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# Throwing the Baby out with the Drinking Water: Unintended Consequences of Arsenic Mitigation Efforts in Bangladesh

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## ABSTRACT

The 1994 discovery of arsenic in groundwater in Bangladesh prompted a massive public health campaign that led 20% of the population to switch from backyard wells to less convenient drinking water sources that had a higher risk of fecal contamination. We find evidence of unintended health consequences by comparing mortality trends between households in the same village that did and did not have an incentive to abandon shallow tubewells. Post-campaign, households encouraged to switch water sources have 46% higher rates of child mortality than those not encouraged to switch. Switching away from arsenic-contaminated wells also increased adult mortality.

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A data appendix is available at http://www.nber.org/data-appendix/w25729

# 1 Introduction

Water contamination is a central cause of morbidity and mortality in developing countries. In most settings, the primary water-borne threat is fecal-oral pathogens which lead to diarrheal disease, the second most common cause of infant and child mortality worldwide (Liu et al., 2015). However, in Bangladesh and a handful of other countries, toxic heavy metals that naturally leach into ground water are a parallel concern. Based on tests conducted by the British Geological Survey (BGS) in 1998, an estimated 20 million Bangladeshis had been consuming well water that contained more than the government's recommended maximum arsenic level of 50 $\mu$g per liter, and many more above the World Health Organization's 10 $\mu$g cutoff (MacDonald, 1999). Although the health effects of arsenic are poorly understood, many believed the Bangladeshi population to be in danger of serious health effects from long-term arsenic exposure (Smith et al., 2000).

In 1999, with help from international donors and NGOs, the government initiated a massive campaign to test over 5 million tubewells throughout the country and actively encourage households to abandon contaminated wells (Ahmed et al., 2006). This international effort to move households away from water sources containing arsenic constitutes one of the most successful public health campaigns in recent history. In a strikingly short amount of time, awareness-building efforts alone led around 20% of the population to transition from backyard wells to less convenient drinking water sources, including deep tubewells outside of the home and surface water. According to household survey data from the Bangladesh Demographic and Health Survey (BDHS), by 2004 there was a high level of awareness of arsenic contamination in endemic regions, and the majority of households had stopped drinking from wells known to be contaminated.

While it reduced chronic arsenic exposure, as we investigate in this paper, the nationwide shift away from backyard tubewells also appears to have inadvertently increased rates of diarrheal disease, with the largest health consequences for children under five (Prüss et al., 2002). This is because shallow tubewells – which frequently contain arsenic – are also "the most appropriate technology in terms of microbiologically clean water" (Lokuge et al., 2003). Tubewell water is very unlikely to be contaminated with fecal bacteria at source, and, because shallow wells are located inside the residence, faces little risk of becoming contaminated in storage.[1] This makes shallow tubewells an extremely valuable prophylactic in settings such as Bangladesh, where surface water contamination frequently causes cholera, dysentery and other potentially fatal water-borne disease. As a result, public health efforts in the early 2000s to move households *away* from shallow tubewells contaminated with arsenic made households more vulnerable to diarrheal disease.

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[1] Proximity of water source is also likely to increase the overall *amount* of drinking water consumed, further decreasing mortality from diarrheal disease.

To investigate this tradeoff, we quantify the impact on child mortality of switching water sources in response to the arsenic awareness campaign by making use of the high degree of natural variation within villages in the level of arsenic in backyard groundwater. Small-scale spatial variability enables us to compare households living relatively close to one another who tested negative versus positive for arsenic contamination, and hence were differentially motivated to abandon shallow tubewells. To identify households that were encouraged to stop using shallow tubewells, we collected water samples from each household's kitchen storage tank and closest tubewell. Consistent with government water tests (MacDonald, 1999), our tubewell tests indicate that over 65% of households in our subdistricts had been drawing water from contaminated tubewells prior to 2000. Meanwhile, our storage tank tests show that only 1% of households are still drinking arsenic-contaminated water by 2009. This implies that almost all affected households in our study area switched from shallow tubewells to deep tubewells or surface water in the decade after testing.

We then compare health outcomes of children born before versus after well-testing took place across these two subsamples in a difference-in-difference specification. Although arsenic in groundwater is concentrated in certain villages due to their position relative to the water table, concentrations are highly variable over short distances and nearly all contaminated villages contain pockets of clean groundwater that are impossible to predict. Hence, we include village fixed effects to absorb differences in mean characteristics between relatively exposed and unexposed villages arising from potential correlations between the macro spatial distribution of arsenic and other household characteristics such as income that may influence child health. In that manner, our identification strategy relies on the fact that the spatial distribution of arsenic is believed to be quasi-random within distances as small as villages, which our data support.

Our results indicate that, while mortality rates were almost identical in contaminated versus uncontaminated households pre-1999, these outcomes diverged sharply immediately after the switching campaign: Post-2000, households with arsenic-contaminated wells exhibit a 46% increase in child mortality relative to those with arsenic-free wells, which coincides with the moment at which contaminated households were pushed to switch to more remote sources.

