



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

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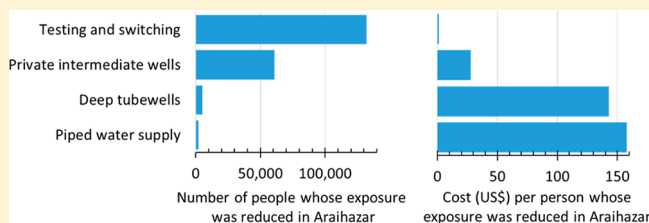
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Supporting Information

ABSTRACT: About 20 million rural Bangladeshis continue to drink well water containing $>50 \mu\text{g/L}$ 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 $<\text{US}\$1$ 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 $\text{US}\$30$ 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 $\text{US}\$150$ 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.¹ The main cause of excess mortality is cardiovascular disease,² rather than the various forms of cancers that have been linked to chronic As exposure elsewhere in the past.³ Fetal exposure to As has been shown to negatively impact birth outcomes and infant mortality.⁴ In addition, motor and intellectual function are diminished in children drinking well water that is elevated in As.^{5,6}

Chronic exposure to As also has significant economic consequences. Pitt et al.⁷ 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.⁸ 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 $10 \mu\text{g/L}$.⁹ 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.^{10,11} Relative to the outdated Bangladesh drinking water standard of $50 \mu\text{g/L}$ As, the corresponding decline in the exposed population over the same period has been from an initial 35 to 22 and 20 million, respectively.^{9–11} 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.^{12,13} Households do not have the option of

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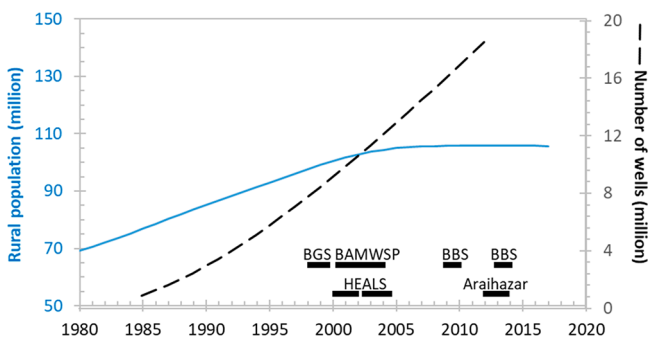


Figure 1. Evolution of population and number of tubewells in rural Bangladesh over time. Source: World Bank (<https://data.worldbank.org/indicator/SP.RUR.TOTL?locations=BD&view=chart>, accessed March 3, 2019) for population. The number of wells was extrapolated from the model of well installation and 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 Arai hazar (2000–2005 for the entire country), and the most recent 2012–2013 Arai hazar blanket survey.

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.¹² 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 Arai hazar upazila (subdistrict) of Bangladesh in 2000–2001 (Figure 1). All 6000 wells within a 25 km² portion of Arai hazar upazila, one of 491 subdistricts in the country, were sampled by local partners and tested in the laboratory by

