Science of the Total Environment 654 (2019) 1358–1363

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Field testing of over 30,000 wells for arsenic across 400 villages of the Punjab plains of Pakistan and India: Implications for prioritizing mitigation

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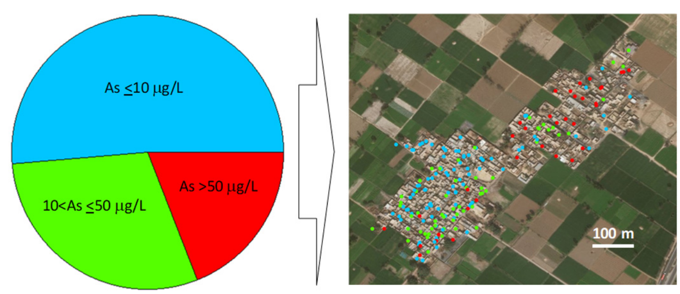
HIGHLIGHTS

- Nearly a quarter of wells tested in the Punjab plains contain >10 μg/L arsenic.
- The vast majority of affected households live within 100 m of a low arsenic well.
- A sizeable proportion of affected households responded by seeking a low arsenic well.
- Much more well testing is urgently needed.

GRAPHICAL ABSTRACT



Proportion of wells within different ranges of As concentrations for a typical affected village

Geographic distribution of wells color-coded by As concentration in the same village

ARTICLE INFO

Article history:
Received 18 September 2018
Received in revised form 13 November 2018
Accepted 13 November 2018
Available online 14 November 2018

Editor: José Virgílio Cruz

Keywords:
Arsenic exposure
Groundwater
Well testing
Mitigation
South Asia

ABSTRACT

Most of the rural population of 90 million in Punjab province in Pakistan and Punjab state in India drinks, and cooks with, untreated water drawn from shallow wells. Limited laboratory testing has shown that groundwater in the region can contain toxic levels of arsenic. To refine this assessment, a total of 30,567 wells from 383 villages were tested with a field kit in northern Punjab province of Pakistan and western Punjab state of India. A subset of 431 samples also tested in the laboratory shows that 85% of wells were correctly classified by the kit relative to the World Health Organization guideline of 10 μg/L for arsenic in drinking water. The kit data show that 23% of the tested wells did not meet the WHO guideline for arsenic but also that 87% of households with a well high in arsenic live within 100 m of a well that meets the WHO guideline. The implication is that many households could rapidly lower their exposure if the subset of safe wells could be shared. In a follow-up conducted one year later in five villages where 59% of wells were elevated in arsenic, two-thirds of households indicated that they had switched to a neighboring well in response to the testing. The blanket testing of millions of wells for arsenic in the region should therefore be prioritized over much costlier water treatment and piped water supply projects that will take much longer to have a comparable impact.

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https://doi.org/10.1016/j.scitotenv.2018.11.201
0048-9697/

1. Introduction

Tens of millions of shallow tubewells have been installed by villagers of Pakistan, India, Nepal, and Bangladesh in unconsolidated sand deposited by rivers draining the Himalayas. Wells are popular because groundwater is much less likely to be contaminated with microbial pathogens than surface water and typically does not require boiling or other treatment. Sadly, most of these wells have never been tested for arsenic (As) despite the serious health impacts of levels in groundwater that can naturally exceed the World Health Organization guideline of 10 μg/L for drinking water by a factor of ten to a hundred (WHO, 2017; Ravenscroft et al., 2009). In Bangladesh alone, a re-analysis of results from two large cohort studies has attributed a staggering 40,000 excess adult deaths per year, over 5% of total mortality in the country, primarily to cardio-vascular disease resulting from drinking well-water containing high levels of As (Flanagan et al., 2012). Exposure to As in drinking water in Bangladesh has also been shown to reduce intellectual function in children and considerably limit adult earnings (Wasserman et al., 2004; Pitt et al., 2015).

This still unfolding public-health crisis was discovered in the 1980s by attributing skin lesions and other visible signs of arsenicosis to the As content of well-water in the Indian state of West Bengal (Chakraborty and Saha, 1987), a decade later in Bangladesh, and has since been extended with various degrees of severity to other low-lying areas across South Asia, including the Punjab plains of the Indus River basin that straddle the border between Pakistan and India (Nickson et al., 2005; Farooqi et al., 2007; Lapworth et al., 2017; Naseem and McArthur, 2018).