To more firmly attribute the mortality increase to lower use of shallow tubewells, we also test whether households experience *less* of a mortality decline when they have access to deep tubewells, which varies across space and over time. When there is a deep tubewell nearby, switching away from backyard tubewells should entail little increase in water storage time or use of surface water, and hence have no adverse effects on child health. As predicted, the mortality effects of abandoning shallow tubewells increase sharply with household distance to deep tubewells. Contaminated households with more than one deep tubewell within 400 meters per 10 village child births do not experience a measurable increase in child mortality, whereas households with no deep tubewell within 400 meters experience a sharp and significant increase in infant and child deaths. This pattern supports our interpretation that the increase in mortality post-2000 is driven by a decrease in access to pathogen-free water among households that are encouraged to abandon arsenic-contaminated tubewells.

Given the scarcity of microbiologically clean and convenient alternative water sources in much of rural Bangladesh, this finding raises the question of whether use of shallow tubewells contaminated with arsenic should continue to be discouraged. Clearly, policy recommendations must weigh the health effects of contaminated water against the health consequences of arsenic exposure. However, our estimates of the impact of arsenic exposure on adult mortality indicate no measurable effect of arsenic ingestion on life expectancy in this setting, increasing the case for promoting shallow tubewells as a drinking water source – at least for young children – even when such wells may contain arsenic.

# 2 Background

## 2.1 Public health efforts surrounding shallow tubewells

Largely because of its geographic vulnerability to flooding and high population density, Bangladesh has historically had one of the highest incidences worldwide of water-borne viral and parasitic infections and corresponding infant and child mortality. To reduce diarrheal disease outbreaks, an estimated 8.6 million shallow tubewells were constructed throughout the country from the 1970s to the 1990s, an effort funded by the Bangladeshi government, UNICEF, the World Bank, and numerous other public and private organizations. This massive infrastructure investment succeeded in moving at least 94% of rural Bangladeshis from parasite-infected surface water to protected ground water (Caldwell et al., 2003).

Unfortunately, these improvements in sanitation were stymied by the discovery of arsenic in Bangladesh's groundwater in the mid-1990s.[2] In 1997, the World Health Organization (WHO) publicly declared groundwater arsenic contamination to be a "major public health issue", and the following year the World Bank approved a $32.4 million grant to address the emergency (Caldwell et al., 2003).

In 1998, the BGS conducted a nationwide study measuring levels of contamination in shallow tubewells (MacDonald, 1999). Results indicated that 15% of the population was in grave danger, drinking water with more than 50 ppb ($\mu$g) As, and 30% in lesser danger, drinking water with more than 10 ppb As (MacDonald, 1999).[3] In response, the government screened all shallow tubewells in contaminated regions. Wells that tested positive for arsenic (1.4 million) were painted red and those tested safe (3.5 million) were painted green (Ahmed et al., 2006).

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[2] Geologists first discovered trace amount of arsenic in 1987, and physical manifestations of arsenicosis, the disease caused by substantial arsenic ingestion, were first documented in 1994 (Rahman, 2002).

[3] These estimates have since been increased by the Government of Bangladesh to 30 million and 70 million (WHO, 2008).

Households were (and continue to be) strongly encouraged to avoid drinking from red tubewells and switch to alternative sources (Jakariya, 2007).

However, safe and feasible alternatives are highly site specific, depending on the groundwater level, water quality and hydrogeological conditions. Arsenic-free alternatives include deep tubewells, piped water, dug wells, surface water, and harvested rainwater.[4] Among these, deep tubewells are the most commonly promoted alternative. Although they are prohibitively expensive for most households to build, between 1998 and 2006 the Arsenic Mitigation Water Supply Project built over 9,000 deep tubewells in 1800 villages (WorldBank, 2007)[5]. Two factors constrained the use of deep tubewells as a safe alternative. First, many villages had limited access to deep aquifers. Second, an unfounded fear of arsenic contamination in deep aquifers led the 2004 National Policy for Arsenic Mitigation report to stress a "preference of surface water over groundwater" (Government, 2004).

Public education campaigns raising awareness of arsenic and promoting alternative water sources have been widespread since 1999 (BMOH, 2004). For instance, during the testing campaign of 1999-2000, UNICEF tubewell testers shared basic information about the dangers of arsenic ingestion and attempted to dispel common myths before revealing test results. In more recent years, UNICEF has established an educational curriculum integrating hygiene and sanitation with arsenic awareness and also involved the community in choosing alternative water sources. The impact has been considerable: By 2004, an estimated 80% of the population was aware that arsenic may be a danger (relative to less than ten percent in the late 1990s), and 70% reported changing water source to avoid arsenic (UNICEF, 2008).

## 2.2 Health benefits of switching away from shallow tubewells

Arsenic is a known carcinogen that has been shown in laboratory studies to cause or catalyze several forms of cancer, particularly of the lung and bladder (Kozul et al., 2009). Numerous field studies have also found a strong dose-response relationship between skin cancer and arsenic exposure through drinking water (Chen et al., 2006). Hence, it is generally accepted that exposure to high levels of arsenic ($> 100\ \mu g$) increases cancer-related deaths and morbidity in the older adult population. The health effects of low-level exposure are largely unknown. However, due to the decades-long latency of most arsenic-related health problems, the National Research Council concludes that "arsenic-related disease due to chronic exposure through drinking water has a relatively low incidence" in settings with low average life expectancy such as Bangladesh (Council, 2001).

