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Bi-tech wells: an effective arsenic mitigation method

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Abstract

With more than 150 million people in India, Bangladesh and Nepal exposed to arsenic through drinking water, arsenic mitigation projects are common in the region, including many failed and abandoned projects. Our nonprofit organization, Project Well, has been working since 2001 to provide cheap, easily adaptable safe-water solutions suitable for the local socioeconomic environment. After years of research and experimentation, Project Well has developed a 'bi-tech' well that fulfills these criteria by tapping arsenic-safe surface water from unconfined aquifers. From 2001 to 2009, Project Well constructed dugwells modified from local traditional dugwells; one important modification was that water was extracted using hand pumps rather than rope-and-bucket, to minimize bacterial contamination. A sizeable percentage of these dugwells were dry during the summer seasons, so in 2009 we began constructing 'bi-tech' wells that combined the features of our bacterial-growth-preventing dugwells with the depth of borewells (8 meters). In the summer of 2014, 94% of bi-tech wells contained water compared to 53% of our modified dugwells. Fecal coliform and *E. coli* were undetected in tests conducted in 2011 and 2014. In 2015, arsenic concentrations were <10 ppb in 95% of the wells. Bi-tech well maintenance is simple, with dredging rarely necessary, and easy for communities to learn. With its low construction costs, easy maintenance, and consistent safe-water output, bi-tech wells are proving an effective water solution in parts of rural India where piped water is not available.

Key words: arsenic, bi-tech well, drinking water, dugwell, India, mitigation, tubewell, water program, West Bengal

INTRODUCTION

In 1995, the world first learned of the problem of arsenic in drinking water in India. Over time, studies have shown there are more than 150 million at risk people in India, Nepal and Bangladesh. Twenty years later, arsenic mitigation in these countries is still a patchwork of often temporary solutions. Pipelines, several types of arsenic removal filters, deep and shallow borewells (locally known as tubewells), traditional and improved/sanitary dugwells, rooftop rainwater harvesting, river and pond sand filters, *in situ* evaporation method: all of these interventions have limitations, but none of these above methods can be 'the one method' for mitigation in the arsenic-afflicted villages of this region (Smith 2001; WHO 2003; Howard *et al.* 2010; Milton *et al.* 2012).

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

In West Bengal, India, the arsenic mitigation options all have drawbacks:

Pipelines–In 2001, the government of West Bengal proposed a scheme to supply safe water through pipelines to eight districts that had arsenic contamination, at enormous construction cost (estimated in 2001 at 437.5 million USD or INR 21 crores). In 2006, the proposed scheme was replaced by a new master plan to tackle arsenic contamination of groundwater in West Bengal (Government of West Bengal 2013), which is ongoing. Pipelines are being constructed without operation or maintenance plans in place. Bagjola panchayat members of Deganga Block of North 24 Parganas district described on video (Project Well 2012) broken taps resulting in wasted water, tampered pipes, and even pipelines installed further than the water is able to flow and thus never working. There are similar complaints of irregular water supply in many parts of the country, and in certain areas, communities do not use the water due to the turbidity (Singh 2005). Pipelines have not been built to reach many remote villages.

Arsenic removal filters–some community arsenic removal filters require ongoing maintenance by trained personnel that communities are reluctant to take responsibility for; community and household filters require collection logistics and disposal of the filtered toxic sludge.

Deep and shallow tubewells– Presence of arsenic in shallow and deep tubewells depends on which aquifer is tapped for the well. In Figure 1, number 4 depicts a generalized and schematic geological section, showing various sedimentary formations and their geogenic arsenic content.

Shallow tubewells, which tap shallow aquifers (<60 m/200 feet) contained in the uppermost Katwa (Kandi) formation sediments (Bhattacharyaa & Banerjee 1979) of the Holocene age, usually deliver

