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Changes in arsenic exposure in Araihazar, Bangladesh from 2001 through 2015 following a blanket well testing and education campaign

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ABSTRACT

Background: Concentrations of arsenic (As) are elevated in a large proportion of wells in Bangladesh but are spatially variable even within a village. This heterogeneity can enable exposed households to switch to a nearby well lower in As in response to blanket (area-wide) well As testing.

Objectives: We document the evolution of As exposure in Araihazar, Bangladesh following a blanket well testing and education campaign, as well as the installation of a considerable number of low As community wells.

Methods: We use well water and urinary As data collected between 2000 and 2008, along with household interviews extending through 2016, within a 25 km^2 area of Araihazar upazila for nearly 12,000 participants enrolled in the Health Effects of Arsenic Longitudinal Study (HEALS). We observe changes in participants' well water and urinary As concentrations following interventions to lower their exposure and use logistic regression to determine the factors associated with participants' decisions to switch primary household wells.

Results: Urinary As for participants drinking from wells with > 100 μg/L As at baseline declined from a mean of 226 μg/L at baseline to 173 μg/L two years later, and further declined to 139 μg/L over 8 years. For comparison, urinary As concentrations for participants drinking from wells with ≤ 10 μg/L As remained close to 50 μg/L throughout. Whereas the interventions only partially reduced exposure, well status with respect to As was predictive of well-switching decisions for at least a decade after the initial testing. Participants with high-As wells were 7 times more likely to switch wells over the first two years and 1.4–1.8 times more likely to switch wells over the ensuing decade.

Conclusions: Arsenic exposure gradually declined following blanket well testing, an education campaign, and the installation of community wells but remained almost three times higher than for a subgroup of the participants drinking from wells with ≤ 10 μg/L. In addition, the number of participants with unknown As concentrations in their primary household wells increased substantially over time, indicating the importance of additional well testing as new wells continue to be installed, in addition to other means of reducing As exposure.

1. Introduction

Natural contamination of groundwater with arsenic (As) poses a health threat in many regions of the world where people rely on wells for drinking water. In Bangladesh, $>$ 50 million people are estimated to have been chronically exposed to As concentrations above the World Health Organization (WHO) guideline of 10 μg/L (BGS and DPHE, 2001; Brammer and Ravenscroft, 2009). Arsenic exposure produces negative health outcomes such as skin lesions, cancers of the skin, bladder, and lung, cardiovascular disease, increased risk of stillbirth and infant mortality, and reduced intellectual function in children (Argos et al., 2010; Chen et al., 2011; Flanagan et al., 2012; Quansah

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et al., 2015; Rahman et al., 2007; Smith et al., 2000; Sohel et al., 2009; Wasserman et al., 2004).

The Bangladesh government and non-governmental organizations have supported a range of methods for reducing As exposure. Many of these interventions have been insufficiently safe, effective, or persistent (Ahmed et al., 2006; Hoque et al., 2006; Howard et al., 2006). A common problem with water filtration, which was the focus of early interventions, is rapid abandonment of filters due to maintenance issues and inconvenience (Ahmed et al., 2006; Hossain et al., 2005; Sanchez et al., 2016). An alternative approach is blanket well testing to provide individuals with information about the As concentration of their own wells and nearby wells, thus facilitating switching to drinking from lower-As wells. This approach is made possible by the high spatial variability of well As concentrations, even within a small area. Since well As concentrations are generally stable (Dhar et al., 2008; van Geen et al., 2014), once a well that meets a certain standard has been identified, additional maintenance or monitoring is generally not required, in contrast with water filtration.

In this paper, we report changes in behavior and As exposure following interventions to facilitate well-switching in an As-impacted 25 km^2 area of Araihazar, Bangladesh. The interventions began with an initial round of blanket well testing for As, with most wells labeled in January through March of 2001. People drinking from wells with As concentrations of > 50 μg/L, which is still the local standard, were encouraged to switch to a well that met the local standard. We use the 50 μg/L threshold when referring to a well that is high in As or a well that meets the local standard throughout this paper, while recognizing that sources of drinking water that meet the WHO guideline would be much preferred.

To help reduce exposure, a set of 51 deeper community wells targeting villages with very few private wells that met the local standard were installed by 2003 through the study's local collaborators (van Geen et al., 2003a, b, 2007). Although some of these community wells were no in use by 2012, the total number of deep wells in the study area grew by then to 239 because of additional government installation of deep wells (van Geen et al., 2014). Unfortunately, the impact of these government wells was reduced by sub-optimal allocations and reduced access (van Geen et al., 2015). Additional blanket well testing in Araihazar was also conducted by the government in 2003, after which wells were painted red or green to indicate whether they were above or below the Bangladesh drinking water standard, and by a team of local village-health workers in 2012–2013 (van Geen et al., 2014). Prior studies have shown positive impacts on well As and urinary As two to three years after blanket well testing (Chen et al., 2007; Madajewicz et al., 2007; Opar et al., 2007). In this paper, we observe the changes in participants' As exposure over sixteen years starting from the initial round of blanket well testing in 2000–2002.