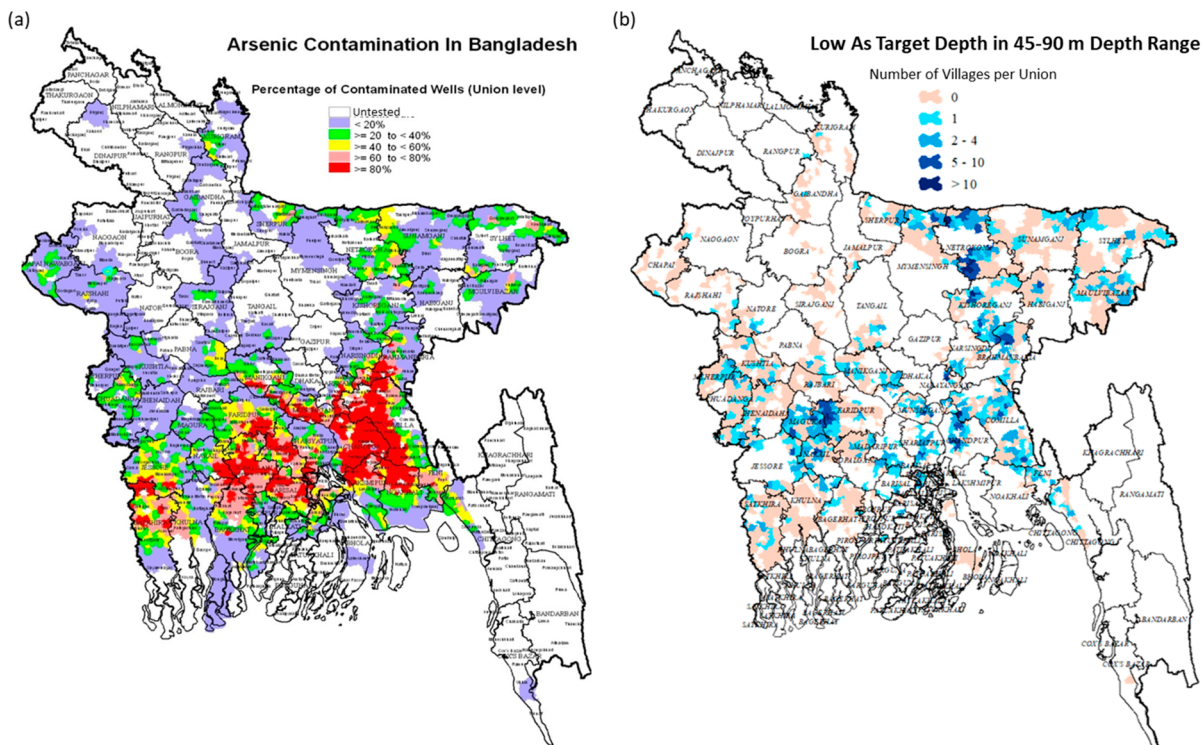


Figure 2. Map of Bangladesh showing (a) the proportion of wells meeting the national standard of 50 µg/L for arsenic in drinking water at the administrative level of the union and (b) the number of villages per union with >20% unsafe wells distributed across a subset of 881 unions where a target depth 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.¹³

