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How to clean a tubewell: the effectiveness of three approaches in reducing coliform bacteria

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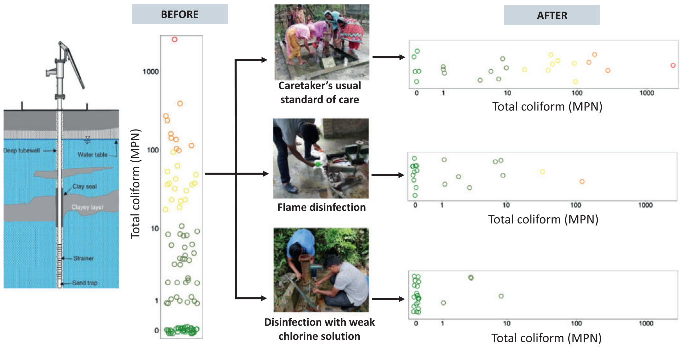
HIGHLIGHTS

- We evaluate how effectively three approaches to cleaning wells reduce coliforms.
- A best-practice approach that uses disinfection with a weak chlorine solution works
- Current local cleaning practices worsen water quality, but not significantly so.
- More effective cleaning practices might improve drinking water quality.
- Adoption of more effective practices would entail widespread behavioural change.

GRAPHICAL ABSTRACT



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ABSTRACT

Access to safe drinking water in rural Bangladesh remains a perpetual challenge. Most households are exposed to either arsenic or faecal bacteria in their primary source of drinking water, usually a tubewell. Improving tubewell cleaning and maintenance practices might reduce exposure to faecal contamination at a potentially low cost, but whether current cleaning and maintenance practices are effective remains uncertain, as does the extent to which best practice approaches might improve water quality. We used a randomized experiment to evaluate how effectively three approaches to cleaning a tubewell improved water quality, measured by total coliforms and *E. coli*. The three approaches comprise the caretaker's usual standard of care and two best-practice approaches. One best-practice approach, disinfecting the well with a weak chlorine solution, consistently improved water quality. However, when caretakers cleaned the wells themselves, they followed few of the steps involved in the best-practice approaches, and water quality declined rather than improved, although the estimated declines are not consistently statistically significant. The results suggest that, while improvements to cleaning and maintenance practices might help reduce exposure to faecal contamination in drinking water in rural Bangladesh, achieving widespread adoption of more effective practices would require significant behavioural change.

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1. Introduction

Fewer than half of the 102 million people in rural Bangladesh collect their drinking water from a source that is free from contamination and available when needed (BBS and UNICEF, 2019). Around 21 million people are exposed to naturally-occurring arsenic in their primary source of drinking water, and 39 million are exposed to contamination with faecal bacteria (BBS and UNICEF, 2019). Exposure to arsenic in drinking water causes a number of serious health impacts including cancer (Kapaj et al., 2006; Shahid et al., 2018), leading Smith et al. (2000) to call the epidemic of arsenic-related disease in Bangladesh "the largest poisoning of a population in history". Exposure to faecal bacteria in drinking water increases the risk of diarrheal disease (Khan et al., 2022; Luby et al., 2015), still the third-leading course of child mortality worldwide (Paulson et al., 2021). These potential impacts on health are both intrinsically important and also more broadly hold back development in Bangladesh (World Bank, 2018). Bangladesh must accelerate progress on eliminating exposure to both arsenic and faecal contamination in order to meet the Sustainable Development Goal of "safe drinking water for all" (WHO and UNICEF, 2021).

The vast majority of households in rural Bangladesh—more than 90 %, according to BBS and UNICEF (2019)—depend on hand-pumped tubewells as their main source of drinking water. Tubewells in Bangladesh are often characterized as shallow and deep. Shallow tubewells draw water from aquifers located just below the surface, while deep tubewells draw water from deeper, older aquifers that are isolated from the shallow aquifers by aquitards (Ahmed et al., 2006). A substantial share of the shallow aquifers in Bangladesh contain arsenic, while the deeper, older aquifers are less likely to contain high levels of arsenic (BGS and DPHE, 2001; Ravenscroft et al., 2005). Engineers also expected deep tubwells to yield water of better microbial quality than shallow tubewells (Howard, 2003), because the deep aquifers from which they draw water are isolated from surface sources of contamination and because microbial contamination decreases with depth (Ahmed et al., 2006). However, studies show that deep tubewells also exhibit important rates of microbial contamination (Howard et al., 2006), comparable to or only slightly better than shallow tubewells (Goel et al., 2019; Ravenscroft et al., 2014; Saha et al., 2018), even when the deep tubewells are installed by experienced contractors under NGO supervision (Cocciolo et al., 2021), avoiding the potential for contamination through inadequate tubewell construction (Knappett et al., 2012) or placement (Dey et al., 2017). Installing community deep tubewells thus reduces exposure to arsenic, but not to faecal contamination in drinking water (Cocciolo et al., 2021).

Widespread evidence for faecal contamination in deep tubewells raises the question of whether tubewells should be phased out in favour of other, potentially more costly approaches to providing safe drinking water. Local piped water systems, for example, might more effectively reduce exposure to faecal contamination, if fewer households use each access point and if transport and storage times are reduced. Both increased transport and storage are associated with higher contamination at the point of use (Cocciolo et al., 2021; Goel et al., 2019). But local piped water systems are considerably more expensive, as are other technically feasible alternatives (Jamil et al., 2019). The current ubiquity of tubewells would make implementation of a new technological solution a massive undertaking.