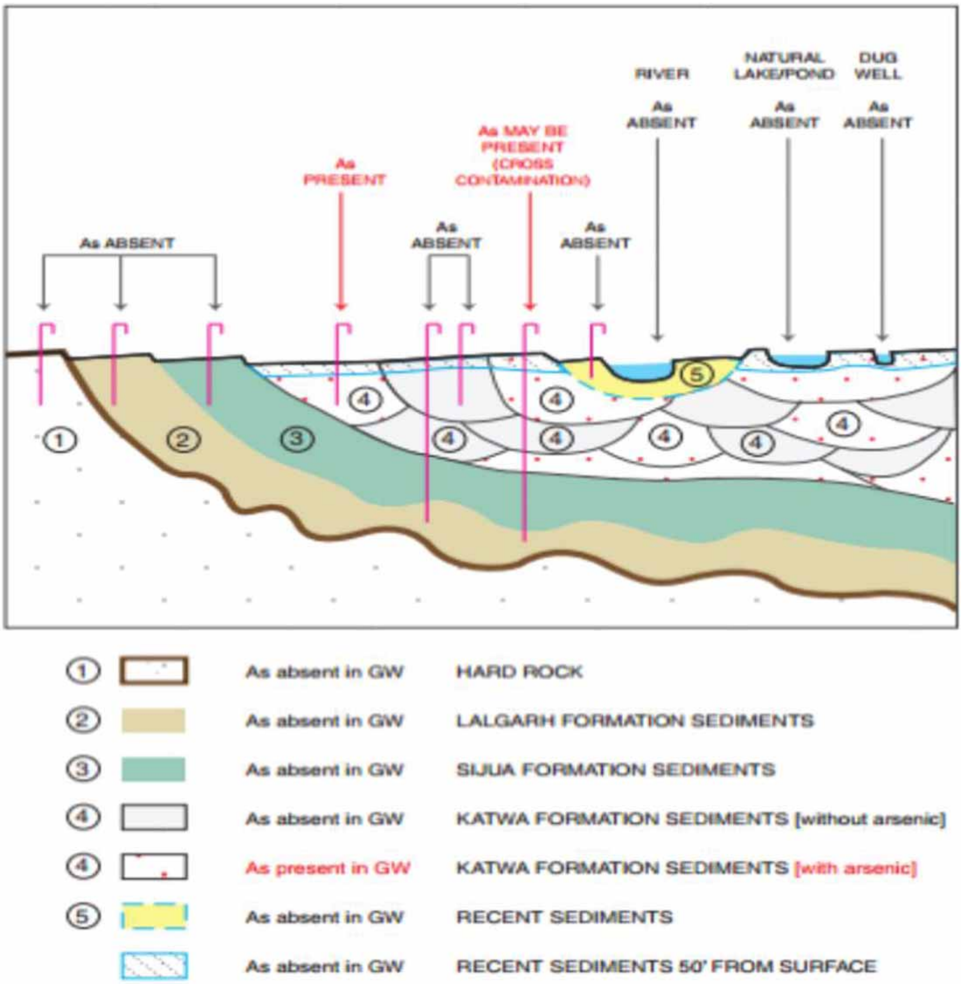

Figure 1 | A diagrammatic geolithological sketch showing different aquifers with presence of arsenic. *Diagram by Protap Chakravarti, reproduced by Sylvia Teng*.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

arsenic-contaminated water (Ravenscroft *et al.* 2005). Deep tubewells, which generally draw groundwater directly from aquifers (>150 m/500 feet) contained within deep sedimentary formations of Sijua & Lalgarh (Banerjee *et al.* 1998) of the Pleistocene age, are free of arsenic. The arsenic-contaminated groundwater from overlying Katwa formation seeps down through the gravel packs of the tubewells. Thus, numerous deep tubewells which were initially safe were subsequently vulnerable to arsenic contamination (Burgess *et al.* 2010).

Our shallow 'modified' dugwells–In 2001, Project Well installed its first shallow modified concrete dugwell, or 'modified dugwell' that tapped arsenic-safe water from an unconfined aquifer (Smith *et al.* 2003). Unlike the traditional rope-and-bucket system, water was extracted with a hand pump attached to the dugwell to prevent contamination, particularly bacterial contamination. Over eight years, Project Well constructed 72 modern dugwells and continued to monitor all the wells, including analyzing the water for arsenic and fecal coliform bacteria, and measuring the height of the water column to calculate the amount of Theoline, the locally available disinfectant containing 5–10% chlorine (Hira-Smith *et al.* 2007) to be used in each well. About 15% of the modified dugwells became dry during the dry seasons, since 'sand boiling' prevents wells from being deepened during construction. Sand boiling occurs when water under pressure wells up through a bed of sand. The water looks like it is 'boiling' up from a bed of sand and prevents the wells from being drilled any further down to the dugwell target depth of 7.6 m (25 feet). Well depths ranging from about 4 to 6 m (14 to 20 feet) were often drying in the summer. The average depth of all the modified wells was 5.7 m (19 feet).