The single most effective form of As mitigation conducted to date in Bangladesh consisted of blanket testing of almost 5 million wells with a field kit (World Bank, 2007). Results provided to individual households in the field is estimated to have led approximately 10 million villagers, a third of the exposed population, to switch to a nearby well that was low in As (Ahmed et al., 2006). Fetching water from a neighbor's well requires extra time and can have a social cost, but even larger proportions of switching have been confirmed by measuring levels of As in urine, a reliable biomarker of exposure, in a large study population (Chen et al., 2007).

The second most effective form of As mitigation documented in Bangladesh has been the installation of several hundred thousand deep wells that tap deeper aquifers that are often low in As (Ahmed et al., 2006; Ravenscroft et al., 2014; Johnston et al., 2014). Unfortunately, many of these deep wells were not installed in the most affected areas of the country and have, in addition, been captured by local elite instead of functioning as a public source as originally intended (DPHE/JICA, 2009; van Geen et al., 2015).

Despite some commendable large-scale testing efforts (Chakraborti et al., 2003), no blanket testing of all wells in regions known to be affected by As has to our knowledge been attempted in India or Pakistan. Systematic testing in the Indian states of West Bengal and Assam has been limited to wells installed by the government, which are a small minority compared to private wells installed by households (Nickson et al., 2007). The objective of this study was to assess the degree of exposure to arsenic in a representative set of villages across the Punjab plains and to evaluate the potential of well switching as a mitigation option.

2. Methods

Water was tested directly at the well by students recruited from local colleges using the ITS Arsenic Econo-Quick (Part No. 481298 from sensafe.com), an inexpensive (US$0.30 per test after volume discount) commercial field kit for As that requires a total of 15 min to process a sample. The kit relies on the visual comparison of the color of a test strip with a reference card to classify concentration of As in the 0–100 μg/L range into 5 bins and concentrations up to 1000 μg/L into another 4 bins (Table 1). An evaluation based on blind testing of 123 wells with the kit in Bangladesh showed that the status of 89% of the wells was consistent with laboratory measurements relative to the WHO guideline of 10 μg/L (George et al., 2012a). The kit tends to overestimate As concentrations above 50 μg/L by about a factor of two. Similar performance of the kit was reported over the course of a more extensive testing campaign (van Geen et al., 2014). Out of the control samples from 502 wells that were collected for this study, not a single well with ≤10 μg/L was incorrectly classified by the kit as containing >50 μg/L and not a single wells with >50 μg/L was as incorrectly classified as containing ≤10 μg/L. The ITS Arsenic Econo-Quick kit is therefore more reliable than some of the kits that were available two decades ago (Rahman et al., 2002).

For the present study, a total of 45 testers were trained and supervised by graduate students from Quaid-i-Azam University and TERI School of Advanced Studies. No attempt was made to filter the water in order to reflect the composition of the water consumed by households as closely as possible. Because the vast majority of screens at the bottom of a well effectively prevent aquifer particles from entering, filtration could if any anything have biased measurements towards lower As concentration due to the precipitation of iron oxides upon exposure to oxygen in the air. The wells were tested in the field from March to November 2016 and from February to March 2017 in Pakistan, and from November 2013 to October 2014 and from January to April 2015 in India.

Members of the household owning a well that were present were informed of the risks of chronic exposure to As before testing and immediately informed of the result afterwards. The importance of switching to a neighboring low-As well was emphasized to households owning a high-As well. Households owning a low-As well were encouraged to allow their less fortunate neighbors to use it. Test results were, in addition, written on a card that was handed over to the household in Pakistan and posted on the well with a colored metal placard in India (blue for As ≤10 ug/L; green for >10 μg/L and up to 50 μg/L; red for >50 μg/L).

Villages were selected for testing along the banks of the major rivers draining the region and a series of perpendicular transects in order to cover different types of environments. The density of villages was adjusted over the course of the study as the spatial scale of variability became apparent during testing. In Pakistan, 184 mostly small- to medium-sized villages were selected on the basis of Google Earth imagery to ensure that all wells in a village could be tested in blanket fashion within a few days. Test results based on visual comparison of the color of the test strip with a reference card were uploaded directly into an online database, along with other well information including geographic coordinates, using a smartphone and a version of the open-source app ODK Collect (SurveyCTO.com). The app does not require a continuous internet connection; field data are stored on the phone until it is connected. In India, at least half of the wells were tested in a total of 199 villages and readings were entered instead on handheld global positioning system (GPS) units that were periodically connected to a laptop to transfer data.

