Groundwater

Methods Note/

Evidence for Elevated Levels of Arsenic in Public Wells of Bangladesh Due To Improper Installation

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Abstract

One of the mainstays of mitigation to reduce the exposure of the rural population of Bangladesh to arsenic (As) from private, mostly <90-m deep wells over the past 15 years has been the installation of over 300,000 deeper community wells. A comprehensive testing campaign previously conducted across a 180 km^2 of area of Bangladesh identified 9 out of total of 927 wells >90 m deep that contained >50 µg/L arsenic. We show here that for five of these nine wells, conductivity profiles obtained after spiking the well bore with salt indicate a shallow leak that could explain the high As in the well water. In two of the five leaky wells, the presence of additional screens at the depth of the leak was documented with a downhole camera. The downhole camera did not detect anomalies in the construction of the remaining three leaky wells or in the four wells that did not leak. The four wells that did not leak were all >150-m deep and located in two villages separated by less than 500 m. Excluding these two villages and a handful of leaky wells, the results indicate an aquifer that is consistently low in As over a sizeable area at depths >90 m. Isolated cases of public wells that are elevated in As that have been reported elsewhere in Bangladesh may therefore reflect improper installation rather than actual contamination of the deep aquifer.

Introduction

Over the past decade and a half, the government of Bangladesh has installed several hundred thousand hand-pumped, deep community wells throughout the country. These wells are mostly low in arsenic (As) and intended to lower exposure of the rural population to naturally elevated levels of As contained in water pumped from shallow, mostly private wells (DPHE/JICA 2009; van Geen et al. 2003; Ahmed et al. 2006; Johnston et al. 2014; Ravenscroft et al. 2014). The approach relies on the observation that in many of parts of the country, although not everywhere, concentrations of As in deep aquifers of Pleistocene age typically meet the World Health Organization guideline of 10 µg/L (BGS/DPHE 2001). A small but significant proportion of these wells, however, does not meet the national drinking water standard of 50 µg/L for As, let alone the WHO guideline. These occurrences are concentrated in northeastern and western Bangladesh and have also been reported in a portion of the Bengal basin within the Indian state of West Bengal (Ravenscroft et al. 2014). The geographic pattern of elevated As levels at depth in these areas suggests a geologic origin that may or may not have been exacerbated by large-scale deep municipal or agricultural pumping (McArthur et al. 2010; Mukherjee et al. 2011).

The focus of the present study is, instead, on the rarer occurrences of elevated As levels in deep aquifers in other parts of the country where, with a few exceptions, heavily used deep community wells have remained low in As for at least a decade (van Geen et al. 2007; Ravenscroft et al.

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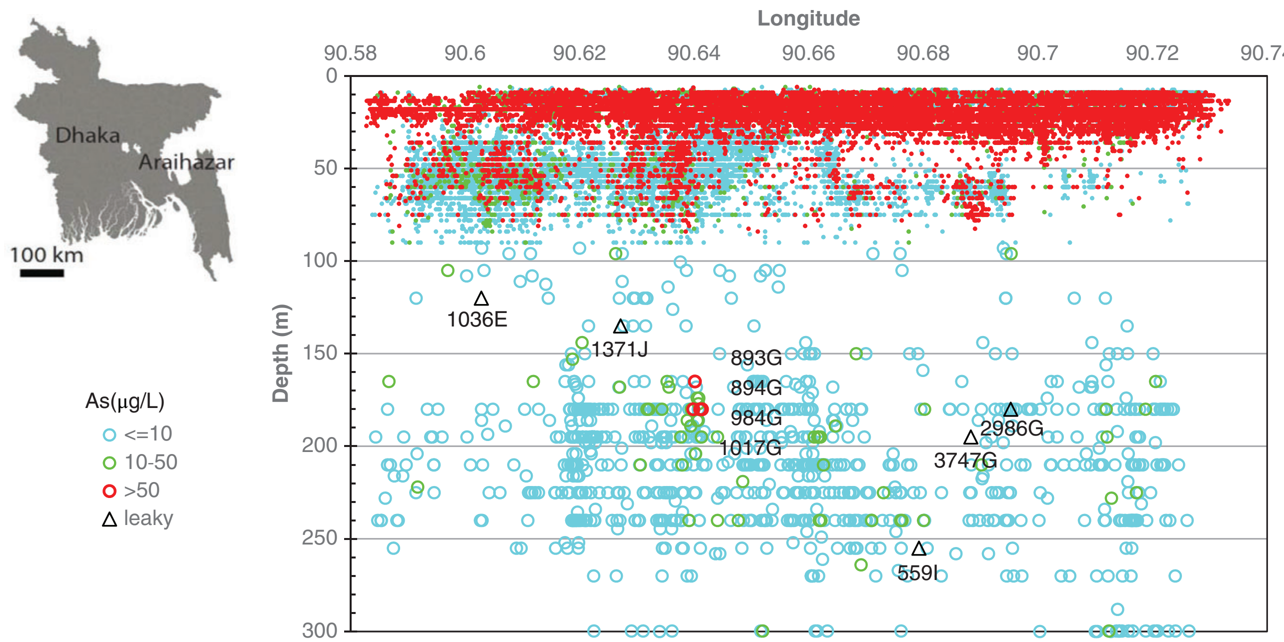