To solve the issue of sand boiling, Project Well decided to change the design of its wells. In 2008, the first Project Well 'bi-tech' well, also known as a bore-dugwell, was constructed, and in 2009, 20 of 25 constructed wells were bi-tech wells. Since even during the driest month of May 2010 none of the bi-tech wells of the North 24 Parganas and Nadia districts became dry, we standardized the design of the well and constructed an additional 198 bi-tech wells during the next five years, from 2010 to 2014.

What is a bi-tech well?

A bi-tech well combines two types of wells: borewell and dugwell. Prior to actual construction, a pilot test is done at the proposed site to determine the depth of the water-bearing sand layer. The sand layer is generally within 4.5 m (15 feet) below ground level (bgl) in the target area and the sites are chosen so the sand layer starts no more than 6 m (20 feet) bgl. Manual excavation of the dugwell portion is limited to 4.5 m (15 feet) bgl and involves mostly clay, with poor porosity inhibiting rapid recharge. This depth was determined from eight years of experience encountering sand boiling at different depths during construction. To overcome the sand boiling problem, a 3 m (10-foot) long pipe is inserted into the sand boiling layer as part of the bi-tech well. This design keeps the depth of all wells at a uniform 8 m (27 feet), including reducers, and prevents wells from drying all year round.

Construction method

The construction procedures start with boring or drilling the larger diameter 10-foot long PVC pipe, followed by digging and finally finishing the housing and setting up the delivery pipe and the hand pump that is used to extract water. A longitudinal section of a bi-tech well is shown in Figure 2. The depth of the well adds up to 8 m (27 feet). The dugwell portion of the bi-tech well extends from 4.6 m (15 feet) bgl to 1.2 m (4 feet) above ground level, with a 3 m (10-foot)-PVC pipe insert. Reducers are added to the bore part that brings the total depth to 8 meters (27 feet). The detailed description and diagrams of the three stages of construction – drilling, digging and housing – is given below. Construction can be done throughout the year except during peak rainy season and one month after. It is important to consider the depth of the water table that varies from place to place, even within the same district.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

