Groundwater

Methods Note/

Detecting Well Casing Leaks in Bangladesh Using a Salt Spiking Method

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Abstract

We apply fluid-replacement logging in arsenic-contaminated regions of Bangladesh using a low-cost, down-well fluid conductivity logging tool to detect leaks in the cased section of wells. The fluid-conductivity tool is designed for the developing world: it is lightweight and easily transportable, operable by one person, and can be built for minimal cost. The fluid-replacement test identifies leaking casing by comparison of fluid conductivity logs collected before and after spiking the wellbore with a sodium chloride tracer. Here, we present results of fluid-replacement logging tests from both leaking and non-leaking casing from wells in Araihazar and Munshiganj, Bangladesh, and demonstrate that the low-cost tool produces measurements comparable to those obtained with a standard geophysical logging tool. Finally, we suggest well testing procedures and approaches for preventing casing leaks in Bangladesh and other developing countries.

Introduction

Shallow aquifers in Bangladesh often are severely contaminated by arsenic (BGS 2001; van Geen 2003; Ravenscroft et al. 2005; Harvey et al. 2006); therefore, deep groundwater wells have been installed throughout Bangladesh to provide drinking water that meets arsenic safety standards. One concern about deep wells is that the well casing must first pass through the shallow contaminated aquifer before reaching the deep uncontaminated aquifer. A leak in the well casing passing through the shallow aquifer could contaminate the entire well. Additionally, in some regions of Bangladesh, hydraulic heads in shallow aquifers are greater than in the deeper underlying aquifers (BGS 2001; Ashfaque 2007). In the presence of a downward gradient, a leak in the upper casing would create a short-circuit flowpath through the borehole, contaminating the deeper aquifer even in the absence of pumping (Figure 1). A few reports describe deep wells that initially produced water with low levels of arsenic but where the water became increasingly elevated in arsenic over time (van Geen et al. 2007; McArthur et al. 2010). In Bangladesh, older wells have statistically higher arsenic concentrations, which is consistent with the hypothesis that some wells develop leaks over time (McArthur et al. 2004). It is important to determine whether increases in arsenic concentration are caused by casing leaks or by changes in aquifer geochemistry. If an increase in arsenic is due to a leak, the well can be repaired or abandoned. An increase in arsenic levels could also be due to flow down the annulus of the well of an improperly grouted wellbore. In the absence of well casing leakage or flow down the well annulus, increases in arsenic levels may suggest changes in arsenic levels or mobility within the deep aquifer, a result that would raise concern about the long-term sustainability of the deep aquifer to provide safe drinking water.

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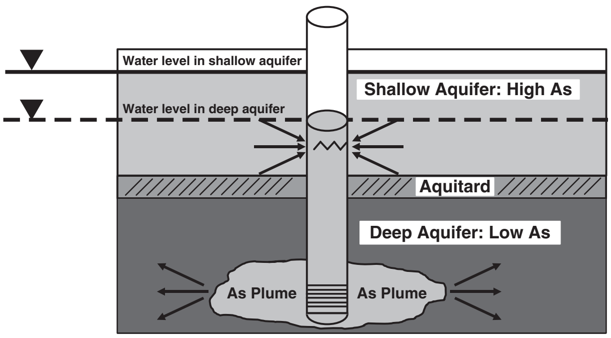

Figure 1. Illustration of a hypothetical leaking well.

Fluid-replacement logging methods using salt tracers or deionized water have been used for decades, primarily for analysis of fractured rock (Tsang and Doughty, 2003). Here, we describe the results of fluid-replacement logging to detect leaks in several wells in Bangladesh. We then describe a low-cost, easily-built, down-well fluid conductivity tool developed for identifying leaking casings in regions where down-well geophysical equipment is unavailable or prohibitively expensive, and show that this leak detection tool produces results similar to those obtained from standard geophysical logging equipment.