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[4] It is possible to remove arsenic from water, but the technology is expensive and very rarely used. Though less emphasized by policymakers, tubewell sharing has been relatively popular in some parts of the country (van Geen et al., 2003).

[5] The cost of constructing deep tubewells in most locations is estimated to be around \$800, while the cost of constructing shallow tubewells is around \$200.

An epidemiological study following over 10,000 adults in the Araihazar District in Bangladesh reached a different conclusion, reporting very high mortality associated with arsenic exposure (Argos et al., 2010). The authors estimated that approximately 20% of all deaths documented over nine years were attributable to arsenic, with mortality rates nearly 70% higher for those exposed to concentrations of over 150 ppb relative to those exposed to less than 10 ppb. An important shortcoming of this study, however, which was not addressed by the authors, is that arsenic concentrations in groundwater are not orthogonal to socio-economic status at the macro-spatial level. As shown in Madajewicz et al. (2007), due to the spatial clustering of arsenic across the 54 study villages, in this setting uncontaminated wells happen to be concentrated in villages with significantly higher average income and assets (with assets 42% higher and expenditures 16% higher).[6] Importantly for this paper, the differences disappear when accounting for mean levels of village income, however, the Argos et al. (2010) study fails to do so, and as a result mortality differentials are almost certainly biased upwards.

On the other end of the spectrum, calculations of the disease burden from arsenic exposure by Lokuge et al. (2003) that take into account only "strong causal evidence" from existing studies estimate that arsenic-related disease leads to the loss of 174,174 disability-adjusted life years (DALYs) per year, which amounts to only 0.3% of the total disease burden. Diarrheal disease, in comparison, accounts for 7.2% to 12.1% of the total disease burden (Lokuge et al., 2003). Researchers almost universally agree that the relationship between arsenic exposure and morbidity and mortality in younger populations is minimal. A handful of studies have reported reproductive health consequences, although the evidence is mixed (Vahter, 2008; Tofail et al., 2009; Milton et al., 2005; Liaw et al., 2008). There is also some concern, based on a highly publicized study of children in Araihazar, that arsenic exposure inhibits the mental development of children (Wasserman et al., 2004), but the estimates face the same bias that the larger mortality study face and should thus be interpreted with caution. In general, since arsenic exposure is also correlated with socioeconomic conditions influencing child development measures, causality cannot be easily inferred from studies that show a correlation between arsenic exposure and various health outcomes (Tofail et al., 2009).

## 2.3 Health costs of switching away from shallow tubewells

Because shallow tubewells are generally built very close to an individual residence, they are associated with less water storage and greater water consumption. Water storage time is an important determinant of water contamination with fecal matter, as water that is not stored

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[6] van Geen et al. (2003) describes these spatial patterns in detail: "Most of the wells with the lowest As concentrations are located in the northwestern portion of the study area (Figure 4)", which appears to contain higher SES villages. According to Madajewicz et al. (2007), there is potentially "a correlation between soil types and arsenic levels and therefore possibly between arsenic levels and incomes. However, this correlation would not be likely to appear within villages. The surrounding fields are fairly uniform geologically, while the dispersion of incomes and wealth within villages is large."

properly is continuously exposed to dirty hands and cups or utensils. In previous studies, distance from water source has been found to be directly correlated with the presence of bacterial infections such as trachoma and diarrheal disease (Esrey et al., 1991). A study in Araihazar District found that those who abandoned shallow tubewells and switched to a safe well increased the time spent obtaining water by fifteen-fold (Madajewicz et al., 2007).

Inconvenience also implies a potential decrease in the amount of water consumed (Hoque et al., 1989), which can have important health consequences for children facing dehydration from diarrheal disease. In fact, the quantity of water used has been shown to be a better predictor of child health than the quality of water used (Esrey et al., 1991). The only water sources equally convenient to shallow tubewells are surface water sources that are also likely to be close to the residence. However, while they are free of arsenic, surface water is highly contaminated with fecal-oral pathogens at source. While water filtering and cleaning methods can address point of use contamination, survey data indicate that these have largely been abandoned in rural Bangladesh since the construction of shallow tubewells (Caldwell et al., 2003). For these reasons, Lokuge et al. (2003) estimate that abandonment of shallow tubewells would increase a household's risk of diarrheal disease by 20%. Nonetheless, to date there have been no empirical investigations into the health costs of moving away from shallow tubewells and health messages continue to promote alternative water sources in endemic areas.

