highly clustered distribution of deep wells.

One way forward might be to require that each Union Parishad, of which there are 12 in Araihazar for instance, provide maps suitable for public posting that indicate the current distribution of deep wells and plans for future installations. Priorities should be explained to the public on the basis of criteria that include public access and keeping a minimum distance between neighboring deep wells. These maps could incorporate any well-testing information that is available, e.g., the As data for ~40,000 villages of Bangladesh blanket tested under BAMWSP more than a decade ago, in the form of pie diagrams for individual villages. This should make it obvious whenever a highly affected village has been neglected and, through locally elected representatives, could create pressure to remedy the situation and reduce the chances of elite capture. In other settings, it has been shown that greater community participation, monitoring, and transparency can result in more equitable allocation of a public good (Bjorkman & Svensson 2009; Chavis 2010; Madajewicz *et al.* 2014). A more even distribution of deep wells will not alleviate the need for education and reinforcement, as previous studies of deep-well usage in Bangladesh have indicated that social factors also affect whether households will stop drawing water from their own unsafe private well for drinking and cooking (Mosler *et al.* 2010; Inauen *et al.* 2013).

Deep aquifers have become an increasingly important public source of drinking water, not only in Bangladesh but also in neighboring countries where an additional population of at least 30 million may be exposed to As by drinking well water in India, Nepal, and Myanmar (Ravenscroft *et al.* 2009). Although the processes by which public goods are allocated in these countries may differ, the possibility of elite capture, including clustering and limited access to deep community wells, should be investigated and corrected if necessary.

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