An alternative potential solution is to improve tubewell cleaning and maintenance practices. Because deeper aquifers are unlikely to be contaminated with faecal bacteria, the most likely mechanism for contamination in deep tubewells is the introduction of faecal bacteria into the tubewell body during use, combined with inadequate cleaning and maintenance practices. Other evidence supports this interpretation. Tubewell bodies act as reservoirs for microbial contamination (Ferguson et al., 2011), and decontaminating the tubewell mouth substantially reduces contamination in samples of water collected from tubewells (Mahmud et al., 2019). If the problem of microbial contamination originates not with the source groundwater but with use and maintenance, improvements to maintenance regimes might make it possible to realize the advantages of deep tubewells—high quality source groundwater with low arsenic contamination—at lower cost than switching to an alternative technology.

An important knowledge gap is whether or not existing cleaning and maintenance practices "work"—that is, whether they improve the quality of water collected from tubewells—and if not, to what extent water quality can be improved using best practice approaches to cleaning and maintenance. This knowledge is essential because, without it, we do not know how to design interventions to improve cleaning and maintenance, such as whether interventions should target the frequency of cleaning and maintenance or the approaches used, or indeed whether such interventions are likely to be effective at all. To better understand these questions, we designed a randomized controlled experiment to measure how effectively three different approaches to cleaning reduce the concentration of coliform bacteria in deep tubewell water. The three approaches we study include the caretaker's usual standard of care, as well as two best practice alternatives: 1) flame disinfection of the interior and exterior of the tubewell body using ethanol; and 2) disinfection of the interior and exterior of the tubewell body using a weak chlorine solution. While these two approaches reflect recommended best practices based on practitioners' experience, they have to our knowledge never been rigorously evaluated in field conditions.

2. Methods and materials

2.1. Study area and design

We implemented this study in Bogra and Gaibandha districts in northwestern Bangladesh. Between 2015 and 2017, we installed a total of 126 deep tubewells in communities in these districts, as part of previous research projects that evaluated the impact of the deep tubewells on access to safe drinking water (Cocciolo et al., 2021), how these impacts vary depending on whether or not communities were asked to contribute towards installation costs (Cocciolo et al., 2020), and how communities prefer to take decisions about well locations (Cocciolo et al., 2019). Each community is a geographically contiguous group of between 50 and 250 households. We used a census of arsenic contamination in community wells to target communities that were exposed to arsenic contamination before our interventions. Among a pool of communities identified from administrative records as potentially exposed to arsenic contamination, we recruited communities in which more than 25 % of wells were contaminated (Appendix Fig. B1). We also recruited communities in which between 15 and 25 % of wells were contaminated if the contaminated wells were spatially clustered, implying that a substantial share of households did not have a nearby well that was free from arsenic contamination.

A partner NGO, NGO Forum for Public Health (NGOF), implemented the project. NGOF field staff offered to install up to three deep tubewells in 144 communities, randomly selected from an original pool of 171 communities. Wells were intended for community use but could be installed either on public land or on private land. Most communities selected well locations through a consensus-based decision-making process, facilitated by field staff, that increased the impact of similar projects relative to other approaches to decision-making (Madajewicz et al., 2021). Field staff ensured that all sites had sufficient drainage, distance from potential groundwater contaminants, such as pit latrines, and space and overhead clearance for the well installation equipment. If communities selected sites that did not meet these criteria, field staff asked them to take a new decision.

In total, the project installed 126 deep tubewells in 92 communities. NGOF employed experienced contractors to install the tubewells, supervised by an NGOF field engineer. Contractors used sediment color to identify potentially safe aquifers (Hossain et al., 2014). All tubewells were then confirmed to be free from arsenic by laboratory testing after handpump installation. The installed tubewells varied between 300 and 800 ft. in depth. Data collected one to three years after installation confirmed that the tubewells continued to provide arsenic-safe drinking water but found that a third of the installed wells tested positive for faecal contamination

(Cocciolo et al., 2021) based on hydrogen sulfide tests (Gupta et al., 2008). User groups selected caretakers for the wells, who participated in a training course and received a caretaker manual (produced by NGOF) and a toolkit.

We randomly assigned the 126 installed tubewells to three different cleaning protocols and to a control group of wells that were not cleaned. Random assignment of cleaning protocols to wells enables us to infer that any statistically significant differences in outcomes are caused by differences in whether and how wells were cleaned. We used pseudo-random number generators in STATA to assign wells to treatment, stratifying by communities assigned to different rules for contribution requirements and decision-making processes during project implementation. Between well installation and data collection for this study, conducted in June and July 2021, 32 (25 %) of the installed wells had ceased to function, meaning that water could no longer be obtained from the wells. The final sample for this study thus comprises the 94 tubewells that were functioning at the time of data collection. Fig. 1 shows all study tubewells, whether or not they were functional at the time of the data collection for this study, and the treatment arm to which they were assigned.