Identification of Leaking Casings Using Fluid-Replacement Logging

In the spring of 2011, initial testing of the fluid-replacement logging method to detect casing leakage was conducted in two wells in Araihazar, Bangladesh (Figure 2). In the deeper well, Ara-1, arsenic

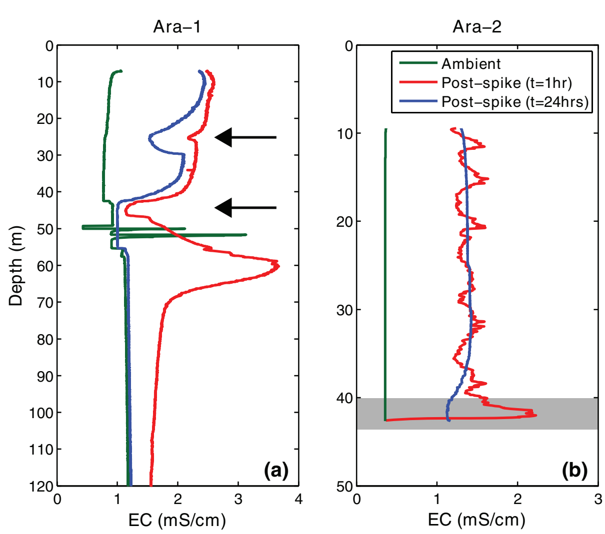

Figure 2. Leak tests from two wells in Araihazar. (a) Fluid conductivity logs on well Ara-1 before, immediately after, and one day after spiking well with salt. Black arrows indicate locations of leak inflow. (b) Fluid conductivity logs on well Ara-2. Ara-1 shows clear indication of leakage while Ara-2 does not. Gray shading indicates screened interval. Screened interval (121 to 124 m depth) was not logged on Ara-1.

concentrations increased dramatically 6 months after well installation, going from 19 ppb (average of 8 samples collected in the 6 months after well installation) to 75 ppb (average of 18 samples collected from 6 to 26 months after installation) (van Geen et al. 2007). In the shallower well, Ara-2, sampled arsenic concentrations are consistently less than 1 ppb.

We collected fluid conductivity logs under ambient conditions; spiked the fluid columns with salt (NaCl) by lowering a salt disc down and back up the well; and collected fluid conductivity logs at 1 and 24 h after spiking the wells. The fluid conductivity logs presented in this section were obtained using a Mount Sopris Instruments, Co., borehole logging system and borehole geophysical fluid conductivity logging tool (BGF). Spiking the well with salt increased the electrical conductivity (EC) of the wellbore water above the ambient values so that we could detect potential inflow of lower conductivity groundwater into the well. Leaks were identified at depths where the logs showed decreases in EC from spiked values toward ambient values with time. We found that a reasonably uniform spike could be obtained if the salt block was lowered down and back up the well at a steady rate. However, achieving a uniform spike is unnecessary because we identify leaks by comparing the 24 h postspike log with the log collected directly (1 h) after spiking.

Inflow of groundwater can be quantified by calculating the fraction of salt from the spike remaining at some time after salt was added:

$$\frac{\text{Mass remaining}}{\text{Mass added}} = \frac{\int \{EC_{PS}(t) - EC_A\}\, dz}{\int \{EC_S - EC_A\}\, dz} \qquad (1)$$

where EC_A is the borehole ambient fluid conductivity at a given depth, EC_S is the borehole fluid conductivity postspike at a given depth, $EC_{PS}(t)$ is the borehole fluid conductivity at time t after the spike at a given depth, and z = depth below water level in the well.

For the fluid-replacement leak-test conducted in well Ara-1, only 40% of the salt mass remained after 24 h, indicating that most of the salt tracer was flushed out of the well by inflow from casing leaks. The logs show leakage points at depths of 25 and 45 m (Figure 2a). The peak in conductivity seen at 60 m depth in the 1 h postspike log is due to the salt disc becoming temporarily stuck at this depth during the spiking procedure. Twenty-four hours after the salt spike, the fluid conductivity in the borehole below 45 m had returned to ambient conditions, indicating that groundwater entering the borehole at 45 m had completely flushed the salt tracer out of the borehole down to the well screen. We calculate a minimum inflow rate of 6.3 L/h, given that the leak flushed at least the wellbore volume from 45 m down to the screen at 120 m (75 m of 2-in ID casing) in a period of 24 h. The log collected 24 h after the spike also shows a substantial decrease in EC starting at 25 m, indicating a leak at this depth.