Figure 1. Map of Bangladesh showing (a) the location of Araihazar upazila relative to metropolitan Dhaka. (b) The depth section shows the status of almost 50,000 wells tested for As with a field-kit in 2012 to 2013 relative to the WHO guideline of 10 µg/L and the national standard of 50 µg/L. The four non-leaky wells are shown as red circles and the five leaky wells, which also contained >50 µg/L As during the first screening, as black triangles. Also shown are well IDs referred to in the text and listed in Table 1.

2013). The underlying hypothesis is that these isolated cases of failure might reflect intrusion of shallow high-As groundwater into a well due to poor construction, intentional or unplanned. The concern is that such practices could have a particularly negative impact near Dhaka or anywhere else in the region where there is a pronounced head gradient favoring intrusion of shallow water due to massive deep pumping (Hoque et al. 2007). In such situations, not only the water within the well but also a sizeable portion of the aquifer tapped by the screen could become contaminated over time. Give that As mitigation efforts in Bangladesh remain inadequate with over 40 million villagers still exposed (BBS/UNICEF 2015), it is important to distinguish technical and engineering issues from other social and political factors that have also limited the impact of on-going installations of deep wells throughout the country (Johnston et al. 2014; van Geen et al. 2015).

The approach followed in the present study builds on traditional ways of detecting leaky well casings using anomalies in physical or chemical properties (van der Kamp and Keller 1993). A clear difference in water level in one well relative to neighboring wells in the same depth range, for instance, can be an indication of a casing leak. This is even more likely if the composition of groundwater relative to that of neighboring wells stands out too. Under these circumstances, direct confirmation of a leak may still require monitoring of a change in water level over time after isolating of a portion of the well casing with an inflatable packer. In the present study, anomalies in groundwater composition, in this case As, were identified from a particularly large number of wells within the same depth range. The composition of the water within the anomalous well was then purposely modified in order to locate the onset and location of re-equilibration with the surrounding aquifer. In addition, a downhole camera was deployed to identify the cause of some of the detected leaks. More sophisticated methods for detecting casing leaks that rely on ultrasound, flowmeters, and various geophysical sensors have been developed for the oil and gas industry but these typically require larger diameter wells and are much more costly (Smolen 1996).

The study builds on a blanket testing campaign of almost 50,000 wells across an area of 180 km^2 that was conducted in 2012 to 2013 in Araihazar Upazilla of Bangladesh, approximately 15 to 20 km east of the capital Dhaka (van Geen et al. 2014). As part of this survey, a total of 927 wells claimed to be over 90-m deep by their caretaker, owner, or local users were recorded and tested for As with a field kit (van Geen et al. 2015). We report here the outcome of further investigation of nine community wells, the only ones identified during the blanket survey of the region that were confirmed to be >90-m deep and elevated in As. We systematically apply the salt-spiking method first demonstrated in the region by Stahl et al. (2014) to these wells and complement the investigation with the deployment of an ultra-slim downhole camera to identify potential anomalies in well construction. We show that some but not all of the high-As outliers are due to defective wells and discuss the implications of these findings for future mitigation.