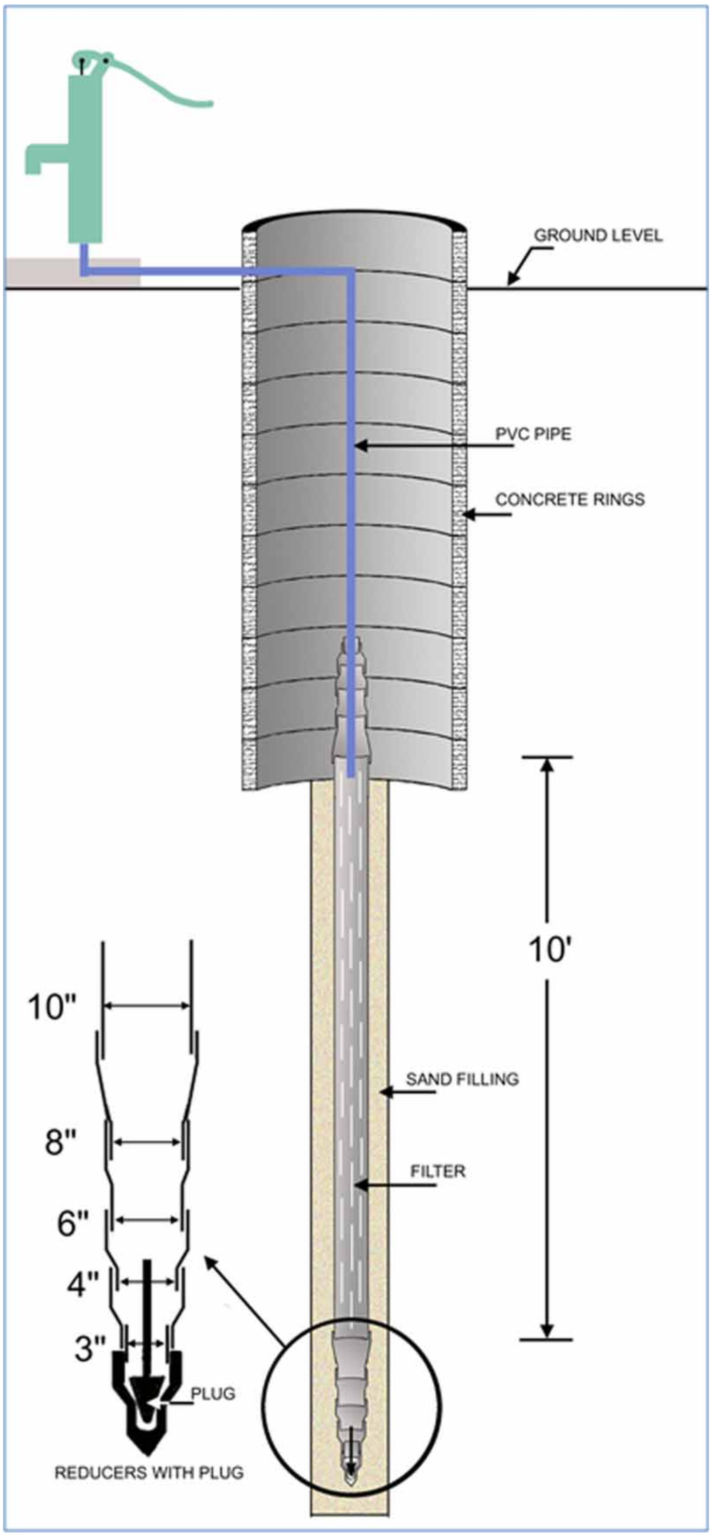

Figure 2 | Longitudinal section of a bi-tech well.

Drilling

Generally, drilling up to a depth of 9 m (30 ft) takes about 3–4 hours. Early in the morning, six laborers set up bamboo scaffolding. They begin drilling using a 46 cm (18 inches) drill bit to insert the 25 cm (10 inches)-diameter PVC pipe (Figure 3). The drill bit is screwed on to the end of a

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

Figure 3 | Lowering of the assembled 3 m by 25 cm PVC pipe into the 9 m by 46 cm hole.

10 cm – diameter metal pipe that is open at both ends. While the pipe with the drill bit at the lower end is rotated manually, water is pumped in to the pipe from the top. This water pressure pushes out the excavated mud from the hole that is formed. A diesel engine with an irrigation pump is generally used, with the nearest source of water feeding it. Next, a 25 cm-diameter PVC pipe with wall thickness of 8 mm and length of 3 m is pushed down by the metal pipe used for drilling to the bottom of the hole. The PVC pipe is perforated with 10 cm (4 inches) longitudinal slits, with a 5 cm (2 inches) gap in between covered by a fine nylon mesh. The mesh is held to the PVC pipe by thin steel wire stitched to the edges of the mesh. The ends of the PVC pipe are fitted with reducers (Figure 4) in three or four stages so that the top end can be screwed to the metal pipe. The bottom end, also fitted with reducers, is fixed with a plug cutter.

As shown in Figure 5, the plug cutter is a small steel cylinder with a narrow opening at one end and a wider threaded opening at the other end. The end with the narrow hole has an arrowhead. The wider hole matches the reduced diameter of the PVC pipe. The bottom end of the PVC pipe attached with the plug cutter has to be kept open while the assembled parts are lowered in to the excavated hole. The open end allows the water in the flooded hole to enter the PVC pipe and prevent it from floating up. Water is again pumped in to the pipe to empty it of any clay/silt that may have entered while the pipe was being lowered. Once the PVC pipe has been lowered to the bottom of the hole, a plug is dropped from the top so that it blocks the hole of the plug cutter. The plug is a conical piece of steel with a long and narrow tail attached to its base (Figure 6).

The plug is dropped with the tail upward so that it fits into the hole of the plug cutter. This seals the bottom end of the pipe by sealing the plug cutter and prevents mud/sand from entering the pipe in the

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

Figure 4 | The assembled reducer.