Results from well Ara-2, using the method described above, provide an example of a well that does not leak

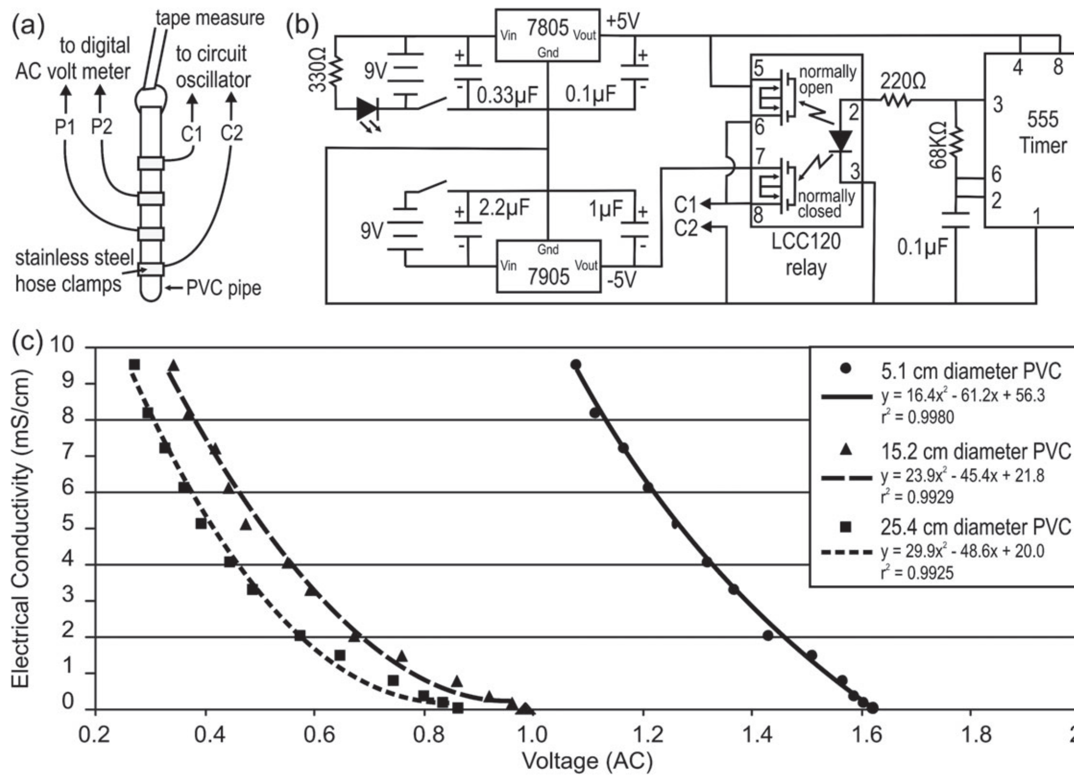

Figure 3. EC-Logger (a) electrode setup, (b) square wave oscillator circuit, and (c) calibration curves for 5.1, 15.2, and 25.4 cm diameter PVC casings.

(Figure 2b). After 24 h, 96% of the salt tracer remained in the borehole. The 24-h postspike log shows no discrete-point reduction in conductivity from inflow (with the exception of the screened interval). The conductivity variation with depth seen in the 1-h postspike log is due to the fact that we did not achieve a perfectly uniform spike. Slight differences between the 1 and 24-h postspike logs are interpreted as the result of diffusion, mixing due to the lowering and raising of the fluid-conductivity tool, and groundwater exchange at the well screen due to lateral flow within the aquifer. In a well that does not leak, the rate of flushing over the screened interval can provide an estimate of lateral flow within the aquifer. However, in a leaking well, water is flushed from the wellbore by both lateral exchanges and vertical displacement due to inflows in the cased section.

Low-Cost Tool for Borehole Casing Leak Detection

Borehole geophysical logging methods are extremely useful for characterizing and monitoring aquifers (e.g., Keys 1990). However, the availability of logging systems in developing countries is limited by their relatively high cost and requirements for vehicles, generators, and specially trained logging operators. To address these limitations, we developed and tested a simple, low-cost, hand-held, down-well fluid conductivity logging tool, EC-Logger, to perform fluid-replacement logging well casing leakage tests (Figure 3). The components for the tool cost about \$100 USD and weigh less than 20 lbs. The system requires two 9 V batteries for power, interfaces with a common electronics multimeter, and can easily be operated by a single person.

The EC-Logger is designed as a 4-electrode resistivity probe. Four stainless steel hose clamps (12.5-mm wide, 29-mm OD), are spaced 3 cm apart, fastened to a weighted polyvinyl chloride (PVC) pipe (27-mm OD, 22-cm long, 650 g) and attached to a 4-wire multiconductor cable to serve as electrodes (Figure 3a). Bipolar power supplies using linear voltage regulated integrated circuits (IC) are connected to a single-pole, double-throw solid state relay (Figure 3b). A 555 Timer IC toggles the relay to generate square waves that switch from +5 V to −5 V at a frequency of approximately 74 Hz. The alternating current (AC) is injected into the two outer electrodes and the potential is read from the two inner electrodes using a digital AC volt meter. Applying an AC waveform prevents polarization and electrolysis on the electrodes. A measuring tape attached to the weighted probe indicates the depth of insertion of the probe in a well. Using a commercial EC meter and different concentrations of KCl solutions, calibration curves relating EC and voltage were made for different casing diameters (Figure 3c).