From a random subset of 431 wells in Pakistan and India, groundwater was also collected in 20 mL polyethylene scintillation vials with a PolySeal-lined cap (Wheaton no. 986706) for laboratory analysis at Lamont-Doherty Earth Observatory. Samples were acidified to 1% high-purity HCl (Fisher Scientific Optima) at least one week before analysis with a Thermo-Finnigan Element2 high-resolution inductively-coupled plasma mass spectrometer (Cheng et al., 2004). The procedure has been shown to ensure redissolution of any As associated with precipitated iron oxides (van Geen et al., 2007). An in-house consistency standard of artificial groundwater containing 430 μg/L As and reference materials NIST1640a (8.08 ± 0.07 μg/L As) and NIST1643e (58.98 ± 0.7 μg/L As) were included with every run to verify accuracy and precision of the method to within <5% of expected values.

Table 1
Comparison of field kit results for As with laboratory measurements for a total of 431 samples from Pakistan and India. The first entry, for instance, indicates that kit readings of 0–10 μg/L for 260 samples were confirmed to be within that range by laboratory measurements.

Lab measurements	Kit readings								
	0	**10**	**25**	**50**	**100**	**200**	**300**	**500**	**1000**
0-10	252	8	9	0	4	3	0	0	0
>10-50	28	10	7	22	15	8	8	0	0
>50	8	1	1	6	12	11	11	4	3

3. Results

A total of 30,567 wells distributed across 383 villages were tested with the As kit. Overall, 23% of the wells did not meet the WHO guideline of 10 μg/L for As in drinking water and As concentrations exceeded 50 μg/L for 11% of wells (Fig. 1). The official standard for As in drinking water is still 50 μg/L in Pakistan, but was recently lowered from that value to the WHO guideline of 10 μg/L in India as a target. Overall, the proportion of kit readings correctly classified wells relative to the WHO guideline of 10 μg/L was 85% (Table 1). This is calculated by summing the number of observations in the upper-left and lower-right quadrant of Table 1 and dividing by the total.

There are four major rivers flowing in southwesterly direction through the study area, but only villages within the floodplain of the Ravi River on both sides of the Pakistan-India border are consistently associated with an elevated proportion of wells elevated in As (Fig. 1). The vast majority of wells in the western half of the study area do not extend beyond 45 m (150 ft) depth, but many wells extend to 150 m (500 ft) in the eastern half of the study area. There is no clear relationship between As and well depth that could explain why the floodplain of the Ravi River is particularly affected. Even within the floodplain of the Ravi River, high- and low-As wells are distributed across all villages. There was no case of a village where all wells were high in As.

Using the geographic coordinates obtained while sampling, the distance from each well that does not meet the WHO guideline for As to the closest well that does was calculated. The results show that 87% of households in the study area with a well elevated in As reside within 100 m of a low As well, as previously documented in Bangladesh and in India (van Geen et al., 2002; Barnwal et al., 2017). At least one well (often several) that is low in As water is therefore within walking distance of the vast majority of households exposed to As. The highly heterogeneous distribution of As within a village means predicting the status of an individual well without additional information is difficult. Every well therefore needs to be tested.

Most wells throughout South Asia are privately installed and are often located within a family compound. Our results emphasize that few if any villages are entirely dominated by wells high in As. In spite of potential social barriers, there is considerable scope for reducing exposure to As by sharing safe wells with neighbors. One year after blanket testing, our team returned to five villages within the Ravi River floodplain southwest of Lahore where 59% out of 829 previously tested wells did not meet the Pakistan standard for As in drinking water of 50 μg/L (Fig. 2). Encouragingly, two-thirds of 150 households with a well with >50 μg/L As who could produce a card with the test result given to them the previous year indicated that they were using an alternative source of water that was lower in As.