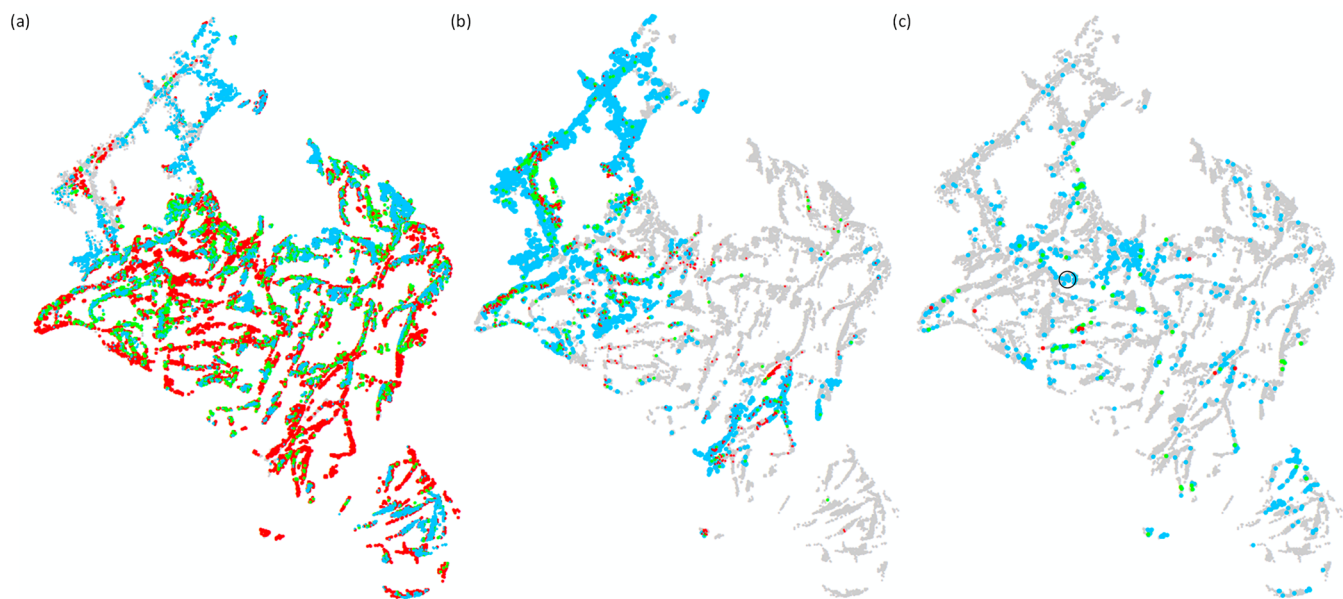


Figure 3. Map of Araihaazar upazila, Bangladesh, showing the status with respect to As of close to 50,000 wells in depth ranges of (a) 10–45 m, (b) 45–90 m, and (c) 90–150 m based on field-kit testing conducted by a team of 10 local women over a period of 18 months in 2012–2013.¹⁸ Color coding shows wells meeting the WHO guideline for As of 10 $\mu\text{g/L}$ (light blue), wells that do not meet the guideline but meet the national standard of 50 $\mu\text{g/L}$ (green), and wells with 50–1000 $\mu\text{g/L}$ (red). The vast majority of households originally installed their well in the shallowest depth range, but a rapidly growing number are now doing so in the intermediate aquifer which, often but not always, is low in As. Wells in the deepest range are essentially all government wells clustered in a subset of villages, not necessarily the most affected ones. The circle in part (c) shows the location of the only piped-water supply system operating in the area.

Columbia University.¹⁴ 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.¹⁵

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.^{15,16} 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 Araihaazar upazila tested in 2003 after the HEALS baseline survey.¹³ 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 $\mu\text{g/L}$, 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 $\mu\text{g/L}$.¹⁷

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 Araihaazar 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.¹⁸ 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 $\mu\text{g/L}$ from wells that do not meet the national standard of 50 $\mu\text{g/L}$ but still misclassifies some wells in between.^{18,19} Blue (≤ 10 $\mu\text{g/L}$ As), green (>10 –50 $\mu\text{g/L}$), or red (>50 $\mu\text{g/L}$) metal placards were attached to all tested pumpheads immediately after each test.¹⁸ 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 $\mu\text{g/L}$ As 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.¹⁸ 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 Araihaazar 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.¹⁸ 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 Araihaazar 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.²⁰

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 Araihaazar (Figure 3a). Intermediate wells, on the other hand, are much more likely to be low in As (Figure 3b), whereas most deep wells in Araihaazar 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.^{9,22–26} A search algorithm developed for Araihaazar 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.²⁷ 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.²² 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.²¹

The installation cost of the single piped-water supply system installed in Araihaazar 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 large-diameter deep wells, a 100,000 L capacity water tank, and a network of connected taps took 2 years to build and started to operate in four villages of Araihaazar in February 2018. The construction cost of US\$250,000 was shared between the World Bank (2/3) and a business partner, Sadia Enterprises (1/3), that is responsible for managing the facility and collects a monthly fee of \$2.50 per household tap from the users.

Household Responses. Even if there is evidence of significant health effects from drinking groundwater with As levels in the 10–50 µg/L range, we use in this study the national standard of 50 µg/L as a reference to define successfully reduced exposure. For consistency with national policy, this is the threshold used to tell households whether their well was safe and against which, therefore, their response should be gauged. The range of household responses to a high As result is derived from several surveys during which test results were delivered in different ways. In the portion of Araihaazar outside the HEALS area where testing was previously conducted only once in 2003 under BAMWSP, 27% of households were by 2005 no longer using water from a well whose spout had been painted red, even if the paint was by then typically no longer visible.²⁸ For comparison, only 2% of households had switched from a safe well over the same

period. In three upazilas studied by UNICEF with a proportion of unsafe wells of 77%, 38% of households with an unsafe well switched to a different well (see ref 29, cited in ref 12). On the basis of these studies, we use 30% as the low end of the proportion of households switching away from a high As well if no special effort is made beyond testing a well and reporting the result to the household.

Other follow-up surveys indicate considerably higher switching rates when the risks of chronic As exposure by drinking well water are emphasized in various ways. Within the HEALS study area of Araihaazar, two studies have shown that the proportion of households switching away from high As wells was twice as high at 60%.^{15,16} An average switching rate closer to 50% was recorded in a study conducted outside the HEALS area during which the implication of test results was emphasized at the group and individual level.³⁰ On the basis of these findings, we use a 60% switching rate for the upper end of the expected household responses to a test result showing a high level of As.

RESULTS

Status of Wells Installed over Time. The increase in the total number of wells in Araihaazar 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.¹⁸ The actual number of new wells installed in Araihaazar 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.¹⁸ 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 Araihaazar 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.¹⁷ The smaller HEALS subarea within Araihaazar 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 2012–2013.¹⁸

Response to Well Testing by Switching. The cost of testing all 48,790 wells in Araihaazar 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 2003.¹⁸ 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.¹⁸ 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.