# 3 Estimation strategy

## 3.1 Data and setting

To study child mortality responses to the discontinued use of shallow tubewells, we capitalize on extensive household survey data collected by the authors in 2007, which include reproductive and child health outcomes for all children ever born to the household head. The data cover 3,160 households randomly sampled from 162 villages in two subdistricts of Barisal, one of the most heavily contaminated districts in the country.[7] According to village-level well testing data collected by the government, over 60% of tubewells in the area were contaminated in 1999. Barisal was also a relatively "successful" region in terms of the public health campaign that followed. Data from the BDHS reveal a uniquely high rate of switching away from contaminated water sources in Barisal Division, attributed largely to the geology of the region, which made it possible to construct deep tubewells in almost all villages.

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[7] The full household survey collected data from 9,155 households in three districts, only one of which (Barisal District) is contaminated with arsenic (Caldwell et al., 2006). Households included in the study were randomly drawn in a two-stage sampling process, in which villages were first sampled from the universe of villages containing more than 50 and fewer than 500 households, and then 20 households per village were selected at random from village-level census data. Because the original purpose of the data was the evaluation of an adolescent girls program operating in the area, households were eligible for inclusion only if they included at least one adolescent girl.

In 2009, 3138 (99%) of these households were successfully revisited. At this time, each household's closest shallow tubewell was tested for arsenic using a standard field testing kit, and a brief survey was administered to household heads that collected data on water sources before and after well testing and respondents' knowledge of arsenic contamination. Our analysis sample includes all children born in the residence between 1980 and 2007 to heads of households.[8] The final sample encompasses 2,862 households and 12,277 children, 3,821 of whom reside in low concentration households and 8,456 in high concentration households.

## 3.2 Identification strategy

Our identification strategy makes use of the fact that there is significant small-scale variability of arsenic concentrations in ground water (Yu et al., 2003) that generates substantial within-village variation in exposure via well contamination: an estimated 88% of contaminated wells are located within 100 meters of an uncontaminated well (Van Geen et al., 2002). Furthermore, within a large area, local pockets of contamination are extremely hard to predict and do not appear to be correlated with observable features of the land.[9] Small-scale variation in arsenic levels is due to heterogeneity of near-surface geology and the resulting biogeochemical environments, both of which are uncorrelated with agricultural land quality. This variation in well contamination allows us to compare households residing close to one another who are and are not exposed to arsenic before 1999 in a difference-in-difference (DID) estimation strategy.

In particular, we define a binary level of arsenic exposure pre-1999 using two methods. The first, denoted "measured contamination," categorizes households as contaminated (or "high concentration") if the concentration of arsenic in the shallow tubewell closest to the household is greater than 60 ppb when measured by our field team in 2009.[10] The second, denoted "reported contamination", categorizes households as exposed if any of the shallow tubewells ever used by the household are reported to have tested positive for arsenic, been painted red, been deemed unsafe to use for drinking, been abandoned, or been built less than three years before the survey.[11] The 48% of households that lack this information because the households report not having used any of the closeby tubewells are categorized using the "measured contamination" method for both measures. The two measures of contamination correspond for 66% of

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[8] The 2697 children (18%) born after 1980 but before the household moved into the current residence are dropped from the analysis, although the results are robust to including them. We also exclude from the sample 167 individuals with missing or implausible data on mother's age at birth. One additional household is dropped because identifying data do not match well between the baseline and arsenic surveys.

[9] Because of this difficulty, encouraging households to build new shallow tubewells on uncontaminated land is not a viable policy alternative.

[10] We chose 60 ppb as the cutoff to reflect the 50 ppb WHO cutoff, taking into account an estimated 10% per decade increase in arsenic levels, so that contaminated wells in our sample are those believed to have tested above 50 ppb in 1999. Relatively constant groundwater As concentrations have been reported in a number of time series studies (Van Geen et al., 2002).

[11] The last condition is included because wells installed recently were likely built to replace contaminated wells.

households. Since our survey data on history of shallow tubewell use indicate a tendency to underreport use of highly contaminated wells, we deem "measured contamination" to be the more conservative variable, but present the reported contamination results in appendix table 2.1 for comparison.

To test the validity of our assumption that within-village variation in arsenic exposure is orthogonal to household characteristics, appendix tables 1.1-1.2 present mean differences between low concentration and high concentration households in a large number of time-invariant characteristics. All rows contain regression-controlled means that account for village fixed effects, as do reported t-statistics of the differences in means. Only one variable out of 20 - fraction of children living in household - is significantly different across the two subsamples at the 10% level under the measured but not the reported contamination measure, and the point estimate of the difference is extremely small (2 percentage points). An F-test of joint significance indicates that the samples are balanced on observables within villages, including a number of indicators of socio-economic status. Importantly, as shown in appendix table 1.3, the same exercise conducted without accounting for mean differences across villages shows a high degree of imbalance, as was also observed in the Araihazar study area.[12]

Although household characteristics are balanced, appendix table 1.1 also reveals significant differences in mean levels of infant and child mortality across subsamples: High concentration households have higher rates of infant and child mortality over the entire period. Note, however, that there is no indication from sample means alone of corresponding differences in the timing of births, which could potentially be influenced by differences in child mortality, and would potentially complicate the interpretation of trend differences. The descriptive data also support other assumptions in our estimation strategy: The fraction of households that report that their closest well was tested during the 1998-2000 campaign was 76%, consistent with estimates from national data.