2. Methods

2.1. Health effects of arsenic longitudinal study (HEALS)

The study is briefly summarized here; a detailed description of the study design is found in Ahsan et al. (2006). Data were collected in a 25 km^2 area in Araihazar, Bangladesh. In 2000–2002, the field team conducted a blanket survey of wells in the study area, recorded their GPS coordinates, and tested them to determine their As concentrations.

From October 2000 to May 2002, paired HEALS study teams (each with one physician and one non-physician interviewer) identified and recruited eligible individuals (aged ≥ 18 years and living in the study area for ≥ 5 years) into the cohort. At baseline recruitment, each eligible participant, following informed consent, completed a structured interview including detailed drinking water history, health, household, and demographic information and provided a blood and a urine sample. As part of the baseline interview, each study participant reported all sources of their current and past drinking water including both primary and secondary drinking water sources. Men and women reported to consume 70% and 91% of their water from primary household wells, respectively.

Soon after the laboratory As data became available, all surveyed wells were labeled with placards indicating values of As concentrations (Ahsan et al., 2006; van Geen et al., 2003a, b). However, individual level health education messages, including information and interpretation of arsenic values posted on placards and specific advice to switch wells for those reported using high As wells at baseline interview were given by study physicians after the completion of baseline interview and bio-sample collection. Subsequently, extensive community level health education campaigns, as well as physician-led individual-level health education messages, were provided to cohort participants during their visits to HEALS study clinic and also during follow-up home visits.

Five follow-up surveys were conducted in 2002–2004, 2004–2006, 2007–2009, 2010–2013, and 2014–2016, respectively. Urinary As was measured during the first three follow-up surveys, i.e. through 2009, but was not measured subsequently due to limited resources. Also due to limited resources, well water As was not tested systematically during surveys after baseline, and thus well As concentrations at follow-up are only known for participants who either remained using their original baseline well or who switched to another baseline well. Well water and urine samples were collected from the HEALS cohort as part of a recently completed, sixth follow-up.

2.2. Determination of well IDs and well-switching

From the data collected during field surveys, well IDs could be determined for a total of 11,744, 8919, 8059, 6671, 5604, and 4838 participants at baseline through follow-up five respectively (Fig. S1). This is because many wells lost their identifying placards over the study period, either because they were abandoned and replaced over time or because the placard fell off or was removed (van Geen et al., 2014).

In this study, when documenting whether a participant switched wells between one survey and the next, we only considered participants with known well IDs at each survey. If the well IDs between one survey and the following survey differed, we concluded that the participant switched wells. If the well IDs for the two surveys matched, we concluded that the participant did not switch wells.

2.3. Logistic regressions

Logistic regression models were used to investigate how well-switching depended on whether a well was above or below the Bangladesh drinking water standard of 50 μg/Land on the As concentration in the well (treated as a continuous variable). Our hypothesis was that participants with wells that did not meet the local standard and participants with higher well As concentrations would be more likely to switch wells at a follow-up visit. The Wald test was used to determine whether individual coefficients were statistically significant and the Pearson chi-square goodness of fit test to determine whether the model was a good fit for the data.

3. Results

3.1. Participant primary household well As exposure over time

The proportion of participants with primary household wells determined at baseline to be high in As relative to the local standard decreased from 56% to 27% between baseline and the first follow-up survey and continued to decline thereafter, reaching 14% by the third follow-up about 8 years after the initial intervention (Fig. 1). The proportion of participants with wells determined at baseline to meet the local standard increased slightly from 44% at baseline to 47% at the first follow-up survey and then declined, reaching 26% by the third