Figure 5 | The plug cutter.

future. The height of the cone is 20 cm (8 inches) and the tail is about 30 cm (12 inches) long. The long tail helps the plug go down vertically without tilting. A final cleaning of the inside of the plugged PVC pipe is done.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

Figure 6 | The plug fitted to close the hole of the plug cutter.

The annular space between the pipe and the borehole is next filled up with 50 kilograms of clean, uniform, coarse yellow sand.

Digging

Four or five local skilled well diggers are usually employed following the drilling. They expand the 18-inch hole radially to about 110 cm (3.5 feet), just the right size to fit the 100 cm (3.3 foot)-diameter concrete rings (specifications are available in the Project Well Guidelines (Smith & Liaw 2012)). Starting from the top, the diggers carefully cut around the inserted pipe up to a level exposing 30 to 60 cm (1 or 2 feet) of the PVC pipe including the reducer. The set-up, with 2.4 m (8 feet) of the larger pipe plus the reducer, extends the bi-tech well to a total depth of 8 m (27 feet). This depth may vary slightly depending on geology (depth & thickness of aquifers), but caution is taken to keep the depth within 30 feet to avoid reaching the arsenic-releasing redox zone (Wagner *et al.* 2005). The concentric rings are stacked on top of one another until the total height of the cylinder reaches approximately 5 m (17 feet) with 1–3 feet above ground level, or 1–3 rings above the surface, depending on whether the site is prone to flooding. To join two concrete rings, mortar (mixture of cement, sand and water) is used.

Housing

Figure 7 shows the specifications of the housing required to complete the construction of a bi-tech well. Local masons are employed for brickwork and to construct the concrete apron/ platform surrounding the well. Masonry work takes about 2–3 days and requires two workers. A hand pump is attached to the dugwell and connected via a delivery pipe. These hand pumps provide a maximum

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

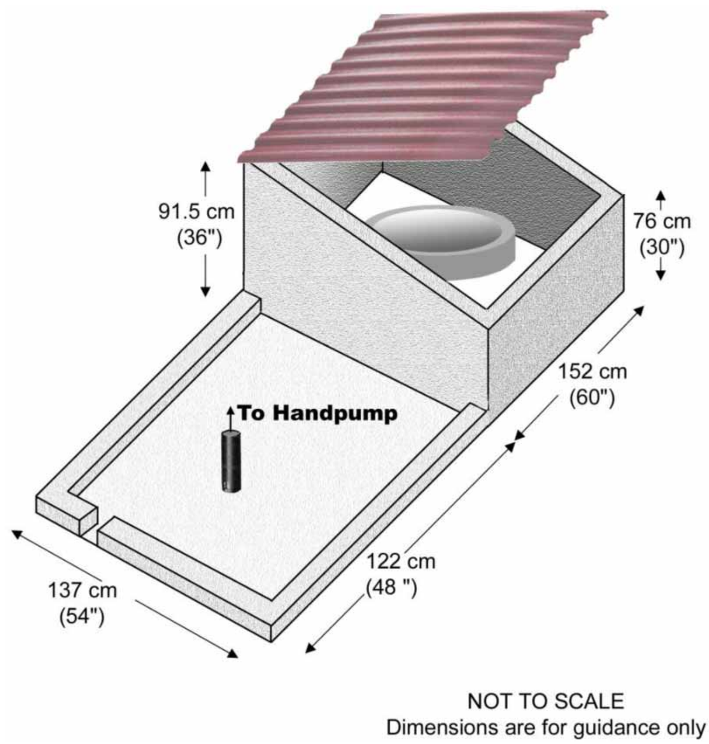

Figure 7 | Housing – the exterior portion of the bi-tech well.

output of 40 liters of water per minute, depending on the efficiency of the hand pump and the person pumping. Hand pumps are used, rather than a bucket-rope system, as they are less prone to contamination.

Following well construction, the water in the well is pumped out, preferably with a small irrigation pump, to remove the finer residue until the water is clear and sediment-free. Before allowing the community to use the water for drinking and cooking, the well water is treated with the chlorine-based disinfectant, Theoline, to kill any bacteria that may have been introduced into the aquifer during well construction. Materials and tools used during construction are generally contaminated with soil materials and certain types of bacteria found living in soils at the well site. Water from a well is considered bacterially safe to drink only when tests show that it contains no more than 1 coliform bacterium per 100 ml. The chlorine concentration must be high enough so that a free chlorine residual remains several hours after treatment. Enough retention time must be allowed so that the chlorine can kill the bacteria. Theoline is applied once a week for one month and the water is analyzed for arsenic concentration.