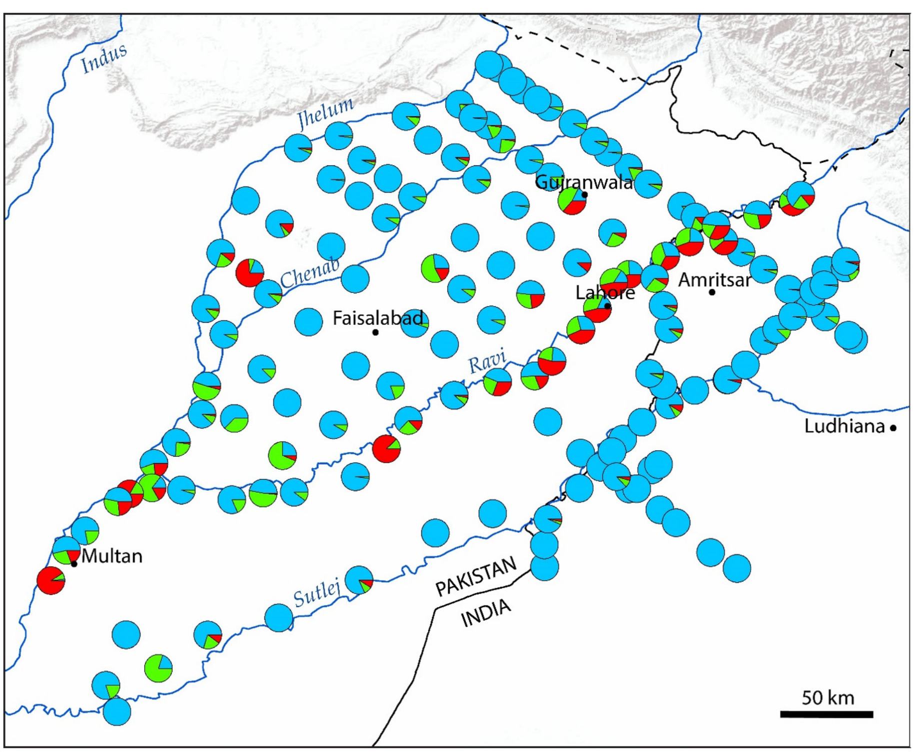

Fig. 1. Map of a portion of the Punjab plains of Pakistan and India showing As test results for 30,476 wells obtained with a field kit. To limit overlap, results from 374 villages were pooled into 149 clusters by applying a k-means algorithm to their geographic coordinates. The 149 pie diagrams corresponding to these clusters shown in blue the proportion of wells that meet the WHO guideline for As in drinking water of 10 μg/L, in green the proportion of wells with >10 μg/L but up to 50 μg/L As, which is still the standard in Pakistan, and in red wells with >50 μg/L As. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