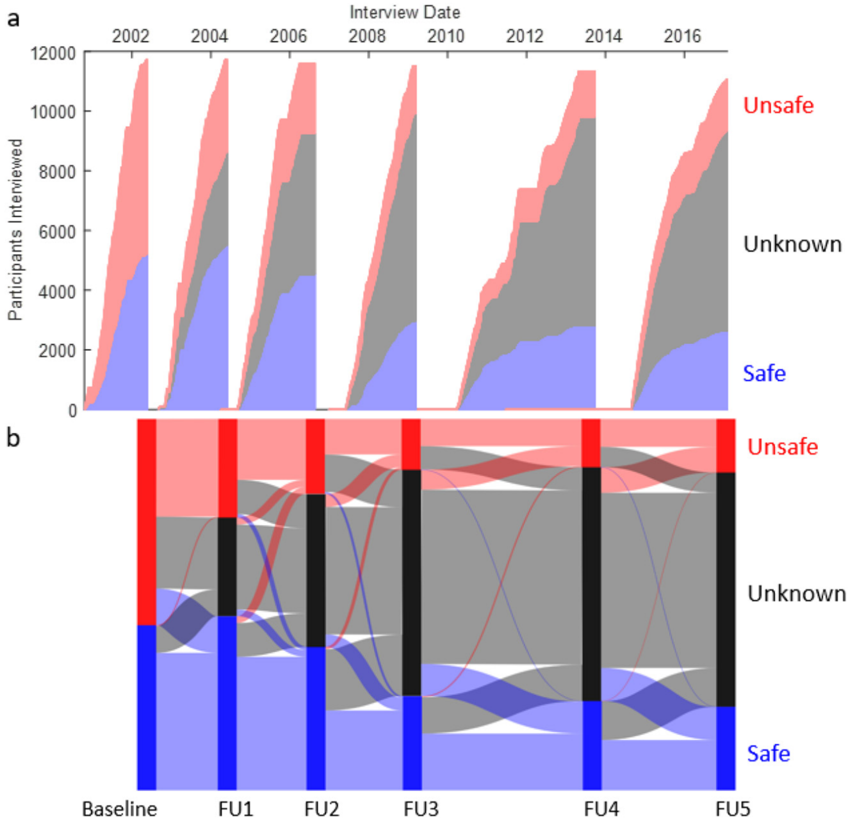

Fig. 1. Number of subjects with primary household wells that are high (red, > 50 μg/L) in As, meet the local standard (blue, < 50 μg/L As), or of unknown As concentration (black) at baseline and at each follow-up. a) Cumulative number of participants approached during each interview cycle b) Flows of participants from one well category to another between interview cycles. The height of each color in a column represents the number of participants with that type of well during that interview cycle. The flows between columns are colored according to the type of well a participant switched to over that time period. BL = baseline, FU = follow-up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

follow-up. The participants with wells of unknown status with respect to As because they were either newly installed and thus untested at baseline, or wells that had lost their identification tags, amounted to 27% at the first follow-up survey and continued to increase to 60% by the third follow-up. The proportion of participants with each type of well held relatively steady between the third follow-up eight years after the initial intervention and the fifth follow-up sixteen years after the initial intervention.

We can further break out the impact of the intervention on well As according to concentrations of As in the participants' wells at baseline (Fig. 2a,b). Changes in primary household well As result from participants switching wells between surveys, and are only reported for the subgroup of participants drinking from household wells tested at baseline that had retained their ID tags. Between the baseline and first follow-up survey two years later, there was a decline in average well As (219 to 153 μg/L) for participants who started with wells with > 100 μg/L As, and a lesser decline (72 to 60 μg/L) for participants who started with wells with 50–100 μg/L As. In contrast, little change in well As occurred for the participants who started with wells that met the local standard at < 50 μg/L As. After this initial effect of the intervention, well As held roughly steady across all groups through the sixteen years of monitoring.

3.2. Participant urinary As over time

Urinary As was measured for eight years after the initial intervention compared to sixteen years of participants reporting primary household well IDs. Urinary As is more representative of the overall population exposure, since it integrates all sources of exposure and is not limited to participants whose primary household well was tested at baseline. Between baseline and the third follow-up, the upper 5 percentile of exposure was delimited by a urinary As concentration declining from 430 to 315 μg/L. The threshold to the upper 10 percentile in exposure declined over the same period from 310 to 230 μg/L. We also examined changes in average urinary As following the initial intervention for participants who had baseline wells with As concentrations > 100, 50–100, 10–50, and < 10 μg/L (Fig. 2c,d). For the group of participants drinking from baseline wells > 100 μg/L As, there was a decline in average urinary As from 226 to 173 μg/L between the initial intervention and the first follow-up two years later. At later times, average urinary As continued to decline for this group, but more gradually, reaching 139 μg/L by the third follow-up eight years after the initial intervention.

In contrast, the participants drinking from wells with 50–100, 10–50, and 0–10 μg/L As showed no average decline in urinary As in the two years after the initial intervention. These groups had relatively stable urinary As concentrations throughout the eight years of monitoring, although all groups had a slight decline in urinary As between the second and third follow-ups.

Participants with a high-As well at baseline had the highest urinary As concentrations at the third follow-up eight years. Participants with a well that met the local standard at baseline had the lowest urinary arsenic concentrations (Fig. 3). More than 50% of participants relied on primary wells that were not tested at baseline or had missing labels by the third follow-up, and these participants had intermediate urinary As concentrations.

3.3. Factors influencing well-switching

To explore how the persistent lowering of household well As and urinary As may have been facilitated by well testing and education, as well as the installation of community wells, we used a logistic regression to determine how well status relative to the local standard, well As concentration posted on a placard on each tested well, age, and sex were related to participants' decisions to switch wells at baseline and at later times (Table S1). Sex and age were not consistently related to well-switching. The most consistent factor associated with participants' decisions to switch wells was well status (Fig. 4a). Participants with high-