RESULTS

After implementing the bi-tech wells, we were interested in comparing availability of water during the hot summer season between the modified dugwells and bi-tech wells. We also measured levels of the two major contaminants of concern that cause disease in this area: arsenic and the diarrhea-causing fecal coliform.

Comparing availability of water in the dry summer season between modern dugwells and bi-tech wells

To compare the dry conditions between modern dugwells and bi-tech wells, we have considered data from the summer months, mainly May, collected from the field over a period of five years from 2010

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

to 2014. In total, 96 modern dugwells were constructed from 2001 to 2009 (Figure 8) and 172 bi-tech wells were constructed from 2010 to 2013 (Figure 9).

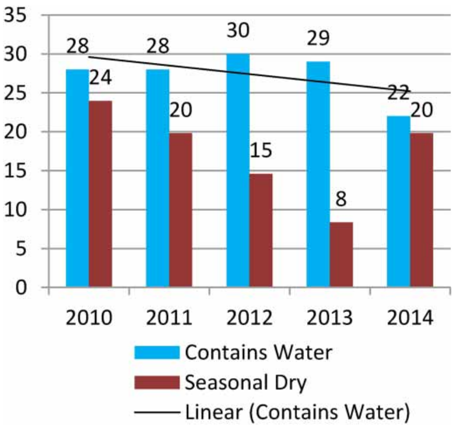

Figure 8 | Status (%) of 96 modern dugwells constructed during 2001 to 2009.

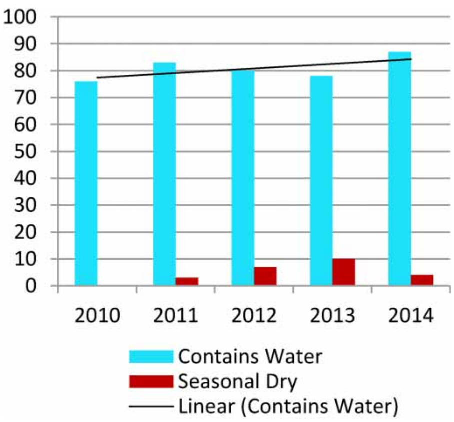

Figure 9 | Status (%) of 172 bi-tech wells constructed during 2010 to 2013.

Table 1 compares wells containing water and wells that dry in the summer season. In 2010, out of 50 modern dugwells, 54 percent contained water and 46 percent were seasonally dry. In the same year, 100 percent of the bi-tech wells contained water; none were dry. In all these five years, the dugwells dried at higher rates than the bi-tech wells; for example, in 2014, 48 percent of 40 modern dugwells were seasonally dry compared to 4 percent of 165 bi-tech wells. Overall, on average over a five-year period, 38 percent of modern dugwells and 5.6 percent of bi-tech wells became dry at some point during the dry season.

Table 1 | Comparing availability of water between modern dugwells and bi-tech wells from summer of 2010 to summer of 2014

Year	2010		2011		2012		2013		2014	
Type of wells	Modern dugwells	Bi-tech wells	Modern dugwells	Bi-tech wells	Modern dugwells	Bi-tech wells	Modern dugwells	Bi-tech wells	Modern dugwells	Bi-tech wells
Contain water	54	100	59	97	67	91	78	89	53	95
Seasonally dry	46	0	41	3	33	9	22	11	48	5

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

Almost half of the modern dugwells eventually became nonfunctional, leading to closure; the remaining half did contain water in the summer season, and by 2014 there was a decreasing trend compared to the bi-tech wells, for which 95 percent contained water.