Methods

This study focuses on wells >90-m deep rather than the much more numerous shallow, private wells that are installed within a single day by a small team of local drillers contracted by a household. Wells >90- to 300-m deep require mobilization of a larger team and heavier equipment for up to a week and are typically installed only with funding from the government or non-governmental organizations (Ali 2003). These deeper community wells have been installed specifically to avoid shallower high-As groundwater and the occasional failure of such wells is therefore of particular interest. The 90-m threshold distinguishes private and public wells but has no particular geological significance. The vast majority of wells >90 m in Araihazar are low in As but in some parts of the study area, Pleistocene low-As aquifers can be reached at considerably shallower depths (Gelman et al. 2004). In other parts of the country, groundwater that is consistently low in As is reached only at depths that exceed 150 m (Ravenscroft et al. 2014). The Bangladesh government's Department of Public Health Engineering defines as "deep" any well that is >150 m deep.

The nine wells discussed in this study were selected after confirming that their depth was indeed >90 m and re-testing them with the field-kit (Figure 1). Three wells initially recorded as containing 100 µg/L As and later only 50 µg/L were retained for the study because of the difficulty of categorizing readings visually with certainty near a threshold (van Geen et al. 2014). Concentrations of As in leaky wells could also conceivably change over time, depending on the level of recent pumping. Concentrations of As in all nine wells were subsequently confirmed to exceed the WHO guideline of 10 µg/L by laboratory analysis (Table 1).

For spiking the well bore, two 3 oz. salt wheels obtained from a pet-supply distributor were broken into large pieces (even coarse table salt dissolves too quickly) and placed within a mesh bag ~0.75″ in diameter and 16″ long, weighted at the bottom. The salt was placed at the end of a tether and was lowered as quickly as possible (free-fall) down the well to maximize the depth range of the increase in conductivity. Before spiking and 1 and 24 h after spiking, conductivity profiles within the well were obtained at 0.5 to 1 m intervals using a Solinst (Georgetown, Ontario) TLC Meter Model 107. The wells were not pumped between 1 and 24 h after spiking. Although more costly (US$2300 with a spool extending to a depth of 300 m) than the device described by Stahl et al. (2014), the 0.75″ diameter of the commercial probe facilitates deployment because wells are typically constructed of 1.5″ ID PVC in Bangladesh. The downhole video records were obtained with a 3/4″ OD GeoVision Nano camera mounted on a hand-operated, heavy-duty winch with 300 m of cable purchased from Allegheny Instruments Inc. (Monterey, Virginia). The unedited videos can be viewed on www.youtube.com by searching for "Araihazar" and any of the well IDs shown in Table 1 or by clicking on the links listed in Appendix S1, Supporting Information.

Table 1
Characteristics of Failed Wells Studied in Araihazar

Well ID	Latitude	Longitude	Union	Village	Installation year	Depth (m)	As (ug/L) Kit 1	Kit 2	ICPMS	Depth (m) Δ salt	Extra screens	Number of joints	% clean	% glue	% drips	% oval
893G	23.76321	90.64103	Haizadi	Roynadi Kalagachhia	2011	174	300	100	84.4	—	0	45	91	2	7	0
894G	23.76340	90.64010	Haizadi	Roynadi Kalagachhia	2007	169	100	200	70.1	—	0	38	89	11	0	0
984G	23.76276	90.63980	Haizadi	Roynadi Kalagachhia	2011	168	100	50	36.5	—	0	41	78	17	5	0
1017G	23.75842	90.64135	Haizadi	Roynadi	2004	187	100	100	76.0	—	0	43	12	79	9	0
1371 J	23.75618	90.62712	Haizadi	Sarapdi	2007	140	500	300	192.6	20 to 120	0	31	77	13	10	0
2986G	23.74907	90.69523	Khagkanda	Lakhi Pura	2004	109	100	50	26.4	40 to 100	1	26	65	27	4	4
1036E	23.76947	90.60282	Brahmandi	Laskardi	2009	110	200	200	208.9	44 to 55	3	23	39	48	4	9
559I	23.78800	90.67921	Fathepur	Bagadi	2000	188	100	100	51.0	70 to 90	0	45	44	31	24	0
3747G	23.74741	90.68827	Khagkanda	Sumbhupura	2011	185	100	50	18.2	60 to 90	0	43	12	86	2	0