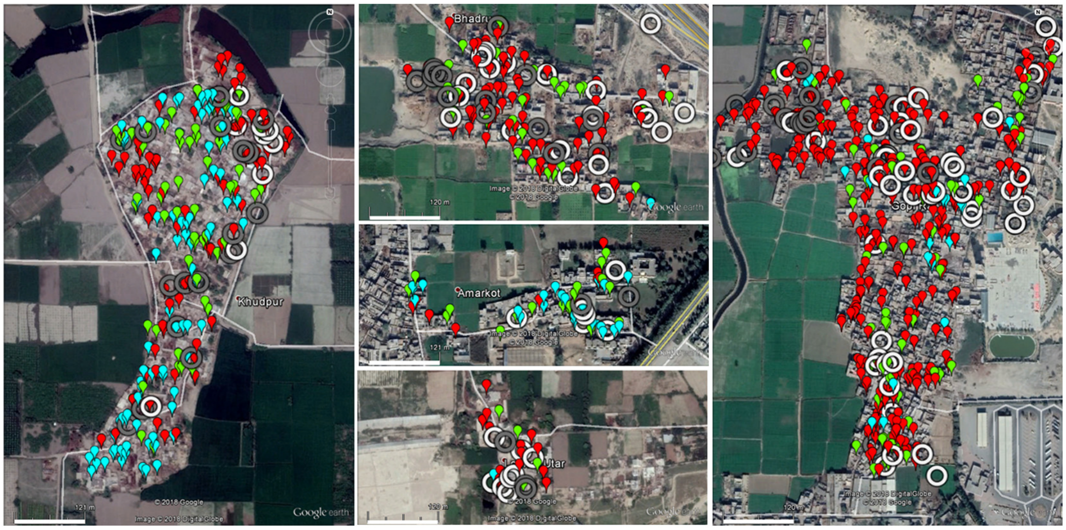

Fig. 2. Close-up of five villages along the Ravi River floodplain in Pakistan where a total 829 wells were tested for As with the field-kit in December 2014. The color coding of markers corresponds to kit readings of 0 and 10 μg/L (blue), 25 and 50 μg/L (green), and 100 μg/L and above (red). Open circles indicate the location of 150 households who, one year later, could produce a results card showing a result of 100 μg/L and above. White and grey circles correspond to households who had and had not switched to a different well, respectively. Portions of the two larger villages without any white or grey circles were not resurveyed in 2015. Some circles are located outside the area tested in 2014 because of the limitations of the GPS receivers on the low-end smartphones that were used to conduct the survey. White scale bar corresponds to 120 m in 5 panels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The well tests conducted for this study show that switching to a neighboring well is a viable mitigation option that could be widely adopted in order to reduce exposure to As. The high degree of spatial variability in the As content of groundwater within a village raises the issue of potential changes over time. Concentrations of As in well water are generally well anchored by the local geology (Dhar et al., 2008). The few extended time series of As in well water that have been collected show that if As concentrations change, they do so gradually and that worrisome trends can therefore be monitored by occasional retesting (McArthur et al., 2010).

The proportion of wells that meet the WHO guideline for As in northern Punjab reported here is considerably higher than recently estimated for the same region from a smaller set of laboratory measurements in combination with a regression model that incorporates geological information (Podgorski et al., 2017). Data provided by the authors of the previous study indicate that only 29% of a subset of 272 of their wells located within 20 km of wells tested under the present study met the WHO guideline for As in drinking water. Spatial block kriging (Cressie, 1993) of these data to avoid over-representing more heavily sampled villages increases the proportion of wells meeting the WHO guideline to 45 $\pm$ 13% (1-sigma) in the area overlapping with the present study. The proportion of wells meeting the WHO guideline for the 21,448 wells in the overlapping area tested under the present study with field kit is 77% and declines only slightly to 74 $\pm$ 9% with block kriging. The contrast between the two surveys seems too large to be explained by the kit's underestimate of As concentrations relative to the WHO guideline in 11% of samples that were also analyzed in the laboratory, most of which still meet the Pakistan standard of 50 μg/L (Table 1). Such discrepancies underline the need to test all wells in all potentially affected villages for the purpose of mitigation instead of relying on broad-scale modeling.

Arsenic is not the only constituent of groundwater that poses a health risk to the rural population of the Punjab plains. Field kit measurements conducted in parallel with the As tests show that 15% and 4% of the tested wells did not meet WHO guidelines of 1.5 mg/L for fluoride and 50 mg/L for nitrate in drinking water, respectively (WHO, 2017; Farooqi et al., 2007). The villages affected by high fluoride and nitrate are not the same as the high-As villages and are concentrated in the southern portion of the study area. The additional cost of blanket testing wells for fluoride and nitrate, in addition to As, would be modest and reducing exposure to these toxicants could often also be achieved by sharing a subset of safe wells.

The response survey conducted in Pakistan had some limitations because the number of recovered cards showing a high As result was lower than expected from the earlier testing phase. We have evidence that some households did not indicate that they still had their card because they wanted another test. In a portion of the two larger villages that were re-surveyed (Fig. 2), household were mistakenly not re-interviewed because they were unwilling to have their well re-tested. In one of the areas that were not re-surveyed, household reported that they had switched to a recently installed community well that was low in As. Some level of courtesy bias also cannot be excluded, although a previous study conducted in Bangladesh that relied on urinary As measurements as an objective measure of well switching reported similar results (Chen et al., 2007). In addition, response surveys conducted after testing for As elsewhere in South Asia have shown that between one- to two-thirds of exposed households will respond to test results and do not revert to an unsafe well if it has been tested (Ahmed et al., 2006; Chen et al., 2007; Barnwal et al., 2017; Pfaff et al., 2017; Balasubramanya et al., 2013). Additional testing, reminders, and information sessions at the group level have all been shown to increase the proportion of switching after testing (George et al., 2012a, 2012b; Inauen et al., 2013). Rather than returning to their original contaminated well, households in Bangladesh have been shown to switch away from contaminated wells in growing numbers over time (Balasubramanya et al., 2013).