There are several characteristics of the EC-Logger that the user should be aware of before deploying the tool. The current injection and voltage measurements of the EC-Logger are affected by the configuration of the electrodes. Thus, each tool requires calibration after it is constructed and recalibration following any adjustment

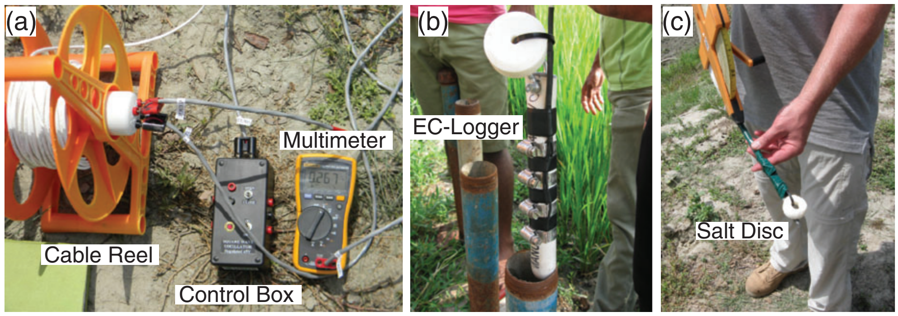

Figure 4. (a) EC-Logger wire reel connected to control box and multimeter. (b) EC-Logger probe being lowered into a well. (c) Salt disc attached to a weighted line for spiking wells.

of the electrode spacing. The electric field generated by the electrodes is affected by the distance to a non-conducting boundary (i.e., PVC casing) with the electric field becoming more compressed and the current flow increasing as the distance to the boundary decreases. This characteristic of the EC-Logger requires that calibration curves are made for different pipe diameters. The tool measures only EC and does not compensate for fluid temperature; if the user wants to temperature correct the data, an independent measurement of the water temperature must be made. The EC-Logger can be deployed in wells with an inner diameter of 2 in or greater.

The field procedure for conducting a casing leak-test with the EC-Logger is as follows:

(1) Power on the EC-Logger and connect the sonde to a fiberglass or plastic tape measure. Once the unit is on and connected to a multimeter it is ready for use (Figure 4a).
(2) Acquire an ambient fluid conductivity log by lowering the EC-Logger sonde down the well, stopping at evenly spaced depth intervals (0.1- to 0.25-m steps) to take readings. If possible, leave the sonde at the bottom of the well (Figure 4b).
(3) Spike the borehole fluid column with salt tracer by lowering a block of salt attached to a weighted line down and then back up the well, pumping a salt solution into the well sufficient to completely replace the borehole fluid column, or by some other equivalent means (Figure 4c).
(4) Immediately after spiking the well, lower the EC-Logger sonde to the bottom of the well (if the sonde was not left at the bottom of the well in step[2]) and acquire a postspike log collecting data on the way up the well.
(5) Collect repeat postspike logs. To the extent possible, allow sufficient time between the down and up logs for substantial changes to be observed between logging runs.

Details on the construction and use of EC-Logger can be obtained from http://water.usgs.gov/ogw/bgas/ec-logger/. The data collected following this procedure are analyzed to identify leaks using the techniques described in the previous section.

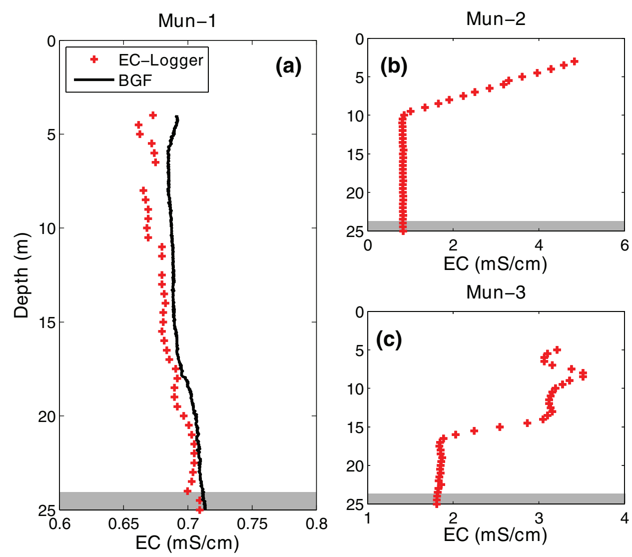

Figure 5. Demonstration of EC-Logger in Munshiganj. (a) BGF and EC-Logger fluid conductivity logs on well Mun-1. (b) EC-Logger fluid conductivity log on partially spiked well Mun-2. (c) EC-Logger fluid conductivity log on partially spiked well Mun-3. Grey shading indicates screened interval.