## 3.3 Estimating equation

We test for changes in infant and child mortality associated with the testing campaign by estimating the following difference-in-difference equation for individual $i$ in village $j$ at time $t$, which includes village fixed effects $\theta$:

$$Y_{ijt} = \alpha + \gamma \times HighCon_i + \delta \times Exposure_t + \beta \times (HighCon_i \times Exposure_t) + \theta_j + \epsilon_{ijt} \tag{1}$$

*HighCon* is a dummy variable equal to one if the individual is in a household exposed to arsenic. *Exposure* denotes the fraction of life that a child was potentially exposed to microbiologically unsafe water due to the household switching *away* from a shallow tubewell as a result

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[12] It is interesting to note that spatial clustering in the Araihazar sample gives rise to a negative correlation between arsenic exposure and socio-economic status, while across Barisal the correlation is largely positive.

of the testing campaign. Hence, for under 1 mortality, $Exposure$ is a dummy variable equal to 1 if the child was born after 2000, and for under 2 mortality, $Exposure$ takes a value of 1 if the child was born after 2000, 0.5 if born in 2000, and 0 if born before 2000.[13] Although the nationwide campaign began in mid-1999, 2000 is our preferred cutoff since behavioral change is presumed to respond with a lag. In appendix table 2.6 we verify that our regression estimates are robust to using 1999 as a cutoff point.

We are interested in the coefficient estimate of $\beta$, our estimate of the change in mortality due to abandoning shallow tubewells. Proper identification relies on the assumption that other events occurring over the observation period did not differentially affect infant and child mortality rates for households that were versus were not encouraged to stop using shallow tubewells. The high variation in arsenic exposure across very small distances and the similarity across contaminated and uncontaminated households in baseline characteristics lend credibility to this assumption. However, to account for any differences in baseline characteristics that may contribute to time trends in mortality, we also estimate versions of equation 1 with basic controls for individual's sex, birth order, birth year, birth year squared, mother's age at first birth, years since birth of last child, parents' education, household income, and years lived in current house, and also with a wider set of control variables that additionally includes house value, solvency, land size, number of rooms, electricity, whether Muslim, monthly income per capita, and years lived in village. Standard errors are clustered at the village level in all regressions.

# 4 Results

Figure 1 presents the trend in five year mortality between 1992 and 2007 using the measured contamination method to divide the sample into switchers and non-switchers. For the most part, mortality trends in households with arsenic closely follow those in households with clean wells until 1998, at which point they diverge sharply. Both child and infant mortality are substantially higher among individuals in households with contaminated wells immediately after but not before the arsenic testing campaign, and differences persist to the time of the survey in 2007. This suggests that most switching, and the resulting health effects of exposure to bacteriologically unsafe water, occurred immediately after the campaign.

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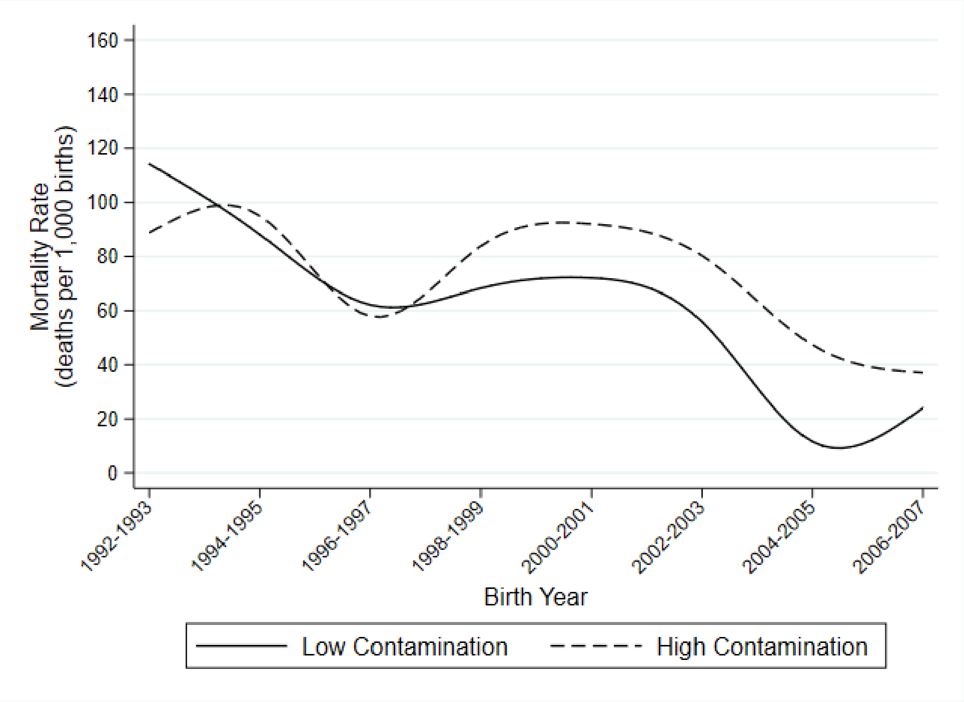
[13] The maximum number of years of exposure is the mortality age (of one, two, or five years) being measured.