The results from this study have significant policy implications. About a quarter of households in the study villages received bad news concerning the status of their well with respect to As, but three quarters received good news and these wells could potentially be shared. Blanket testing of all wells in the region is therefore urgently needed, with an initial emphasis on the most affected floodplain of the Ravi River (Fig. 1). Based on a combined rural population of 90 million in Punjab province and Punjab state and an average number of 10 users per well recorded during the testing, an estimated total of 9 million wells need to be tested. The number is very large but not unrealistic given that almost 5 million wells were tested using a field kit a decade and half ago in Bangladesh (World Bank, 2007). The cost of recent testing campaigns conducted in India and Bangladesh has been on the order of US$2/well, including test supplies, smartphones, labor, and supervision (Barnwal et al., 2017; van Geen et al., 2014). The cost of laboratory measurements and the logistics of collecting samples and returning the results to well owners would probably be higher by at least an order of magnitude.

Unlike the health effects of As, elevated levels of fluoride and nitrate in drinking water are typically visible: teeth discoloration and skeletal deformation in the case of excess exposure to fluoride, methemoglobinemia (blue-baby syndrome) for elevated levels of nitrate in drinking water. The increased likelihood of dying from cardiovascular disease (Flanagan et al., 2012) is more difficult to attribute to As exposure by individual households. A combined field-testing campaign for fluoride, nitrate, as well as As may therefore have the benefit of leading to more households responding to either of these hazards by seeking alternatives sources of water.

Rather than blanket testing and sharing of uncontaminated wells, initial government efforts to address the groundwater As and fluoride issue in both Pakistan and India have relied on groundwater treatment and piped water supply. The Punjab government in India has installed 1200 village-level reverse osmosis (RO) plants, but arsenic does not appear to have been a criterion for selecting their location among the much larger number of 13,000 villages in the state (http://www.pbdwss.gov.in/dwss/left_menu/major_achievement.html). Similarly, the Punjab government in Pakistan has issued a call for tenders to treat groundwater in a subset of only 1800 out of 26,000 villages in the province, with little evidence that water quality was taken into account (https://hudphed.punjab.gov.pk/system/files/PQD%20Aab-e-Sehat%20%5BFinal%2014-10-2017%5D.pdf). In addition to helping millions of exposed villagers identify a nearby safe well, a systematic blanket testing campaign across the region would therefore provide a rational basis for targeting a subset of the most affected villages for government investment in centralized water treatment and distribution.

Sadly, even in Bangladesh, no systematic testing has been conducted at the national scale since the blanket testing campaign conducted in 2000–05. The majority of these wells have been replaced and more wells have been installed over the past decade. Most existing wells in Bangladesh are therefore untested today (van Geen et al., 2014). Widespread drinking from wells of unknown status helps explain why exposure to As in Bangladesh has stagnated after an initially impressive decline (BBS/UNICEF, 2015). Well testing should therefore be made available at the village level throughout the Indus River plains on a continuous basis instead of through a single blanket testing campaign.

5. Conclusion

Results from two sizeable well-testing campaigns conducted with field kits in the Indus plains of Pakistan and India show that drinking untreated well water can pose a significant health risk, particular in the case of As along the Ravi River. The only way for individual households to know whether they are exposed to As or other contaminants of health concern is by having their well tested. In most villages, testing alone can already significantly reduce exposure by providing the information necessary for neighbors to share the subset of safe wells. Despite the social and other barriers, considerable well switching and sharing has already been well documented elsewhere in South Asia and, in this study, in a handful of villages in the Punjab plains. Over the long term, large investments in water treatment and possibly pipe water delivery will be needed. The anticipation of such large investments should not delay a much less costly form of mitigation based on well testing and well sharing.

Funding

Field work in India was supported by the United States Agency for International Development (USAID) under the aegis of PEER Science Award (Project 2-61) sub-grant number NAS 2000003428. Well testing in Pakistan was also supported by USAID under the Pakistan-U.S. Science and Technology Cooperation Program with grant NAS 2000006111. US participation was supported in part by NIEHS grant P42 ES010349 and NSF grant ICER1414131. We thank M. Rajib Mozumder for his advice on spatial kriging using R. This is LDEO contribution no. 8266.

Competing interests

None.

References

Ahmed, M.F., Ahuja, S., Alauddin, M., Hug, S.J., Lloyd, J.R., Pfaff, A., et al., 2006. Ensuring safe drinking water in Bangladesh. Science 314, 1687–1688.