Comparison of Data From EC-Logger and Standard Borehole Geophysical Fluid Logging

In the spring of 2012, we conducted fluid-replacement logging tests using the EC-Logger tool and a standard BGF in three wells at a field site in Munshiganj, Bangladesh (Figure 5). We were unable to return to Araihazar to test the EC-Logger on a known leaking well. However, our tests in Munshiganj reveal that the EC-Logger can be used effectively in fluid-replacement testing for the identification of casing leaks. Voltage values for the EC-Logger method were converted to EC.

Figure 5a shows successive EC-Logger and BGF conductivity logs collected in well Mun-1. EC-Logger results are in good agreement with the BGF logs obtained by the standard borehole logging system. The small differences between the two datasets are likely a result of the lower spatial resolution of the EC-Logger tool.

The ability of the EC-Logger to detect zones of contrasting fluid conductivity is shown in Figures 5b and 5c. Fluid conductivity logs collected in wells Mun-2 and Mun-3, which were spiked with a salt tracer to depths of 9 m and 15 m, respectively, and logged within 20 min, clearly capture the upper spiked regions and lower unspiked intervals of the boreholes.

Although we were not able to return to Araihazar to test the EC-Logger on the previously tested wells known to have discrete leaks, the results from Munshiganj demonstrate close agreement between the simple EC-Logger and standard geophysical logging method, suggesting that use of the EC-Logger to perform fluid-replacement logging tests will prove an effective, inexpensive method for detecting casing leaks.

Discussion

In Bangladesh, well casings are commonly constructed by connecting 20-ft sections of 1.5-in or 2-in inner diameter PVC pipe that have not been factory jointed. Instead of using threaded joints or couplings, a common practice is to join sections of PVC by flame-softening the end of one section of pipe so that the next section can be forced into it creating a flared joint. In our experience, PVC primer is not used along with the PVC glue applied to the joining pipe ends. Although we cannot cite a specific investigation of casing leaks directly resulting from these practices, the use of PVC primer and glue, and threaded or factory manufactured coupled joints, while more expensive, would undoubtedly reduce the risk of leaks.

Leaks through the casing of deep wells that provide safe water in Bangladesh may contaminate the well because these wells commonly pass through shallow arsenic-contaminated aquifers with heads that are higher than those of the deeper uncontaminated aquifers. Our test results show that this was the case for well Ara-1 (referred to as CW44 in van Geen et al. 2007). Wells at the Araihazar field site have been extensively monitored for up to 5 years (van Geen et al. 2007). This specific example of arsenic increasing in a leaking well suggests that some or all of the observed changes in deep aquifer arsenic levels in this region may result from inadequate well construction procedures. Testing of a subset of deep wells across Bangladesh could be performed to assess the prevalence of leaks. Use of the low-cost tool we developed and the simple fluid-replacement methodology we have demonstrated could reduce the cost of such a project compared to use of conventional methods.

Standard well sampling techniques could result in a failure to identify arsenic contamination from casing leaks. For example, the standard practice of purging wells prior to sampling could remove the contaminated water from the wellbore if the amount of well leakage is small compared to lateral inflow from the screen. For this reason, a sample should be collected prior to purging the well to characterize the water used for drinking.

The arsenic concentrations that a user is exposed to can be affected by well usage patterns. Given that domestic wells are pumped more during the daytime, leaking wells may pose a greater risk in the early morning. During the night, inflow from a shallow leak in a deep well may fill the wellbore with contaminated water, so that the first user in the morning gets the most contaminated water resulting from a leak. On the other hand, if a leak is vigorous enough to flow down the well and out the screen to contaminate the aquifer, the leak could pose a risk throughout the day as the contaminated plume is drawn back into the well.

In areas where changes in the deep groundwater quality do not appear to be the result of compromised well casing, further investigation should be considered to determine the root cause of the changes. Other possible causes for increases in arsenic include, but are not limited to, flow down the well annulus, contaminated water from the shallow aquifer being drawn into the deep aquifer, or geochemical shifts in the deep aquifer that result in the mobilization of arsenic.

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