Pathogenic bacteria: *E. coli* and fecal coliform

Initially, from 2001 to 2009, bacteriological analysis of the newly constructed modern dugwells was done routinely before communities were allowed to use the well water. The water was then continuously treated with Theoline once a week or once every two weeks. Most of the analysis reports found fecal coliform to be 'undetected,' with only a few wells with detected numbers. At the same time, there were no reports of diarrhea related to any of the modern dugwells from the target villages. Nevertheless, bacteriological tests of the newly constructed wells continued to be conducted at random. In January 2011, water from 47 bi-tech wells constructed in 2010 and two in 2009 were analyzed for bacteria (total coliform – a group of closely related bacteria that are generally not harmful to humans – and *E. coli*) at a reputable laboratory in the nearby city of Kolkata. The samples were submitted in duplicate and blind. The method of collection and analysis is described in a previous article published in 2007 (Hira-Smith *et al.* 2007). All the samples showed undetected *E. coli*, while total coliform was absent in 20% of the wells. In August 2011, water from 11 functional sources was selected using computer-generated random numbers from 214 sources comprising both dugwells and bi-tech wells to measure total coliform and *E. coli*. There were samples from 7 modern dugwells and 4 bi-tech wells, all of which had 'undetected' levels of *E. coli*.

In January 2014, water samples were collected in duplicate from two bi-tech wells (PW153 and PW155) constructed in 2010 and from one pond to test for fecal coliform and *E. coli*. All the samples were collected on February 10, 2014, and neither of the wells was treated with disinfectant during the previous 30 days. As per protocol, within six hours of collection, the samples were submitted to two different laboratories: (1) CABC – a laboratory near the target villages of Berachampa, established by UNICEF; (2) Envirocheck in Kolkata as before. The methods of analysis followed by the two laboratories were different but the results were similar. Envirocheck followed the method 9222B (*Standard Methods for the Examination of Water and Wastewater* 1998); CABC followed the multiple tube fermentation method. Total coliform was detected by Envirocheck and not by CABC. CABC tested for and found no fecal coliform, while Envirocheck tested for and found no *E. coli*.

Arsenic

In March 2012 (during the summer season in this region), arsenic was analyzed in 15 of the 112 bi-tech wells. Selection of these sources was done using computer-generated random numbers. Water was collected in 100 ml plastic bottles after washing the bottles with water from the same well. The method used by the Kolkata laboratory to analyze arsenic is *3500* (*Standard Methods for the Examination of Water and Wastewater* 1998). All the samples were collected in duplicate and submitted blind to the laboratory. 87% of these bi-tech wells showed arsenic concentration <50 ppb, and 13% (or two wells) >50ppb; these two wells PW161 and PW166 were kept under observation, since their levels were high at 53.5 ppb and 111.5 ppb respectively.

From 2013 onwards, arsenic has been analyzed in the Project Well local field office by two trained field staff using Wagtech's Visual Color detection kit. The manufacturer product number is WAG-WE10600 (UNICEF 2010). The measuring range (color scale graduation) is: <10, 20–40, 50, 60–80, 100, 100–200, 200–300, 300–400, 400–500, 500 ppb. In 2013, the total water samples were collected from 141 sources during January to August 2013, of which 114 samples were from bi-tech wells and 27 from modern dugwells. 97% of the wells contained arsenic <10 ppb, 2% contained arsenic 10–

doi: 10.2166/wpt.2015.102

40 ppb and 1% (PW246) had arsenic level of 60–80 ppb. PW 246 was tested again on February 2013 and had concentrations <10 ppb.

Annual arsenic measurement was not done in 2014, and in 2015 (Table 2) arsenic analysis using the Wagtech field kit was done on 191 wells in the summer months of March and April. The reports show 96 percent of the wells with arsenic concentration <10 ppb, 3 percent with arsenic concentration 10 to 40 ppb and 1 percent with arsenic more than 40 ppb.

Table 2 | Arsenic concentrations in parts per billion in functional wells in 2013 and 2015

	Bi-tech wells		Percentage		Modern dugwell	
	2013	2015	2013	2015	2013	2015
Total samples	114	163			27	28
< 10	111	156	97	96	26	27
10 to 40	2	5	2	3	1	1
> 40	1	2	1	1	0	0

Of the 15 wells measured in 2012, 8 were also measured in 2013 and 2015 (Table 3) using the Wagtech field kit. There is a decreasing trend of arsenic concentration in three years. In fact, PW166 showed a fourfold reduction in two years.

Table 3 | Arsenic concentrations in parts per billion of wells in 2012, 2013 and 2015

Source	2012	2013	2015
PW118	13	0	<10
PW128	8	<10	<10
PW135	15	0	10 to 20
PW139	25	Na	<10
PW140	36	Na	<10
PW152	9	0	<10
PW161	53.5	0	<10
PW166	111.5	200	50

*na = not available.