Treatment was correctly implemented as assigned, except that due to a data entry error in the field, one well that was assigned to the flame disinfection protocol was treated under the caretaker usual standard of care. An enumerator initially entered the wrong well details in the field. As a result, the form pulled the treatment status for a different well. Since the error was itself random, the error does not compromise the experiment, and we analyze the experiment as implemented. However, the conclusions are not sensitive to analyzing the experiment as originally designed. The final numbers of functional tubewells assigned to each treatment arm are shown in Table 1. To confirm that random assignment yielded comparable groups across the different treatment arms, we check that well failure rates and water quality *before* cleaning are uncorrelated with treatment status (Appendix Table B1).

Field staff visited each installed tubewell once to conduct the cleaning experiment and to measure water quality in tubewells before and after cleaning. We did not inform caretakers or community members about the visit in advance. This allowed us to observe the tubewells in their usual conditions. Had caretakers or community members known in advance about our visit, they might have taken additional measures to clean the wells, which might have given a misleading impression of the usual standard of cleanliness and maintenance in the study wells.

Table 1
Assignment of tubewells to cleaning treatments. Table shows number of installed tubewells and number of functional tubewells assigned to each cleaning protocol and to the control group.

Cleaning treatment	# of installed tubewells	# of functioning tubewells	% tubewells functioning
Caretaker usual standard of care	33	24	73 %
Flame	30	20	67 %
Weak chlorine	32	25	78 %
Control	31	25	81 %
Total	126	94	75 %

Beyond the cleaning treatments, everything else in our study protocol was as far as possible held constant across treatment arms. One way in which data collection varied across treatment arms is that two staff members visited communities assigned to the best practice treatment arms—flame disinfection and disinfection with a weak chlorine solution—while only one staff member visited communities assigned to control or to the caretaker's usual standard of care. Implementing the best practice protocols required two people.

2.2. Measuring faecal contamination in tubewells

Field staff collected two 100 ml water samples for testing for faecal contamination, before and after implementing any cleaning protocol. Field staff followed a detailed sample collection protocol (Appendix A). First, field staff collected a sample from each well upon arrival at the tubewell. The contamination measured in this first sample is representative of contamination to which well users would be exposed when collecting drinking water from the tubewell. After collecting the first sample, field staff pumped the well for 5 to 8 min, depending on well depth, and collected a sample for arsenic testing. We do not report results of arsenic contamination tests here as they were the focus of a separate study. After collecting the sample for arsenic testing, field staff cleaned the wells, if applicable, and then collected a second sample for testing for faecal contamination. We did not collect or test blanks.

We also collected a sample from the nearest shallow tubewell to each installed deep tubewell for comparison. Field staff did not clean or pump

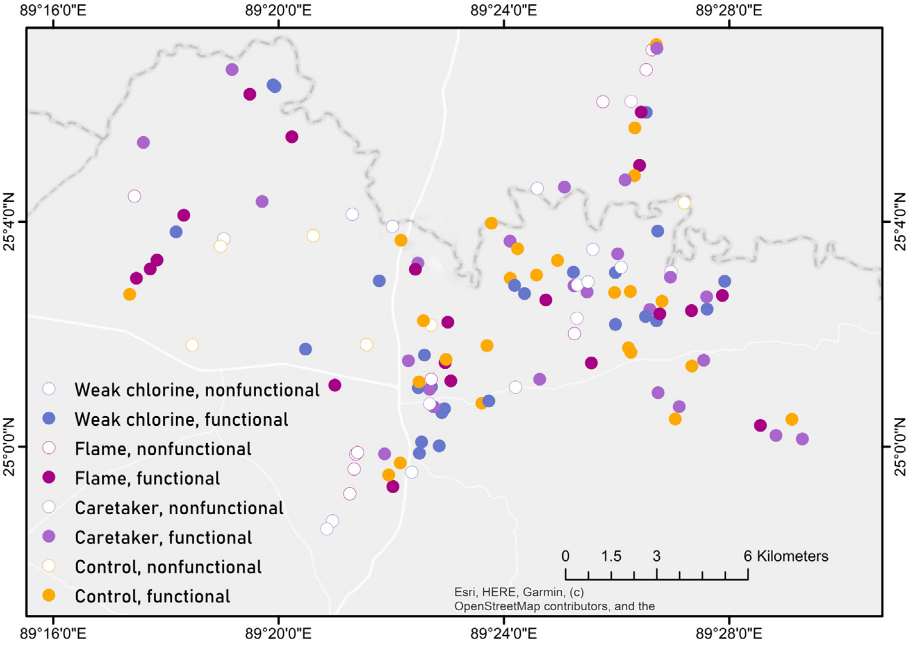

Fig. 1. Installed tubewells by functionality and assignment to treatment. Map shows all tubewells constructed between 2015 and 2017, their functionality status at the time of data collection for this study in 2021, and their assignment to cleaning protocols or to the control group.

the shallow tubewells before collecting these samples, making the samples comparable to the first samples collected from the deep tubewells.

The sample vessels contained sodium thiosulfate for neutralizing chlorine and were sealed with tamper-evident shrink bands. Sample vessels were stored in a clean icebox between collection and processing, usually for less than 5 h. We used IDEXX Colilert kits to measure both total coliforms and *E. coli*.[1] Field staff added Colilert-18 reagent to each sample vessel and then decanted the sample into a Quanti-Tray/2000 testing tray. Field staff confirmed that they did not observe a blue flash when adding reagent to the samples, suggesting that the samples did not contain excessive chlorine, which would have invalidated the test results (Gregorio, 2010). Testing trays were sealed and incubated at 35 °C for 28 h. Each testing tray has 96 wells, 48 large wells and 48 small wells. After incubation, field staff counted the number of large and small wells that had turned yellow, and the number of wells that were both yellow and fluorescent. We entered these counts into the IDEXX MPN Generator software in order to obtain the Most Probable Number (MPN) of colony forming units (CFU) per ml of total coliform and *E. coli* respectively.