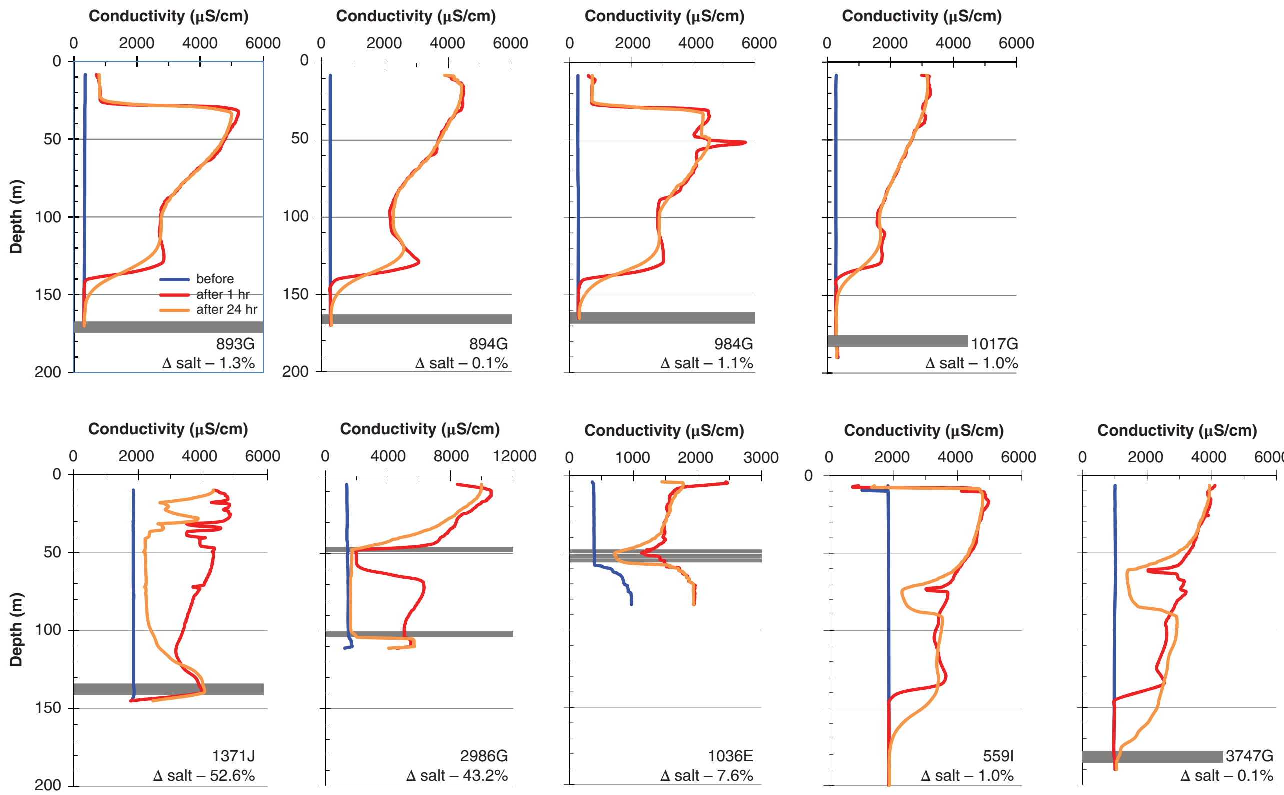

Figure 2. Profiles of conductivity obtained before and after spiking of nine wells >90-m deep with >50 µg/L As when tested in 2012 to 2013. The horizontal grey bands indicate the depth range of the slotted PVC screens documented with the downhole camera. The bottom screen of well 1036E was not reached because it had been partially filled with sediment and the bottom screen of well 559I was blocked by a brick fragment (Figure 3). Also listed are the changes in salt content over background in each well (%) between 1 and 24 h after spiking.

Results

An average increase in conductivity of 6000 µS/cm over a range of 150 m is predicted assuming exactly two salts wheels dissolved, a well ID of 1.5″, and a conductivity of 2000 µS/cm for a 0.01% solution of NaCl. This is within the range of observed increases in conductivity (Figure 2) although considerably less salt was evidently used in one case (1036E) and considerably more in another (2986G).

With the exception of one well (1036E), the conductivity profiles were essentially uniform before spiking. Of the total of nine wells that were spiked, four showed little or no difference between conductivity profiles collected after 1 and 24 h. In some cases below a shallow rapid rise, conductivities gradually declined with depth by about a factor of two, starting from maxima of 3000 to 5000 µS/cm. In each of these four wells, this was followed by a rapid decline to conductivities of ∼300 µS/cm at about 130-m depth that was indistinguishable from the pre-spike background, indicating that the salt had completely dissolved. The sharp drop-off in conductivity was centered at the same depth at 1 and 24 h, but broadened from a width of about 10 to 30 m over the intervening period. A few features in the conductivity profiles recorded after 1 h due to brief interruptions in the descent of the salt wheels were also smoothed over time at shallower depths. An inventory of excess salt within each of the wells is calculated by subtracting the pre-spike conductivity from measurements at 0.5 to 1 m intervals at 1 and 24 h and summing over the entire depth range of the increase in conductivity. Within 1%, there was no change in the excess salt over background inside these four wells between 1 and 24 h after spiking (Figure 2).