Figure 1: Under 5 mortality rate $(0 - 5 \text{ yrs})$



*Notes:* Data from our 2007 data collection and 2009 tubewell tests. "Under 5 mortality rate" is deaths between 0 and 60 months of age per 1,000 births observed in each two-year period, which are plotted as cubic splines for smoothness. High contamination households defined as those with tubewells that contain arsenic contamination greater than 60 ppb according to field tests of the shallow tubewells closest to the residence.

## 4.1 Regression results

Table 4.1 presents the corresponding regression results from equation 1 for infant, under two, and under five mortality. As reflected in figure 1, the coefficient estimates indicate a substantial and statistically significant increase in mortality after 2000 among individuals with arsenic-contaminated tubewells. As reported in column 2, being born into a household that has been encouraged to stop using their shallow tubewell is associated with a 1.9 percentage point (48%) increase in the likelihood of death within 12 months, a 2.9 percentage point (63%) increase within two years, and a 5.2 percentage point (46%) increase within five years. These magnitudes imply that mortality from diarrheal disease, which was estimated to account for approximately one-quarter of deaths under age five in 2000 (Morris et al., 2003), more than doubled after the well-testing campaign for households that abandoned shallow tubewells.

Table 4.1: Child mortality: measured contamination

| | Death < 12 mon | | Death < 24 mon | | Death < 60 mon | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| High con. | 0.00790 | 0.00526 | 0.01245 | 0.00873 | 0.00753 | 0.00252 |
| | [0.00743] | [0.00737] | [0.00801] | [0.00789] | [0.00975] | [0.00944] |
| Exposure | -0.03561 | -0.00131 | -0.04828 | -0.01205 | -0.05792 | -0.10734 |
| | [0.00807] | [0.01369] | [0.00993] | [0.01714] | [0.01544] | [0.03407] |
| High con. * Exposure | 0.01426 | 0.01870 | 0.02219 | 0.02889 | 0.04658 | 0.05157 |
| | [0.01192] | [0.01226] | [0.01344] | [0.01396] | [0.01933] | [0.01913] |
| Control Mean | 0.03918 | 0.03918 | 0.04569 | 0.04569 | 0.11111 | 0.11111 |
| Observations | 12126 | 12126 | 11947 | 11947 | 11147 | 11147 |
| FE | Village | Village | Village | Village | Village | Village |
| Controls | No | Yes | No | Yes | No | Yes |

*Notes:* Data from our 2007 data collection and 2009 tubewell tests. Linear probability estimates with village fixed effects. Standard errors clustered at the village level. High contamination households defined as those with tubewells that contain arsenic contamination greater than 60 ppb according to field tests of the shallow tubewells closest to the residence. Samples exclude children under the age cutoff in 2007, for whom mortality is censored.

## 4.2 Robustness checks

The estimates are robust to a number of alternative specifications, detailed in the appendix. Replacing early life exposure with the number of years exposed (appendix table 2.2) or a binary measure equal to 1 if the child was born after 2000 (appendix table 2.3) results in quantitatively similar but noisier estimates, as we would expect. To gain precision on the date of switching, appendix table 2.4 makes use of survey data on the year in which a household's well was reported to be tested, replacing the binary indicator of a child being born after 2000 with an indicator of being born after the household's well was tested. In this specification, the DID estimate is *more* precise and comparable in magnitude for deaths under 12 and under 24 months, as one would expect if we take the survey reports at face value. Using a 50 ppb cutoff (appendix table 2.5), and using 1999 instead of 2000 as the switching date (appendix table 2.6) produce very similar results.

Finally, to further test the assumption of parallel time trends between switchers and non-switchers, we exclude households with arsenic contamination below 60 ppb and run a placebo check in which we test whether an imaginary cutoff point of 100 ppb produces similar patterns within the subsample of households that we know were *all* encouraged to abandon shallow tubewells (appendix table 2.7). If level of arsenic contamination in groundwater is correlated with unobservable characteristics of the household that are giving rise to differential time trends in mortality, we should expect to see positive and significant point estimates on the interaction terms in both regressions. On the other hand, if we only observe a significant DID estimate when the true cutoff is used, we can deduce that the estimates reflect the causal effect of changing water sources rather than time trends in unobservables correlated with arsenic. Indeed, regression results indicate no significant effect on mortality of arsenic levels above 100 ppb relative to those between 50 and 100 ppb.

## 4.3 Impact of deep tubewell constructions

To more firmly attribute the mortality increase to the shift away from shallow tubewells, we evaluate whether households that had greater access to alternative clean water sources experienced fewer adverse health consequences when they were encouraged to switch sources. Although backyard tubewells are always more convenient than sources outside the home, the increase in water collection cost will be minimal if the external source is very close. For these households, switching away from backyard tubewells should entail little increase in water storage time or use of surface water, and hence have little adverse impact on child health.