2.3. Cleaning protocols

We compared three different approaches to cleaning tubewells. We trained field staff to carry out the best practice approaches, including a field demonstration. Field staff wore protective clothes, goggles, and sanitized gloves throughout the experiment. The three cleaning protocols were as follows:

2.3.1. Caretaker usual standard of care

Field staff asked caretakers to clean the tubewell using their own standard approach, i.e., what they normally do in order to maintain the well with the cleaning materials that they had to hand. Field staff left the caretakers alone while they cleaned the well, to minimize any potential effects on behaviour from being observed (or "Hawthorne" effects, see Festinger and Katz, 1953). After the caretakers cleaned the well, field staff asked caretakers what steps they had followed to clean the well. The vast majority (22/24) reported only scrubbing the exterior of the tubewell. One caretaker reported additionally scrubbing the interior of the well, and one reported only cleaning the tubewell platform. Caretakers did not report using any disinfecting reagents or solution (e.g., bleach powder, detergent) when cleaning tubewells nor did field staff observe their use.

2.3.2. Flame disinfection

Field staff used flame to disinfect the tubewell. Mahmud et al. (2019) previously showed that flame disinfection of the tubewell mouth was effective in reducing contamination in water from tubewells. Field staff disassembled the tubewells by detatching the pump body from the base plate of the suction pipe and removing the plunger valve and flapper valve. Field staff then cleaned and scrubbed the exterior and accessible interior parts of the pump body and the exterior of the well cap and casing. Field staff then poured ethanol with concentration greater than or equal to 99.5 % (v/v) over the pump body, the plunger (excepting the valve, if made of plastic or rubber), and the plunger rod. Field staff then set the ethanol alight, allowing it to burn for 3 to 4 min. Field staff repeated the flame disinfection three times, using in total 250 ml ethanol valued at approximately 3 USD, for a total of around 10 min burning time. After cooling, field staff replaced their gloves, reattached the suction pipe and pumped sterile water through the tubewells, until the pump was primed and groundwater was present in the barrel.

2.3.3. Disinfection with weak chlorine

Field staff cleaned and scrubbed the exterior and accessible interior surfaces of the pump body before disinfection using a weak chlorine solution. As with the flame disinfection approach, field staff disassembled the tubewells before cleaning the interior surfaces. Field staff took special care to remove all oil, grease, scum and other material that could harbour and protect bacteria from disinfectants. The weak chlorine solution was a 0.025 % solution prepared with 1 g/2.5 l bleaching powder (Water Mission, 2019), valued at 0.04 USD. After scrubbing, all surfaces were doused with the chlorine solution before staff replaced their gloves, and rinsed and reassembled the tubewell. Field staff then pumped the tubewell for ten minutes to rinse all residual chlorine from the tubewell body and confirmed that the pH was neutral before collecting the second sample for testing. This is the cleaning protocol that NGOF recommends and teaches when installing community wells.

2.4. Statistical analysis

We use regression analysis to compare contamination in wells assigned to the different cleaning protocols and the control group. The estimated effects correspond to the net effects of following each of the cleaning protocols in its entirety. Our data and experimental design do not allow us to separately estimate the consequences of each different stage of the cleaning protocols.

We compare contamination with total coliforms and with *Escherichia coli* (*E. coli*). When we analyze contamination with total coliforms, we use an arcsinh or log transformation to reduce skewness in the data. When we use a log transformation, we add one before transforming to deal with zeroes (values below the detection threshold) in the contamination data. Five observations ($N = 280$, 1.8 %) have total coliform concentrations above the detection limit of 2419.6 CFU/100 ml. We code these observations at the detection limit.

Relatively few samples test positive for *E. coli* (21/94 or 22 %, before cleaning) and only a small handful have concentrations higher than 10 CFU/100 ml (3/94 or 3 %, before cleaning), all of which are below the detection limit. Because analyses of the *E. coli* data are very sensitive to these outlier values, we primarily analyze an indicator which takes the value one when *E. coli* contamination is detected and zero otherwise, using both a probit model and a linear probability model.

For both total coliforms and *E. coli*, we estimate models that use: i) only data collected after flushing the well and cleaning, if applicable; and ii) data collected before and after flushing and cleaning. When we include data from before flushing and cleaning, we include fixed effects that account for baseline differences in contamination between wells, and we include an indicator that takes the value one if the sample is collected after flushing (and if applicable cleaning) to account for the effect of flushing the well. Standard errors account for heteroskedasticity (Long and Ervin, 2000). Results are very similar for different transformations of the outcome variable and for different statistical models.