Balasubramanya, S., Pfaff, A., Bennear, L., Tarozzi, A., Ahmed, K.M., Schoenfeld, A., van Geen, A., 2013. Evolution of households' responses to the groundwater arsenic crisis in Bangladesh: information on environmental health risks can have increasing behavioral impact over time. Environ. Dev. Econ. https://doi.org/10.1017/S1355770X13000612.

Barnwal, P., van Geen, A., von der Goltz, A., Singh, C.K., 2017. Demand for environmental quality information and household response: evidence from well-water arsenic testing. J. Environ. Econ. Manag. 86, 160–192.

BBS/UNICEF, 2015. Bangladesh Multiple Indicator Cluster Survey 2012–2013, Progotir Pathey: Final Report. Bangladesh Bureau of Statistics (BBS) and UNICEF.

Chakraborti, D., Mukherjee, S.C., Pati, S., Sengupta, M.K., Rahman, M.M., Chowdhury, U.K., et al., 2003. Arsenic groundwater contamination in middle Ganga plain, Bihar, India: a future danger? Environ. Health Perspect. 111, 1194–1201.

Chakraborty, A.K., Saha, K.C., 1987. Arsenical dermatosis from tubewell water in West Bengal. Indian J. Med. Res. 85, 326.

Chen, Y., van Geen, A., Graziano, J., Pfaff, A., Madajewicz, A., Parvez, F., et al., 2007. Reduction in urinary arsenic levels in response to arsenic mitigation in Araihazar, Bangladesh. Environ. Health Perspect. 115, 917–923.

Cheng, Z., Zheng, Y., Mortlock, R., van Geen, A., 2004. Rapid multi-element analysis of groundwater by high-resolution inductively coupled plasma mass spectrometry. Anal. Bioanal. Chem. 379, 513–518.

Cressie, N.A.C., 1993. Statistics for Spatial Data. J. Wiley.

Dhar, R.K., Zheng, Y., Stute, M., van Geen, A., Cheng, Z., Shanewaz, M., et al., 2008. Temporal variability of groundwater chemistry in shallow and deep aquifers of Araihazar, Bangladesh. J. Contam. Hydrol. 99, 97–111.

DPHE/JICA, 2009. Situation Analysis of Arsenic Mitigation. Department of Public Health Engineering, Government of Bangladesh, Dhaka, Bangladesh, and Japan International Cooperation Agency.

Farooqi, A., Masuda, H., Kusakabe, M., Naseem, M., Firdous, N., 2007. Distribution of highly arsenic and fluoride contaminated groundwater from east Punjab, Pakistan, and the controlling role of anthropogenic pollutants in the natural hydrological cycle. Geochem. J. 41, 213–234.

Flanagan, S.V., Johnston, R.B., Zheng, Y., 2012. Arsenic in tube well water in Bangladesh: health and economic impacts and implications for arsenic mitigation. Bull. World Health Organ. 90, 839–846.

George, C.M., Zheng, Y., Graziano, J.H., Rasul, S.B., Mey, J.L., van Geen, A., 2012a. Evaluation of an arsenic test kit for rapid well screening in Bangladesh. Environ. Sci. Technol. 46, 11213–11219.

George, C.M., van Geen, A., Slavkovich, V., Singha, A., Levy, D., Islam, T., Ahmed, K.M., Moon-Howard, J., Tarozzi, A., Liu, X., Factor-Litvak, P., Graziano, J., 2012b. A cluster-based randomized controlled trial promoting community participation in arsenic mitigation efforts in Bangladesh. Environ. Health 11, 41.

Inauen, J., Tobias, R., Mosler, H.J., 2013. The role of commitment strength in enhancing safe water consumption: mediation analysis of a cluster-randomized trial. Br. J. Health Psychol. 19, 701–719.

Johnston, R., Hug, S.J., Inauen, J., Khan, N.I., Mosler, J.H., Yang, H., 2014. Enhancing arsenic mitigation in Bangladesh. Findings from institutional, psychological, and technical investigations. Sci. Total Environ. 488–9, 477–483.

Lapworth, D.J., Krishan, G., MacDonald, A.M., Rao, M.S., 2017. Groundwater quality in the alluvial aquifer system of northwest India: new evidence of the extent of anthropogenic and geogenic contamination. Sci. Total Environ. 599–600, 1433–1444.