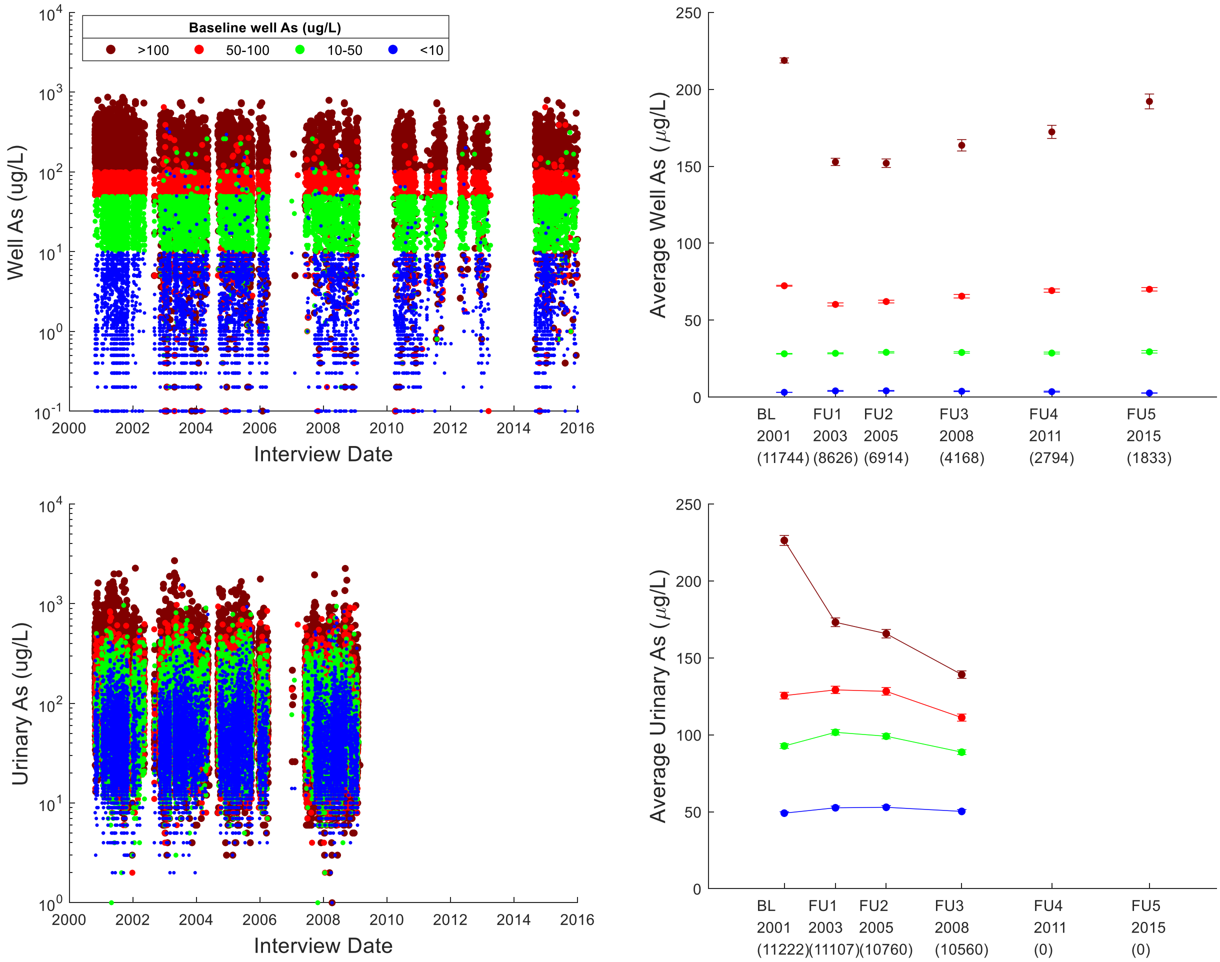

Fig. 2. (a) Primary household well As, (b) average primary household well As, (c) urinary As, and (d) average urinary As over time after the intervention for subjects drinking from baseline wells with < 10 μg/L, 10–50 μg/L, 50–100 μg/L, and > 100 μg/L As. The x-axis labels in (b) and (d) list the median year of data collection and the number of participants included in each average (in brackets). The averages in (b) are unconnected by lines since the number of individuals whose well As is known substantially declines between follow-ups, whereas the averages in (d) are connected by lines because the same group of people is tracked across all follow-ups. BL = baseline, FU = follow-up.

As wells were 6.8 times more likely to have switched wells between baseline and first follow-up compared to participants with wells that met the local standard. Between the first and second, second and third, and third and fourth follow-up surveys, participants with high-As wells were 1.4–1.8 times more likely to switch wells, with well status becoming negligible after the fourth follow-up. Thus the relationship between well status and well switching was weaker at later times but well status continued to be related to participants' switching decisions more than a decade after the intervention.

Well As concentration remained a significant factor after controlling for well status, indicating that providing participants with information about well As concentration in addition to well As status informed their behavior. However, well As concentration was only related to participant well switching between baseline and the first follow-up and between the first and second follow-ups. At both times, each 100 μg/L increase in As concentration led to participants being about $1.003^{100} = 1.35$ times more likely to switch wells (Fig. 4b).

Comparing the well-switching behavior of participants drinking from wells that met the local standard versus high-As wells suggests that participants drinking from wells that met the local standard may more strongly and persistently take their well As concentrations into account when deciding whether to switch wells (Fig. 5). For participants drinking from wells that met the local standard, at times from baseline through the third follow-up, a 10 μg/L increase in As concentration led to about a $1.008^{10} = 1.08$ times higher likelihood of switching wells, with diminishing effects at times after that.