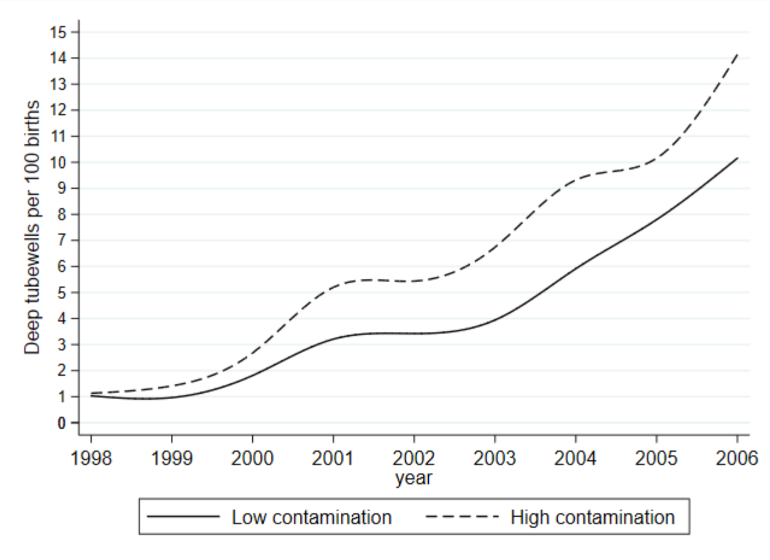


Figure 2: Number of existing deep tubewells per 100 births per year since 1998

*Notes:* Data from our 2007 and 2016 data collection and 2009 tubewell tests. High contamination households defined as those with tubewells that contain arsenic contamination greater than 60 ppb according to field tests of the shallow tubewells closest to the residence.

Access to deep tubewells varies across space and over time in our sample. To test this hypothesis, we use survey data on the location and timing of deep tubewell construction in each village that were collected in 2016 to characterize each household in each year according to its distance to the nearest deep tubewell, and construct a variable equal to the number of deep tubewells within 400 meters of the home in any given year per 10 births in that year. We then run a triple-difference regression equivalent to equation 1 that also contains $Tubewells$ and its interaction with $Exposure$, $HighCon$, and their interaction. Our prediction on deep tubewell access implies a significant negative coefficient estimate on the triple difference term, which would indicate that mortality effects of the campaign fall with proximity to arsenic-free water sources.

As shown in figure 2, there was a large increase in access to deep tubwells over the time period of the study, largely motivated by the discovery of arsenic in shallow wells. While there were on average only 4 deep tubewells per study village in 2000, by 2007 there were 7 deep tubewells per village and the average household had 3 deep tubewells within 400 meters of their home. As predicted, the mortality effects of abandoning shallow tubewells decrease sharply with household proximity to deep tubewells. Switcher households with more than two deep tubewells within 400 meters per 10 births do not experience a measurable increase in child mortality, whereas households with no deep tubewell within 400 meters experience a sharp and significant increase in infant and child deaths. Regressions controlling for the number of deep tubewells within 750 meters per 10 births in appendix table 2.8 yield similar but weaker results. This pattern lends credibility to our interpretation that the increase in mortality post-2000 is driven by a decrease in access to pathogen-free water among households that are encouraged to abandon shallow tubewells.

Table 4.2: Child mortality: impact of deep tubewell construction

| | Death < 12 mos | | Death < 24 mos | | Death < 60 mos | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| High con. | 0.00065 | -0.00064 | 0.00681 | 0.00464 | 0.00165 | -0.00139 |
| | [0.00790] | [0.00785] | [0.00839] | [0.00835] | [0.01023] | [0.00984] |
| Exposure | -0.04703 | -0.01103 | -0.06789 | -0.02958 | -0.08575 | -0.12600 |
| | [0.01063] | [0.01509] | [0.01394] | [0.01983] | [0.01848] | [0.03506] |
| Tubewells | -0.01893 | -0.01214 | -0.01760 | -0.00994 | -0.02270 | -0.01343 |
| | [0.00730] | [0.00600] | [0.00731] | [0.00598] | [0.00851] | [0.00633] |
| High con. * Exposure | 0.02284 | 0.02637 | 0.03453 | 0.04067 | 0.05411 | 0.05439 |
| | [0.01458] | [0.01456] | [0.01747] | [0.01747] | [0.02429] | [0.02332] |
| High con. * Tubewells | 0.02278 | 0.01848 | 0.01936 | 0.01421 | 0.02447 | 0.01685 |
| | [0.00615] | [0.00580] | [0.00603] | [0.00601] | [0.00716] | [0.00598] |
| Exposure * Tubewells | 0.02695 | 0.02355 | 0.04026 | 0.03538 | 0.06286 | 0.04517 |
| | [0.01026] | [0.00886] | [0.01423] | [0.01297] | [0.01790] | [0.01495] |
| High con. * Exposure * Tubewells | -0.02664 | -0.02297 | -0.03447 | -0.03039 | -0.04138 | -0.02688 |
| | [0.01144] | [0.01101] | [0.01586] | [0.01552] | [0.02136] | [0.01990] |
| Control Mean | 0.03918 | 0.03918 | 0.04569 | 0.04569 | 0.11111 | 0.11111 |
| DID, low tubewells/births | 0.02284 | 0.02637 | 0.03453 | 0.04067 | 0.05411 | 0.05439 |
| DID, median tubewells/births | 0.02284 | 0.02637 | 0.03453 | 0.04067 | 0.05411 | 0.05439 |
| DID, high tubewells/births | 0.00717 | 0.01286 | 0.01425 | 0.02279 | 0.02977 | 0.03857 |
| N | 12126 | 12126 | 11947 | 11947 | 11147 | 11147 |
| FE | Village | Village | Village | Village | Village | Village |
| Controls | No | Yes | No | Yes | No | Yes |