Within 1 h of spiking, the conductivity profiles for the five other wells showed localized decreases indicative of dilution with fresher water (Figure 2). In the case of well 1371 J, declines in conductivity recorded within 1 h indicate multiple leaks within the upper 50 m and an additional leak at about 70 m depth. For well 2986G, a more pronounced reduction in conductivity to almost background values after 1 h extended from about 50 to 60 m depth. After 24 h, conductivities were uniformly low across the entire 50 to 100 m interval in both these wells. The excesses of salt over background in these two wells decline between 1 and 24 h after spiking by 53% and 43%, respectively (Figure 2). Conductivity profiles for wells 1036E, 559I, and 3747G all show a single well-defined minimum after 1 h that expanded to a width of 20 to 30 m at 24 h. The minima in conductivity expanded primarily downward but did not quite reach initial background values after 24 h. Within this group of three wells, only in the case of well 1036E did the excess salt decline measurably by 7.6% between 1 and 24 h after spiking.

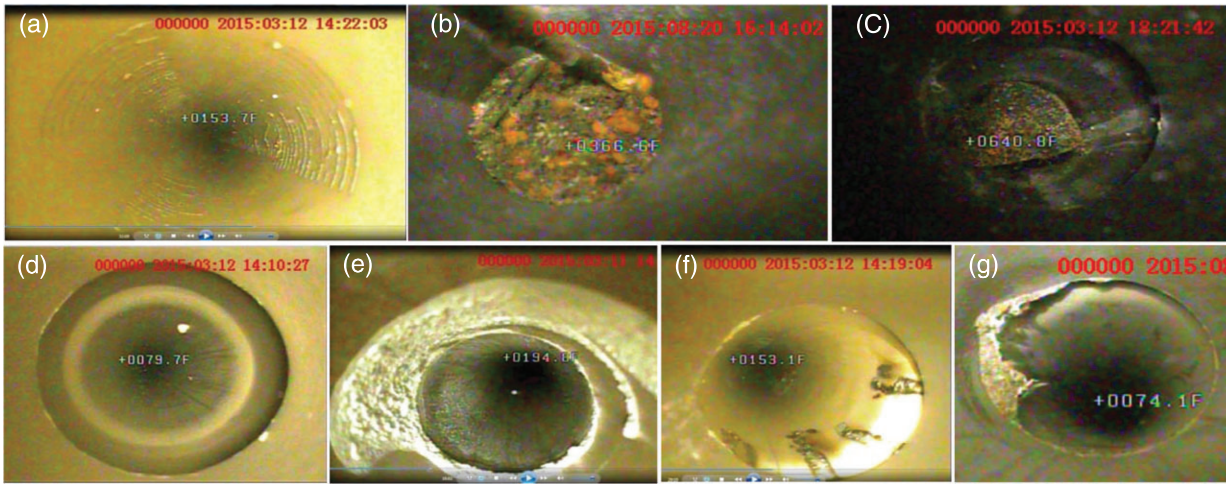

Figure 3. Examples of screen shots of the downhole camera video. (a) shallow screen in well 2986G, (b) bottom of well 1036E filled with sediment and a twig, (c) brick fragment at the bottom of well 559I, (d) clean PVC joint, (e) joint streaks of PVC glue, (f) drip features that may indicate intrusion of water through the joint, and (g) joint deformed to an oval shape. See Table 1 for a compilation of the different types of joints recorded from the video.

The videos obtained with the downhole camera were used to record the depth and status of each of the PVC joints and other features inside the nine wells under investigation. The video camera was prevented from reaching the lower screen by sediment in well 1036E and by a single piece of brick in well 559I (Figure 3). Most striking was the discovery of a slotted PVC screen inserted at 46 to 49 m depth in well 2986G and another three screens installed in series between 48 and 56 m depth in well 1036E. The depths of these screens correspond closely to the onset of the decline in conductivity recorded in both wells (Figure 2). No shallow screens were observed in the remaining three leaky wells. The downhole camera neither detected a single broken or split PVC pipe nor any obviously failed joint. Deformations and the presence of drip-like features around the joints, possibly PVC glue or precipitated calcium carbonate, were systematically compiled from the video records (Table 1). There was no systematic difference in the appearance of the PVC joints within and outside the leaky intervals identified by the declines in conductivity.