3. Results

3.1. Water quality in deep tubewells before cleaning

Fig. 2 maps water quality before cleaning or flushing the wells. These measures of water quality reflect the contamination that deep well users will typically be exposed to when collecting water from the wells. Before cleaning, we detect total coliforms in 62 % of wells (58/94): 34 % (32/94) are below 10 CFU/100 ml, 17 % (16/94) between 10 and 100 CFU/100 ml, and 11 % (10/94) above 100 CFU/ml. We detect *E. coli* in 22 % (21/94) of wells before cleaning, breaking down to 19 % (18/94) low risk (below 10 CFU/100 ml) and 3 % (3/94) intermediate risk (10–100 CFU/100 ml), following risk classifications established by WHO (2017).

3.2. Comparison between deep tubewells and shallow tubewells

Fig. 3 compares contamination in the deep tubewells and the nearest shallow wells Shallow wells have higher rates of contamination with total

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[1] See manufacturer information: https://www.idexx.com/en/water/water-products-services/colilert/.

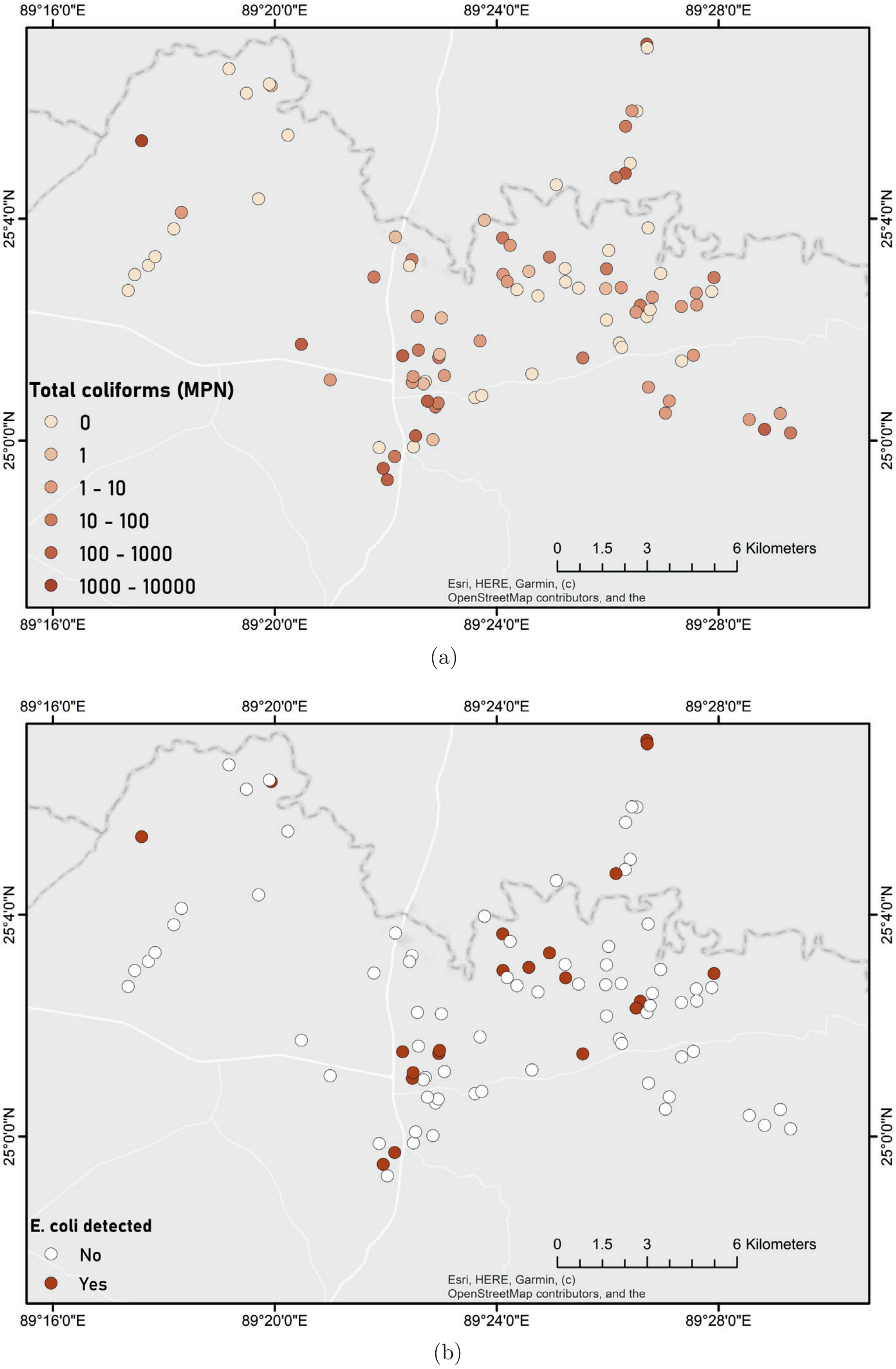


Fig. 2. Water quality in deep tubewells before cleaning. Maps show deep tubewells that were functional at the time of the study by water quality. Figure (a) shows concentrations of total coliforms. Figure (b) shows presence of *E. coli*.