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

mitigation method	Araihaazar activity	exposed population reached	exposure proportion reduced	exposed population reduced	cost ea. govt/NGO (US\$)	total cost govt/NGO (US\$)	cost ea. household (US\$)	total cost household (US\$)	total cost per exposure reduced (US\$) actual
testing and switching	48,800 wells tested (21,300 safe)	220,000	60%	132,000	2.5	122,000			1
private intermediate wells	8450 intermediate wells installed (7610 safe)	67,600	90%	60,800			200	1,690,000	28
deep tubewells	916 deep wells installed (907 safe)	51,200	10%	5120	800	733,000			143
pipled water supply	312 connections installed (all safe)	2180	100%	2180	250,000	250,000	300 ^a	93,600	158

^a10 years @ US\$2.50/month.

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 Araihaazar 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 Araihaazar 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 Araihaazar 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

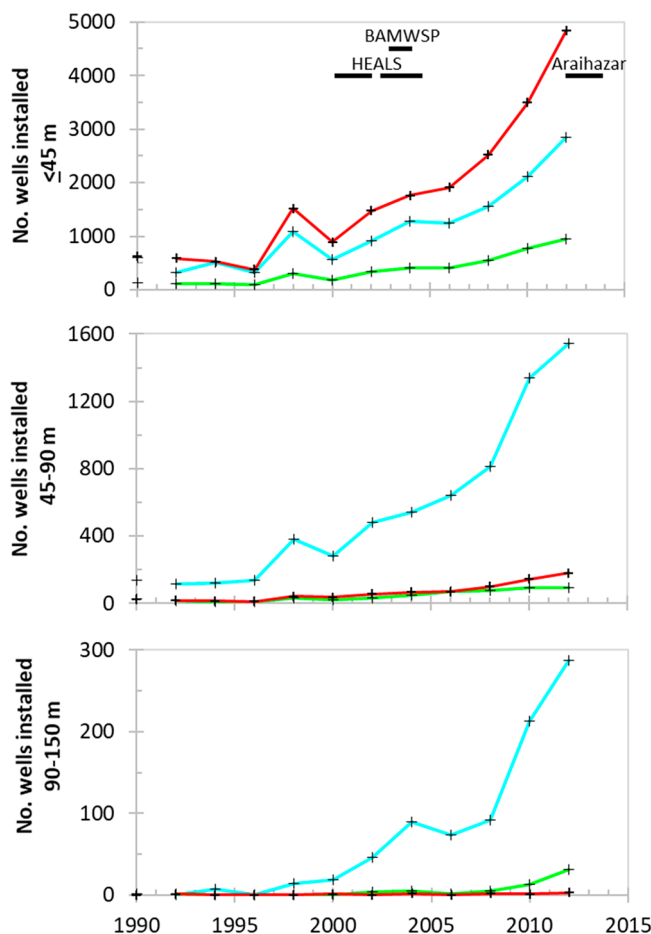


Figure 4. Time series of the number of wells installed in 2-year intervals according to their status with respect to As for three different depth ranges. Compilation based on a blanket survey conducted in 2012–2013 during which, in addition to testing wells with a field kit for arsenic, owners were asked 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 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 Araihaazar 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

deep wells were counted only once.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 Araihaazar. 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.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 Araihaazar, 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).

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.^{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 Araihaazar 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 Araihaazar 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-

ern portion of Araihaazar, 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 Araihaazar be extrapolated to other upazilas of Bangladesh? According to BAMWSP data,¹³ the water pumped from 32% of the 29,000 wells tested in Araihaazar in 2003 contained >50 µg/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).¹³ Even if the kit used for the 2003 testing under BAMWSP underestimated the number of high As wells,¹⁷ the similar proportions using the same kit suggest that the findings concerning mitigation in Araihaazar 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 Araihaazar (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.¹⁴ Target depths that are likely to be low in As based on village-level BAMWSP data can be recombined 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 algorithm²⁷ 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 Araihaazar 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 Araihaazar.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 Araihaazar probably increased awareness of the As issue as well, possibly beyond the villages where cohort participants reside,²⁸ 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.^{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 Araihaazar, 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.²⁸

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 Araihaazar, 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 tubewells 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 Araihaazar 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 allocation 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.^{34,35,42} 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 Araihaazar are a clear indication of the value attached to safe drinking water. The potential of this approach was not fully realized even in Araihaazar. 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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