McArthur, J.M., Banerjee, D.M., Sengupta, S., Ravenscroft, P., Klump, S., Sarkar, A., et al., 2010. Migration of As, and $^{3}H/^{3}He$ ages, in groundwater from West Bengal: implications for monitoring. Water Res. 44, 4171–4184.

Naseem, S., McArthur, J.M., 2018. Arsenic and other water-quality issues affecting groundwater, Indus alluvial plain, Pakistan. Hydrol. Process. 32, 1235–1253.

Nickson, R.T., McArthur, J.M., Shrestha, B., Kyaw-Myint TO, Lowry, D., 2005. Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. Appl. Geochem. 20, 55–68.

Nickson, R., Sengupta, C., Mitra, P., Dave, S., Banerjee, A., Bhattacharya, A., et al., 2007. Current knowledge on the distribution of arsenic in groundwater in five states of India. J. Environ. Sci. Health A 42 (12), 1707–1718.

Pfaff, A., Schoenfeld, A., Ahmed, K.M., van Geen, A., 2017. Reduction in exposure to arsenic limited by insufficient testing and awareness in Bangladesh. J. Water Sanit. Hyg. Dev. 2, 331–339.

Pitt, M.M., Rosenzweig, M.R., Hassan, N., 2015. Identifying the Cost of a Public Health Success: Arsenic Well Water Contamination and Productivity in Bangladesh; NBER Working Paper No. 21741. National Bureau of Economic Research, Cambridge, Massachusetts, USA.
Podgorski, J.E., Shah Eqani, S.A.M.A., Khanam, T., Ullah, R., Shen, H., Berg, M., 2017. Extensive arsenic contamination in high-pH unconfined aquifers in the Indus Valley. Sci. Adv. 3 (8), e1700935. https://doi.org/10.1126/sciadv.1700935.
Rahman, M.M., Mukherjee, D., Sengupta, M.K., Chowdhury, U.K., Lodh, D., Chanda, C.R., et al., 2002. Effectiveness and reliability of arsenic field testing kits: are the million dollar screening projects effective or not? Environ. Sci. Technol. 36, 5385–5394.
Ravenscroft, P., Brammer, H., Richards, K., 2009. Arsenic Pollution: A Global Synthesis. RGS-IBG Book SeriesWiley-Blackwell, Chichester, UK.
Ravenscroft, P., Kabir, A., Hakim, S.A.I., Ibrahim, A.K.M., Ghosh, S.K., Rahman, M.S., et al., 2014. Effectiveness of public rural waterpoints in Bangladesh with special reference to arsenic mitigation. J. Water Sanit. Hyg. Dev. 4, 546–562.
van Geen, A., Ahsan, H., Horneman, A.H., Dhar, R.K., Zheng, Y., Hussain, I., et al., 2002. Promotion of well-switching to mitigate the current arsenic crisis in Bangladesh. Bull. World Health Organ. 81, 732–737.
van Geen, A., Cheng, Z., Jia, Q., Seddique, A.A., Rahman, M.W., Rahman, M.M., et al., 2007. Monitoring 51 deep community wells in Araihazar, Bangladesh, for up to 5 years: implications for arsenic mitigation. J. Environ. Sci. Health A 42, 1729–1740.
van Geen, A., Sumon, E.B.A., Pitcher, L., Mey, J.L., Ahsan, H., Graziano, J.H., et al., 2014. Comparison of two blanket surveys of arsenic in tubewells conducted 12 years apart in a 25 km^2 area of Bangladesh. Sci. Total Environ. 488–9, 484–492.
van Geen, A., Ahmed, K.M., Ahmed, E.B., Choudhurry, I., Mozumder, M.R., Bostick, B.C., et al., 2015. Inequitable allocation of deep community wells for reducing arsenic exposure in Bangladesh. J. Water Sanit. Hyg. Dev. 6, 142–150.
Wasserman, G.A., Liu, X., Parvez, F., Ahsan, H., Factor-Litvak, P., van Geen, A., et al., 2004. Water arsenic exposure and children's intellectual function in Araihazar, Bangladesh. Environ. Health Perspect. 112, 1329–1333.
World Bank, 2007. Implementation, completion and results report (IDA-31240 SWTZ-21082) on a credit in the amount of SRD 24.2 million (US$ 44.4 million equivalent) to Bangladesh. Report No: ICR000028. http://documents.worldbank.org/curated/pt/309151468002142598/text/ICR28.txt.
World Health Organization, 2017. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. http://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/.