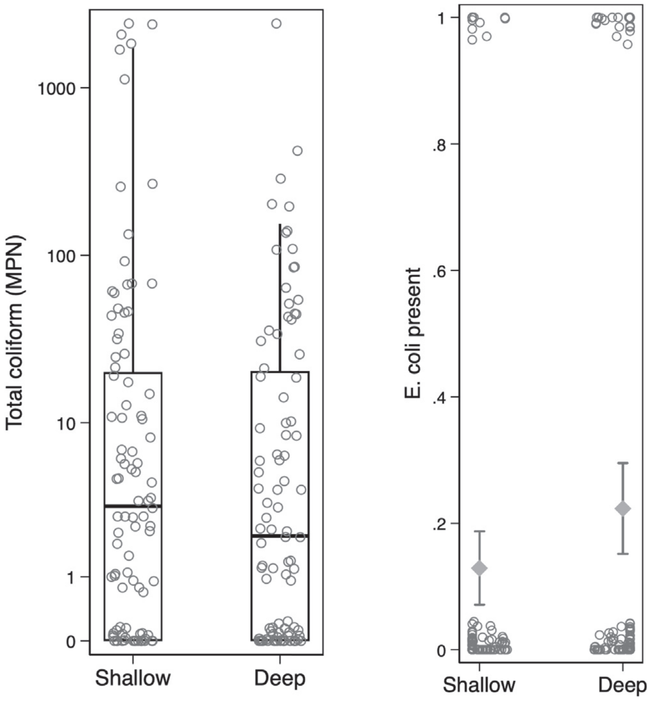
coliform and lower rates of contamination with *E. coli*, but the differences are small. Among shallow tubewells, 71 % test positive for total coliform (66/93). The distribution of contamination values is very similar to that for the deep tubewells, although there are more wells (4/93, compared to 1/94) above 1000 CFU/ml. Fewer shallow wells (13 %, 12/93) than deep wells test positive for *E. coli*. For one deep tubewell, we are missing data from a paired shallow tubewell because the test data was not correctly tracked. The differences in water quality between shallow and deep wells are not statistically significant (Appendix Table B2). Thus, the deep tubewells have comparable bacterial drinking water quality before cleaning to nearby shallow tubewells, despite the deep tubewells drawing on aquifers that are better isolated from surface pollutants and despite having been installed by experienced contractors that were monitored by a NGO that specializes in drinking water supply and sanitation.

3.3. Effects of cleaning treatments

We evaluate the effects of cleaning on contamination with total coliforms and with *E. coli*. We only consistently detect reductions in contamination for the chlorine disinfection treatment.

3.3.1. Effects on total coliforms

Fig. 4 visualizes the effects of flushing and where applicable cleaning on total coliforms. Flushing the wells has limited effect on contamination in



(a) (b)

Fig. 3. Comparison of water quality in deep and nearby shallow tubewells. Each hollow circle represents one functional deep or shallow well. Points are jittered for readability. Figure (a) shows concentrations of total coliforms. Boxes show median and interquartile range; spikes show 5th and 95th percentiles. Figure (b) shows mean rate of *E. coli* presence and 90 % confidence interval.

control wells, which were not cleaned. Total coliform concentrations are slightly lower in samples taken from wells before and after flushing (panel a). Total coliform concentrations actually rise on average after caretakers clean wells (panel b). Contamination is generally lower after flame disinfection, but the improvement is incomplete and in a few cases is it substantially worse (panel c). Only disinfection with the weak chlorine solution consistently reduces contamination. No well has contamination above 10 CFU/100 ml after cleaning the well using this approach, and a large share (83 %, 20/24) are free from contamination (panel d).

Statistical analysis confirms that only disinfection with weak chlorine leads to a statistically significant reduction in contamination relative to flushing alone and that we can reject the null hypothesis that the effects of disinfection with weak chlorine are equal to the effects of the caretaker's regular standard of care and flame disinfection (Appendix Table B3). The reduction in contamination observed after flushing alone is statistically insignificant. The increase in contamination after caretakers clean wells compared to flushing alone is only statistically significant in one out of four statistical models.

3.3.2. Effects on E. coli

Fig. 5 visualizes the effects of cleaning on *E. coli* contamination. A substantial share of wells test positive for *E. coli* after flushing (24 %, 6/25) and after caretakers clean wells (33 %, 8/24). The presence of *E. coli* also rises slightly after caretakers clean wells. No well tests positive for *E. coli* after disinfection with the weak chlorine solution and only one does so after flame disinfection. However, by chance, wells assigned to these best practice approaches had somewhat lower rates of contamination to begin with. After accounting statistically for these initial differences, the only difference between treatment arms that we consistently reject as being equal to zero is the difference between the chlorine disinfection protocol and the caretaker's usual standard of care (Appendix Table B4). Neither the fall in contamination after flushing nor the rise in contamination after caretakers clean the well are statistically significant.

4. Discussion

The main objective of this study was to investigate and compare three different cleaning approaches for deep tubewells. Despite drawing water from an arsenic-safe aquifer that has limited potential for microbial contamination (Howard, 2003), deep tubewells nonetheless have similar rates of contamination with coliform bacteria to shallow tubewells in the same communities, as we show in this context in the present study (Fig. 3) and as shown previously in other areas in rural Bangladesh (Goel et al., 2019). Three years prior to this study, coarser tests showed somewhat lower rates of faecal coliform bacteria in these deep tubewells compared to a larger representative sample of shallow tubewells in the same communities (Cocciolo et al., 2021). That even those modest advantages of deep tubewells appear to have attenuated three years later may reflect different measurement of contamination, a different comparison sample of shallow tubewells, or increasing contamination in the deep tubewells with time since construction (Ercumen et al., 2017).