3.4. Impacts of switching away from wells that met the local standard and high-As wells

We investigated how primary household well As changes for participants who switch away from wells that met the local standard and from high-As wells. Participants who switched away from wells high in As between the baseline and first follow-up had a mean decrease in well-water As of 106 μg/L (Fig. 6). At later times after the intervention, participants who switched away from high-As wells had a lesser mean decrease in well As, with a mean decline of only 47 μg/L between the fourth and fifth follow-up. Similarly, users of wells that met the local standard who switched wells between the baseline and first follow-up had only a slight increase in mean primary household well As of 8 μg/L. However, users of wells that met the local standard who switched wells at later times had larger increases in mean primary household well As of 30–50 μg/L.

We also look at changes in urinary As over time for people who switched and did not switch primary household wells. Changes in urinary As can occur with or without changes in primary household well As because urinary As integrates drinking water from primary household wells as well as other potential wells, in addition to As exposure from food and other sources. Participants drinking from high-As wells who switched wells between the baseline and first follow-up and first

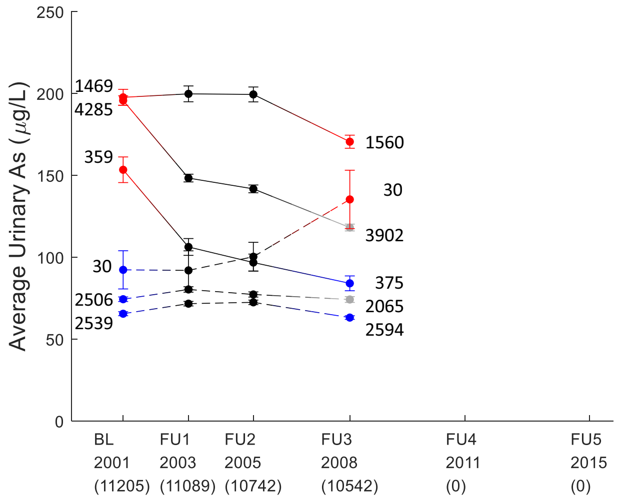

Fig. 3. Average urinary As over time for subjects with baseline wells that met the local standard (blue) and high-As baseline wells (red) who were drinking from wells that met the local standard (blue), high-As wells (red), or wells not tested at baseline or with missing labels (gray) by the third follow-up. The colors of the data points represent the well type used by participants. Since each series is based on the well type used at baseline and at the third follow-up, the data points for the first and second follow-ups are black, representing participants using a mix of well types. The x-axis labels list the median year of data collection and the number of participants included in each average (in brackets). BL = baseline, FU = follow-up. To the left of baseline symbols and to the right of 3rd follow-up symbols are listed for each subgroup the numbers of HEALS participants with available urinary As data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and second follow-up had declines in urinary As over those intervals of 62 μg/L and 45 μg/L (Fig. 6). In contrast, urinary As did not change for participants drinking from high-As wells who did not switch wells between baseline and the first follow-up or between the first and second follow-ups.

Urinary As concentrations for participants drinking from wells that met the local standard also did not change much between baseline and the first follow-up or between the first and second follow-ups, regardless of whether those participants switched wells between follow-ups (Fig. 6). Urinary As declined for all participants between the second and third follow-ups (Figs. 2, 6), and it declined most strongly (by > 40 μg/L) for participants drinking from high-As household wells, regardless of whether those participants switched wells during that interval.

4. Discussion

4.1. Summary of intervention impacts

We investigated how behavior and As exposure changed in a 25 km^2 area of Araihazar, Bangladesh following blanket well testing and education conducted by HEALS beginning in 2001 and blanket well testing by the Bangladesh government in 2003. A considerable number of community wells low in As were also installed during the study period. Within the first two years after the initial HEALS intervention, there was a decline in primary household well As and in urinary As for the individuals with the highest exposure at baseline. Beyond these two years, significant further gains were not realized. Urinary As and primary household well As remained at the new, lowered level for at least eight years and an additional slight decline in urinary As occurred about 6 to 8 years after the initial intervention. Participants with high-As wells remained more likely than participants with wells that met the