Discussion

The 1% of rate of failure community wells in Araihazar (with a Wald confidence interval of ±0.3%) relative to the national standard of 50 µg/L is remarkably low compared to other parts of the country. Ravenscroft et al. (2014) calculated a county-wide rate of failure of 3.6% on the basis of a large number of wells >150-m deep installed by DPHE, but also report failure rates of >25% in some portions of western (Jessore) and northeast Bangladesh (Sylhet). Although the same study reported that 6% of wells that were supposed to be deep according to the DPHE definition turned out to be <150-m deep when verified, the particularly low failure rate of community wells in Araihazar is likely to be of geologic origin. Unlike some other portions of the Bengal basin, Pleistocene aquifers that are typically low in As are often reached at depths <90 m in Araihazar (Dhar et al. 2008).

The grouping of the four cases of well failure relative to the national standard of 50 µg/L without any obvious leak in two neighboring villages suggest local contamination of the deep aquifer, although the contamination is not systematic. Within the same two villages, there are an additional 25 wells of >150-m deep that tested low for As, in most cases below 10 µg/L. The underlying cause of the four failures in these two villages could be geological (Planer-Friedrich et al. 2012), although leakage along the well bore the outside the PVC pipe cannot be ruled out.

Salt spiking showed that in five out of nine cases failures relative to 50 µg/L were due to improper installation of the wells, blatantly so in two wells where additional screens were installed within the depth range where As levels are known to be elevated in the region. Using solely a mechanical criterion, only the three leaky wells without shallow screens were truly installation failures since these leaks were not intentional. The additional screens were presumably installed by a driller concerned that the flow of water might be insufficient. Local residents and users were not aware of these shallow screens. The video record could not identify what other installation practice needs to change to avoid leaks in wells without shallow screens. The lack of threaded joints or even factory-made straight joints as well as poor cementing of the joints are likely factors (van der Kamp and Keller 1993; Stahl et al. 2014).

The downward shift and expansion of the low conductivity portions of the profiles are consistent with regionally lower heads at depth due to massive deep Dhaka pumping (Zheng et al. 2005; Hoque et al. 2007). In the case of well 1036E with three shallow screens, the impact of fresh water intrusion through three shallow screens on the salt content may have been muted by the fact that the bottom of the well was at least partially clogged by sediment (Figure 3). The elevated conductivity of water below the depth of the screens before spiking (Figure 2) also suggests that most of the water in the well is drawn from the shallow screens.

The sample of investigated wells was biased by relying on As to identify outliers. There may be more leaky or poorly installed wells in Araihazar that do not lead to elevated As concentrations, either because the leak is small or because the leak is at a depth where groundwater As outside the well is low. An obvious target for future depth checks, leak tests, and camera deployments is the group of 55 wells of >90-m deep in Araihazar reported to contain 25 or 50 μg/L As according to the field tests. These As levels are significantly higher than readings of 0 and 10 μg/L typically obtained with the field kit for wells that extend to Pleistocene aquifers and might therefore also be indicative of shallow leaks.

A practice observed elsewhere in Bangladesh that should be more widely encouraged is the permanent posting of the name of the contractor who installed the well as well as its depth. If the local DPHE office could commit to check independently the actual depths of a subset of wells, in addition to their As content, the permanent marking could discourage unscrupulous behavior by contractors. This practice might also discourage the installation of screens at shallower depths, especially if the contractors are informed that potential leaks can be checked using a relatively inexpensive method such as salt profiling.

Even if deep aquifers are not universally low in As and some wells are leaky, the small proportion of failures compared to successes clearly indicates that the installation of additional deep wells should be promoted in Bangladesh (Flanagan et al. 2012; Ravenscroft et al. 2013; Johnston et al. 2014). The documented rate of failure, which is remarkably low given inherent weaknesses in the design of the joints, is likely to be robust given the particularly large pool of wells from which outliers were drawn on the basis of anomalies in As. A far more significant issue than the occasional failure due to a leak in terms of access to safe water in the region is the recently documented geographic clustering of community wells resulting in villages being provided with numerous deep community wells and others that are equally affected none at all (van Geen et al. 2015).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. YouTube links to downhole videos for the wells tested in this study.

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