We then evaluate the effect of cleaning on *E. coli* and total coliform in water collected from the deep tubewells. We compare contamination in two samples of well water taken before and after flushing and cleaning. Disinfecting the wells using a weak chlorine solution performs better than flame disinfection or the caretaker's usual standard of care. The first approach but not the latter two consistently improves water quality relative to control wells that are flushed but not cleaned. Regression analysis shows that the only difference between treatment approaches that we consistently reject as being equal to zero across different outcomes and specifications is the difference between disinfection with weak chlorine and the caretaker's standard practice. That disinfecting the well interior surfaces with chlorine improves water quality supports an interpretation that contamination in deep tubewells occurs via the tubewell body rather than the source groundwater.

When caretakers clean the wells, total coliform concentrations and the presence of *E. coli* actually increase rather than decrease, suggesting that tubewells may even be re-contaminated during cleaning by the caretaker (Figs. 4 and 5), although the increases are not consistently statistically significant across statistical models. Since caretakers only appeared to clean the exterior surfaces of the wells, it may be not be surprising that water quality did not improve.

The results of this study will help inform the design of programs to improve safe drinking water in Bangladesh. Existing tubewell maintenance practices appear inadequate to maintain water quality. The presence of faecal bacteria in wells already suggests that the caretakers' usual standard of care may not be adequate, but the presence of faecal bacteria does not reveal whether cleaning techniques are ineffective or whether cleaning is insufficiently regular compared to the speed of reintroduction of contamination during use. Our experiment does not speak to how frequently cleaning occurs but demonstrates that the cleaning techniques in use are ineffective. Cleaning may also be insufficiently frequent. However, repeating an ineffective cleaning process more frequently would not improve water quality.

One of the best practice approaches we tested—dismantling, scrubbing, and disinfecting with a weak chlorine solution—consistently reduced contamination. If caretakers can be trained and incentivized to adopt and sustain practices closer to this approach at low cost, then deep tubewells combined with increased support for cleaning and maintenance might still prove the most cost-effective way to ensure safe drinking water access for all in rural Bangladesh. If not, then more extensive technological change may be necessary.

Flame disinfection appeared less effective than disinfection with weak chlorine, was more expensive, and, requiring the use of an open flame, potentially less safe. Thus we do not recommend promotion or adoption of this approach.

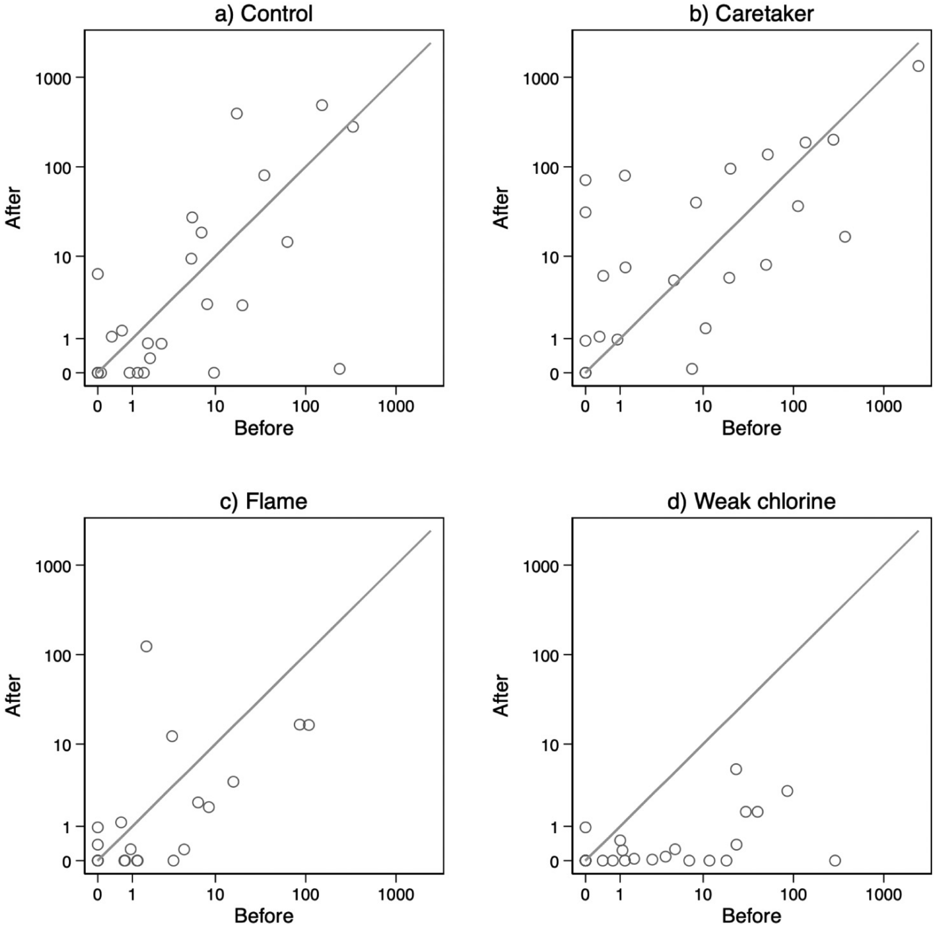


Fig. 4. Effects of cleaning on total coliforms (MPN). Figures summarize contamination with total coliforms before and after flushing and, where applicable, cleaning, under each treatment arm and for the control group. All axes show MPN of CFU/100 ml, plotted on an arcsinh scale. Each hollow circle represents one well. Points are jittered for readability. The diagonal line plots the locus of points that would reflect equal contamination before and after flushing and/or cleaning.