DISCUSSION

Dug-cum-bore wells are used for irrigation in many parts of Peninsula India (Singh 2005). The Project Well-designed bi-tech well, based on these dug-cum-bore wells, has been introduced to increase water availability in the summer season. Over eight years (2001 to 2009) of observation of water levels and assessment of having more than 15% of modern dugwells being dry in the summer months, Project Well came up with a well design that overcame this problem while being appropriate for the local conditions of remote Indian villages unsuitable for large construction equipment.

Historically, drinking water from surface water and traditional dugwells was used by people in West Bengal and many parts of India that caused cholera and diarrheal diseases (WHO). These traditional rope-and-bucket dugwells were replaced by tubewells in the sixties to reduce exposure to pathogenic bacteria, but these borewells introduced the new problem of arsenic contamination. Our modified dugwells, and later our bi-tech wells, replaced the rope-and-buckets of traditional dugwells with

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.102

hand pumps, thus reducing the source of contamination. Care is taken in treating the water with a chlorine-based disinfectant weekly. The user community is trained to apply the disinfectant. Some user communities use their own discretion in administering the disinfectant after getting the training. For instance, Theoline was applied to PW153 and PW155 34 days and 28 days prior to the collection of water for bacteriological analysis (and not weekly as recommended by our program), yet *E. coli* and fecal coliform were undetected in these samples. The users of these wells also had no complaints of diarrhea.

Bi-tech wells were introduced in the arsenic-affected areas to reduce the exposure of the people and since then, 97% of these sources supplying water from the unconfined aquifer contain arsenic concentration less than 10 ppb while 1% contains more than 40 ppb. This report is of water collected from different bi-tech wells in different months of the year. Project Well continues to monitor and research the fluctuation in arsenic concentrations of the water in the bi-tech wells during different seasons.

Because some of our modern dugwells were drying during the summer, Project Well introduced bi-tech wells. Our observations from 2010 to 2014 indicated that on average, 38% of the shallow modern dugwells became dry in summer compared to fewer than 5.6% of bi-tech wells; the popularity of the bi-tech wells is growing, since water is available in 95% of the wells during the summer season.

According to the monthly survey record of May 2014, only 5% of the bi-tech wells became dry and 95% contained water. In the driest month, May, the water table falls to approximately 5 m (16 feet) bgl in the target districts of North 24 Parganas and Nadia; the water tables gets recharged by the onset of the monsoon in mid-June and rain falls until mid-October (Mukherjee *et al.* 2007). The annual rainfall in this region is about 150 cm (60 inches), and this amount of rainfall is enough to make water available in the bi-tech wells throughout the year.

A major component of dugwell maintenance is dredging – our modified dugwells average 19 feet deep, and every year during heavy monsoon rains, the pressure of the water pushes 2–3 rings of the dugwell into the mud. As a consequence, many dugwells require dredging after the monsoons. In contrast, the dugwell portion of bi-tech wells is only 15 feet deep and so bi-tech wells do not encounter this problem. This cuts maintenance costs considerably.

Bi-tech wells have a simple design and ongoing maintenance that is easy to adopt and adapt – the skills needed to construct and maintain the wells and the raw materials are available locally, thus enhancing the economy of rural India. These wells provide water to more than 100 persons in some areas and 40 in others. The construction cost (not including training, education and monitoring program) of each bi-tech well is approximately US$500 (INR 30,000 in 2014) and the maintenance cost is approximately US$10 (INR600) annually to purchase Theoline and repair the valve and handle of the hand pump if needed; these maintenance costs are paid for by most of the communities.

CONCLUSION

From the design and construction point of view, bi-tech wells are easily adaptable and feasible, especially in remote areas where transport and delivery of large equipment is difficult. Water is available all year round in more than 96 percent of the bi-tech wells and these wells rarely need to be dredged, making maintenance simple – mainly the regular application of disinfectant to prevent bacterial growth. Random water tests for *E. coli* bacteria have indicated 'undetected' levels, and we have not received any reports of diarrhea from users of our wells. With its low construction costs, easy long-term maintenance, and consistent safe-water output, bi-tech wells are proving an effective water solution in rural India.

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