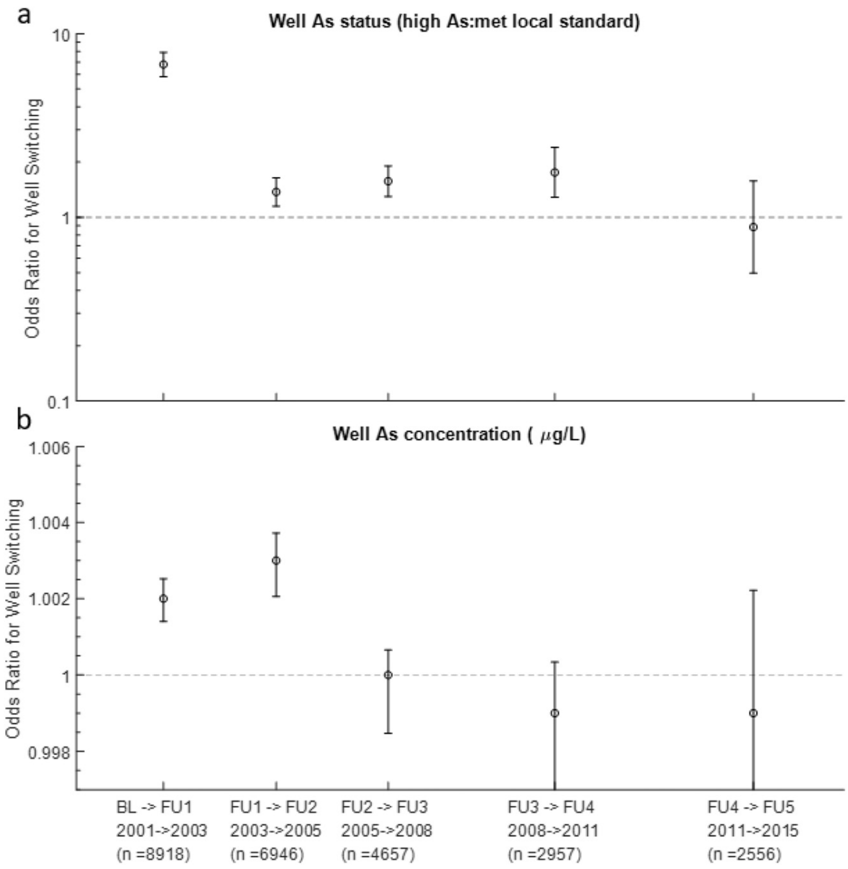

Fig. 4. Odds ratio of well-switching as a function of (a) well As concentration (μg/L) and (b) well As status (high-As:met the local standard). The x-axis labels list the median years of data collection and the number of participants included in each regression. BL = baseline, FU = follow-up.

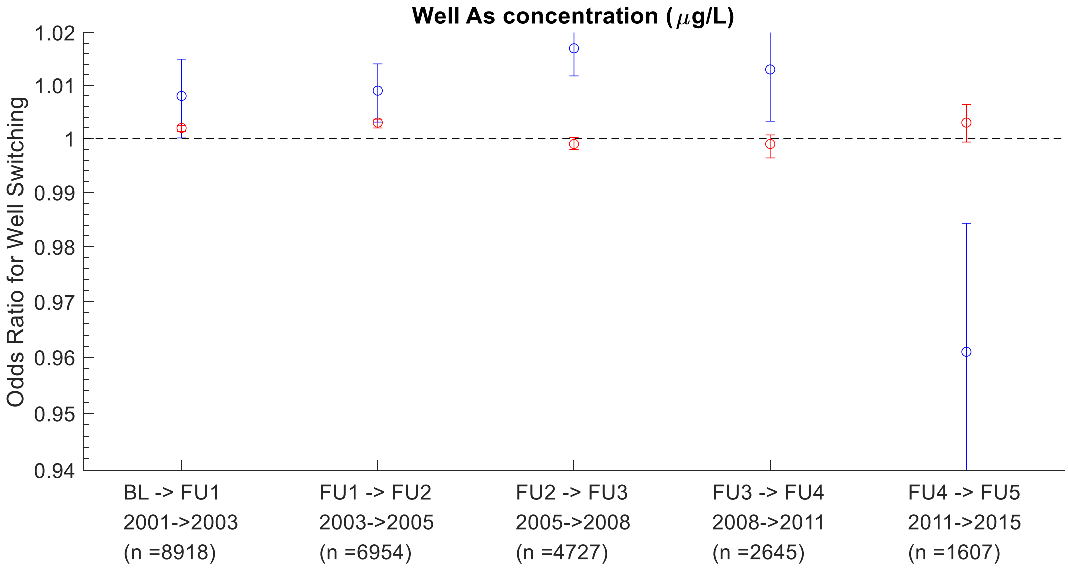

Fig. 5. Odds ratio of switching away from a well that met the local standard (blue) or a high-As (red) well as a function of As concentration (μg/L). The x-axis lists the median years of data collection and the number of participants included in each regression. BL = baseline, FU = follow-up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

local standard to switch wells for at least ten years after the initial well testing. Among participants drinking from wells that met the local standard, those with higher well As concentrations also remained more likely to switch.

4.2. *Comparison with prior studies of blanket well testing*

The impacts we observed were broadly consistent with previously reported impacts of the 2003 government blanket well testing in other areas of Bangladesh. In a nearby area of Araihazar, 27% of households