We leave several further questions for future research. First, we only measure impacts on water quality immediately after cleaning wells. Water quality will deteriorate again as soon as contamination is reintroduced, for example via the tubewell mouth. An important question for future research is how rapidly water quality declines and how this varies with use patterns. While the effectiveness of disinfection with weak

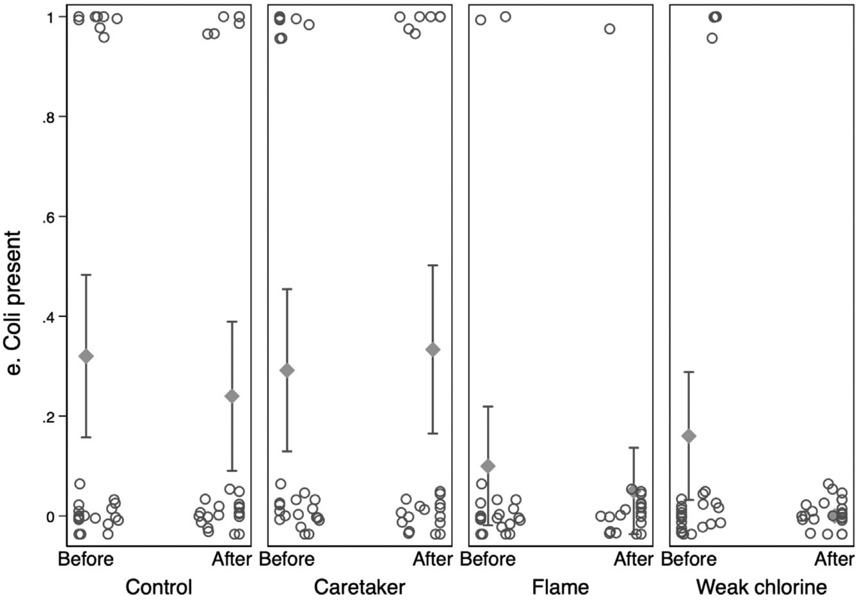


Fig. 5. Effects of cleaning on *E. coli* presence. Figures summarize *E. coli* presence before and after flushing and, where applicable, cleaning. Each hollow circle represents one well. Points are jittered for readability. Bar shows mean rate of *E. coli* presence and 90 % confidence interval.

chlorine suggests that the primary source of contamination is via the tubewell mouth or body, future research is needed to establish the exact mechanisms via which contamination is introduced. Second, we only analyze the concentration of coliform bacteria and the presence of *E. coli*. Future research should investigate the concentration of *E. coli*, the types of *E. coli* strain, and the presence of other faecal contaminants. Third, there are many potential reasons why caretakers' usual standard of care may fall short of best practice approaches, for example, limited information or limited ability to purchase necessary inputs. Future research is needed to understand which barriers are important and whether interventions can overcome these barriers.

Another approach to reduce exposure to faecal contamination in drinking water is point-of-use chlorination. This approach has proved effective in experimental contexts but not been widely adopted (Arnold and Colford, 2007; Clasen et al., 2015; UNICEF and WHO, 2011; Waddington and Snilstveit, 2009). An open question for future research is whether improvements to cleaning and maintenance practices are easier or more difficult to sustain at scale than point-of-use chlorination.

5. Conclusion

Faecal contamination of deep tubewell water is a significant obstacle to providing safe drinking water in rural Bangladesh, yet cleaning and maintenance are sometimes an afterthought in program design and implementation. In this study, we show that an approach to cleaning wells that includes disinfection with a low-cost weak chlorine solution improves water quality in deep tubewells. Current local maintenance practices are ineffective and may worsen water quality. The fact that disinfection of the tubewell body with chlorine reduces or eliminates contamination provides reassurance that the source of faecal contamination in well-constructed deep tubewells is unlikely to be the source groundwater. Improving cleaning and maintenance practices for deep tubewells may be a cost-effective way to improve access to safe drinking water in rural Bangladesh. However, the gulf between current and effective cleaning and maintenance practices is wide, both in terms of the nature of the practices themselves and how effectively they reduce contamination. Which interventions can successfully improve cleaning and maintenance practices remains an important open question.

CRediT authorship contribution statement

Md. Ahasan Habib: Conceptualization, Methodology, Investigation, Writing – original draft, Data curation, Supervision. **Serena Cocciolo:** Conceptualization, Methodology, Software, Data curation. **Md. Abdul Haque:** Investigation, Data curation. **Md. Mir Abu Raihan:** Investigation, Data curation, Project administration. **Prosun Bhattacharya:** Supervision, Writing – review & editing. **Anna Tompsett:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Data availability

Anonymized data and replication code are available online.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Md. Ahasan Habib reports a relationship with NGO Forum for Public Health that includes: employment. Md. Abdul Haque reports a relationship with NGO Forum for Public Health that includes: employment. Md. Mir Abu Raihan reports a relationship with NGO Forum for Public Health that includes: employment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161932.

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