*Notes:* See notes to table 4.1. Tubewells is number of deep tubewells within 400 meters/10 births per year. *DID, low, median, and high tubewells/births* is the effect of switching to pathogenically unsafe water after 2000 for high-contamination households at the 25th percentile, the 50th, and the 75th percentile in deep tubewells per 10 births.

## 4.4 Impact of arsenic on adult mortality

In light of our evidence on the protective health effects of shallow tubewells for infants and children, it is important to determine whether there are offsetting negative health consequences of low-level chronic arsenic ingestion that might justify the current policy recommendation that households avoid arsenic-laden tubewells even when there are no other pathogen-free water sources available. To estimate the magnitude of health *gains* from abandoning shallow tubwells, we use survey data collected in 2011 on the age of death of the mother and father of the household head - who, according to local custom, are very likely to have lived in the same household as their son and thus have been exposed to arsenic in the drinking water for a number of years.

Our empirical analysis of adult mortality calculates the hazard of dying each year from 1970 to 2010 as it relates to arsenic levels of drinking water.[14] As in the child mortality analysis, we compare households above and below the 60 ppb cutoff, the level of arsenic that has been deemed unsafe for chronic exposure, and also interact arsenic contamination with an indicator of *Post-2000* (analogous to “Exposure”) to test whether adult mortality improves when households with contaminated wells are encouraged to stop using shallow tubewells.

As shown in table 4.3, there is no difference between contaminated and uncontaminated households in the hazard of dying prior to 2000. While there is some indication that mortality differences emerge, elevated mortality risk only appears after households with arsenic wells are encouraged to switch sources. In particular, *after* 2000, the hazard ratio of dying is 1.27 in high-contamination households, which implies that adults in high-contamination households had a risk of dying that is 1.27 times that in low-contamination households (+27%) and statistically significant.[15] The control test in appendix table 3.2 shows that the hazard of dying did not diverge between high- and low-contamination households at an earlier point in time, indicating that differences in mortality risk post-2000 are not due to differential time trends in adult mortality but indeed due to the change in water sources.

Overall, our findings suggest that arsenic exposure had little direct adverse effect on adult mortality. Moreover, switching to more inconvenient water sources appears to have decreased not only child but also adult life expectancy.

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[14] Overall, 39% of mothers and 12% of fathers are still alive at the end of the period. Questions on age of death were added to the 2016 survey midway through data collection, and we attempted to reach all households that had already completed the survey by that point by phone. Ultimately, age of death data were collected from 53% of households, with the majority of attrition due to respondents failing to answer the phone, followed by failure to recall age of death.

[15] Displayed hazard ratios are significant if the confidence interval does not include 1, meaning that the hazard of dying does not significantly differ by group.

Table 4.3: Adult mortality: hazard of dying, 1970-2010

| | (1) | (2) |
|---|---|---|
| High con. | 0.91235 | 0.91054 |
| | [0.08686] | [0.08615] |
| Post-2000 | 1.56585 | 1.63330 |
| | [0.15463] | [0.16635] |
| High con. * Post-2000 | 1.26557 | 1.27207 |
| | [0.14744] | [0.14799] |
| Observations | 76493 | 76493 |
| FE | Village | Village |
| Controls | No | Yes |

*Notes:* See notes to table 4.1. Breslow marginal likelihood estimations. Observations are person-years from 1970-2010, outcome is whether died. Sample includes individuals born before or in 1960 (age 40 at campaign).

# 5 Conclusion

Our results show evidence from Bangladesh of strong protective effects of shallow tubewells on infant and child health that appear to outweigh the health risk they pose in terms of arsenic exposure. In particular, while the Bangladeshi arsenic mitigation campaign has been heralded by the international medical community as a life-saving effort, our estimates indicate substantial *negative* health consequences of moving households away from shallow tubewells as sources of drinking water. Using data from a district in which shallow tubewells were readily abandoned for less convenient but arsenic-free deep tubewells, we find that households that were encouraged to switch sources experienced a significant increase in the rate of infant and child mortality, and no evidence of corresponding gains in adult life expectancy. In light of this evidence, future public health interventions need to reconsider efforts to convince households to abandon shallow tubewells when alternatives that are equally safe in terms of water-borne pathogens are not readily available.

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