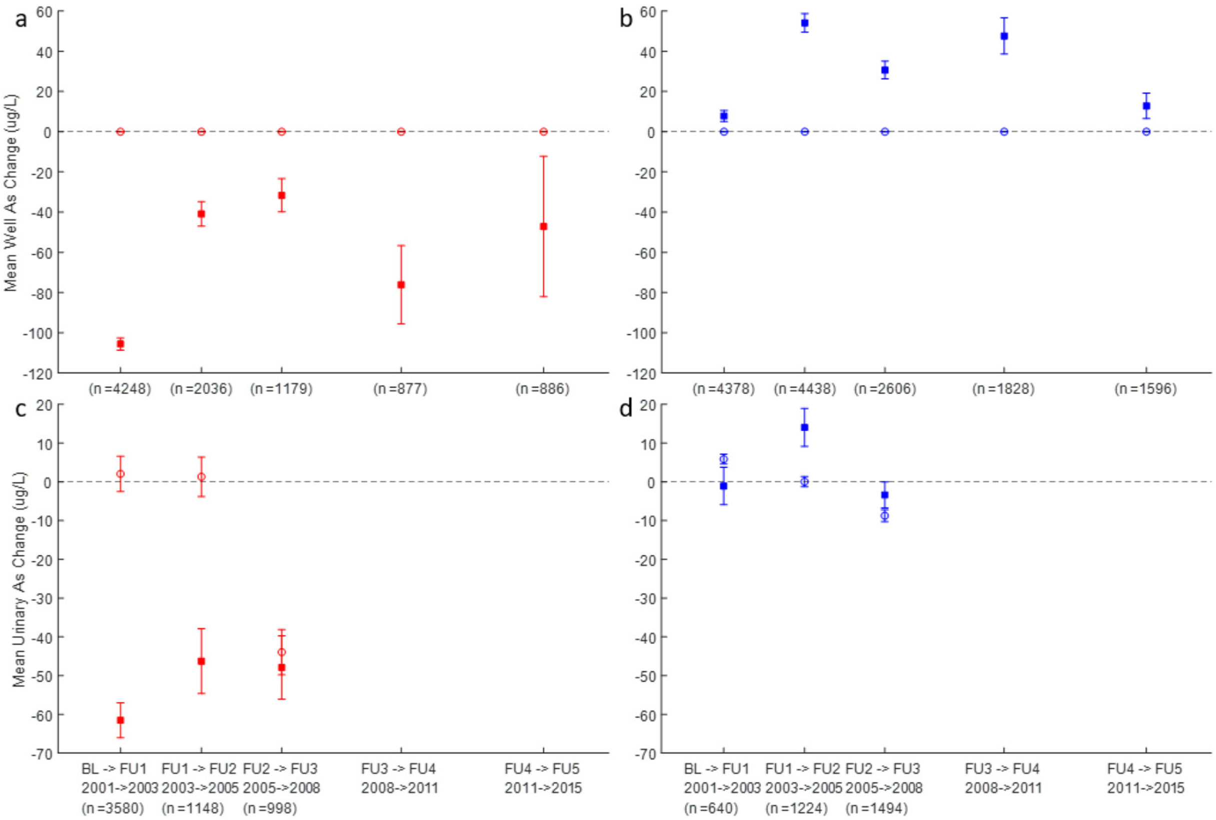

Fig. 6. Mean difference in well As concentrations for participants who switched away from (a) high-As primary household wells and (b) primary household wells that met the local standard and mean difference in urinary As concentration for participants who switched away from (c) high-As primary household wells and (d) primary household wells that met the local standard in the interval between each survey. Filled squares represent participants who switched wells and hollow circles represent participants who did not switch. The x-axes list the median years of data collection and the number of participants included from each time period. BL = baseline, FU = follow-up.

with high-As wells (and only 2% of households with wells that met the local standard) had switched wells within 2 years of government well testing, although average As concentrations in primary household wells only declined from 109 to 93 μg/L (Pfaff et al., 2017). At a follow-up survey in the same area three years later, no households had switched back to their high-As wells and additional households had switched away from high-As wells (Balasubramanya et al., 2013). In Matlab, Bangladesh, following the government well testing, mean primary household well As evolved from 93 μg/L in 2003 to 55 μg/L in 2008 and 60 μg/L in 2013 while the percentage of individuals with primary household wells that did not meet the local standard declined from 58% to 28% to 27% over the same time period (Kippler et al., 2016). Lower percentages of well-switching were observed in these studies as compared to HEALS, possibly due to the fact that HEALS involved an As education component in addition to well testing. However, these studies reflect a similar trend of an initial decrease followed by a plateau in As exposure in response to blanket well testing, as was observed in the HEALS cohort.

We additionally compare our observations of well-switching with those reported previously for HEALS. In our analysis, we recorded a well switch or lack of switch between each pair of surveys only for participants with a known well ID before and after the switch. At the first follow-up survey only, participants additionally directly reported whether they had switched wells, and we can compare our estimates to this direct measure. We measured less switching away from both wells that met the local standard (7% versus 14–17%) and high-As wells (42% versus 58–65%) between baseline and first follow-up than HEALS studies that used the direct report of switching (Chen et al., 2007; Madajewicz et al., 2007; Opar et al., 2007). This indicates that our measure underestimated well switching by not capturing switching to wells with unknown well IDs (i.e. new wells or wells that had lost their labels).

Similarly, our metric of well switching indicated that participants with high-As wells were 6.8 times more likely to switch than participants with wells that met the local standard between baseline and first follow-up, higher than the ratio of 4-to-1 based on participants' direct reports of well-switching (Chen et al., 2007). This suggests that our odds ratios may be skewed by the fact that participants drinking from high-As wells may more often switch to known wells than participants drinking from wells that meet the local standard. This could occur if participants switch from high-As wells primarily in order to lower their As exposure while participants switch from wells that met the local standard primarily due to external factors such as well failures that require the installation of a new well.

4.3. Decline in urinary As between six and eight years after the initial intervention

An overall decline in urinary As was observed throughout the study area from the second to the third follow-up, that is, about six to eight years after the initial intervention (Fig. 2). Given that this decline was observed for participants who switched primary household wells and participants who did not switch wells (Fig. 5b), this suggests that many participants lowered their As exposure from other sources. One possibility is that participants lowered their As exposure by drinking less from their primary wells and more from non-primary wells with low As concentrations. Another possibility is that the proportion of water that participants consumed from non-primary wells stayed the same, but that participants switched to using non-primary wells with lower As concentrations. These behavior changes could occur due to increased availability of information about water sources that met the local standard, increased installation of water sources that met the local standard, or an increased interest in drinking low-As water.

4.4. Protective effect of the interventions for participants drinking from wells that met the local standard

If the interventions had not taken place, we would expect participants drinking from wells that met the local standard at baseline to switch wells just as frequently as participants drinking from high-As wells and on average to increase their As exposure. Instead, we observe that participants who start out drinking from wells that met the local standard maintain roughly constant average concentrations of primary household well As and urinary As over time (Fig. 2).

This is at least partly attributable to the fact that participants drinking from wells that met the local standard are less likely to switch wells than participants drinking from high-As wells (Fig. 4b). Participants drinking from wells that met the local standard also appear to take their well As concentrations into account more strongly and persistently when making decisions about well switching compared with participants drinking from high-As wells (Fig. 5). Furthermore, even those participants drinking from wells that met the local standard who did switch show little increase in their urinary As (Fig. 6). If participants were switching wells randomly rather than strategically, we would have expected a larger negative impact of switching. Thus, in addition to lowering As exposure for the study participants drinking from high-As wells, the interventions had a protective effect on participants drinking from wells that met the local standard at baseline.

4.5. Limitations of a well testing and education campaign

Our study reveals a significant limitation of one-time blanket well testing: with the rapid increase in the number of new and unlabeled wells, participants had diminishing access to information about well As at later times. Immediately after the blanket survey of well As in 2000–2002, essentially all subjects knew the As concentration in their primary household wells, allowing them to use this information when deciding whether to switch wells (Fig. 1). However, over the ensuing years, the proportion of participants drinking from wells that were not tested at baseline or had lost their labels increased rapidly (Fig. 1). Our observation of 27% unlabeled wells by the first follow-up is consistent with the observations of Opar et al. (2007) that two to four years after the initial round of well testing, new labels could be attached to only 68% of the previously tested wells because the well had moved or its identification tag was missing. Our observation of 61% unknown wells by the fourth follow-up (2010 − 2013) is comparable to the 58% unknown wells observed in 2014 (van Geen et al., 2014).

It has previously been reported after blanket well testing in nearby areas of Araihazar that the proportion of newly installed wells that met the local As standard was not any higher than in older wells (Pfaff et al., 2017). Additionally, households who no longer knew their well As 5 years after the blanket well testing were more likely to switch away from wells that met the local standard than from high-As wells, opposite of the trend observed for households that did know their well As concentrations (Balasubramanya et al., 2013). This suggests that follow-up well testing should be done frequently so that people can continue to incorporate information about well As into their decision-making. One way to accomplish this would be to test all wells for As at the time that they are drilled using a field kit (George et al., 2012).

We also observed that well switching was more strongly predicted by well As concentrations and well status within the first few years after wells were labeled by HEALS staff in 2001. The importance of this information then appeared to fade over time, becoming negligible by about fourteen years after the initial intervention (Figs. 4, 5). Overall, the increase in the proportion of unlabeled wells along with the diminished impact of well As status and well As concentration on well switching decisions appear to have resulted in diminishing benefits in terms of As exposure for participants switching away from high-As wells at later times after the intervention (Fig. 6). This suggests that additional well testing and education is needed to make further gains.

4.6. Limitations of this study

The impacts of well testing, education, and community well installations that occurred after baseline in our study area are not consistently captured in this analysis. The Bangladesh government conducted a blanket well testing campaign throughout the study area in 2003, and a small number of additional wells were tested by HEALS field staff after the baseline survey. Another round of blanket well testing was conducted in the study area in 2012–2013. The results of any additional well testing that occurred before the end of urinary As testing in 2008 may have contributed to the observed decline in urinary As documented in this paper. Any re-testing of wells tested and labeled by HEALS staff at baseline could have reinforced this information and contributed to the well-switching decisions documented in this paper. However, the impacts of testing new wells on participant well-switching decisions is not captured, since these new wells are not among the wells tracked in the HEALS surveys. Factors such as education and socio-economic status were not considered in this study, although previous studies based on the first follow up only have shown that the proportion of switching increased with the education level of the well owner but not the amount of land owned (Chen et al., 2007; Madajewicz et al., 2007).

5. Conclusions

Following a blanket well testing and education campaign in 2000–2002, As exposure substantially decreased for HEALS participants with household wells high in As and these lower levels of As exposure were maintained. Participants with wells that met the local standard maintained even lower levels As exposure for > 8 years after the interventions. However, the number of participants with wells that were untested at baseline or had lost their labels increased substantially over time, and participants appeared to decreasingly take their well As status and concentration into account when switching wells at later times, highlighting the need for continued well testing and education campaigns.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.01.026.

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