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MINIATURIZATION OF THE FLOWING FLUID ELECTRIC CONDUCTIVITY LOGGING TECHNIQUE

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ABSTRACT

An understanding of both the hydraulic properties of the aquifer and the depth distribution of salts is critical for evaluating the potential of groundwater for conjunctive water use and for maintaining suitable groundwater quality in agricultural regions where groundwater is used extensively for irrigation and drinking water. The electrical conductivity profiles recorded in a well using the flowing fluid electric conductivity logging (FEC logging) method can be analyzed to estimate interval specific hydraulic conductivity and estimates of the salinity concentration with depth. However, irrigation wells that are common in agricultural regions have limited access into them because these wells are still in operation, and the traditional equipment used for FEC logging cannot fit through the small access pipe intersecting the well. A modified, miniaturized FEC logging technique was developed such that this logging method could be used in wells with limited access. In addition, a new method for injecting water over the entire screened interval of the well was developed to reduce the time required to perform FEC logging. Results of FEC logging using the new methodology and miniaturized system in two irrigation wells are also summarized.

INTRODUCTION

In regions where the salinity of the groundwater varies considerably with depth, such as the Central Valley of California, an understanding of both the hydraulic properties of the aquifer and the depth distribution of salts is critical for evaluating the potential of aquifers for conjunctive water use. Groundwater is also used extensively for irrigation in agricultural regions and maintaining suitable groundwater quality levels is becoming an increasing concern. The electrical conductivity (EC) profiles recorded in a well using the flowing fluid electric conductivity logging (FEC logging) method can be analyzed to estimate interval specific hydraulic conductivity and estimates of the salinity concentration with depth (e.g., Tsang and Doughty, 2003; Doughty and Tsang, 2005).

As described by Tsang and Doughty (2003), the flowing FEC logging method involves first replacing the wellbore water by de-ionized water or water of a constant salinity distinctly different from that of the formation water. This is done by injecting de-ionized water down a tube to the bottom of the well, while simultaneously pumping from the top of the well, until the EC of the water pumped out of the well stabilizes at a low value. Next, the pumps are turned off and the well is pumped only from the top at a constant low flow rate, while an electrical conductivity probe is lowered into the borehole to record the EC as a function of depth and time.

Although the FEC logging method has been successfully conducted over the past 15 years (e.g., Tsang et al, 1990; Kelly et al., 1991; Pedler et al., 1992; Bauer and LoCoco, 1996; Doughty et al., 2005), the method has generally only been conducted in easily-accessible vertical wells with diameters ranging between 5 to 15 cm. These studies were performed on wells that were not actively producing water with permanently installed well pumps and motors. Existing irrigation wells can provide valuable information on aquifer properties and the vertical salinity distribution. A drawback of using existing wells is that the accessibility into them is limited because the well pumping equipment blocks access to traditional probes used for FEC logging. Access into these wells can only be achieved through a 3.8 cm diameter metal pipe intersecting the well at approximately a 45° angle (Figure 1). The restricted access also limits the size of piping used to inject water for FEC logging. The diameter of irrigation well casing encountered during this study was large, typically around 46 cm, so the traditional method of injecting water at a single point to replace the water in the casing was not practical with a small diameter injection pipe.

Devising a method where FEC logging can be used in irrigation wells with limited access and large diameters is important since there are thousands of wells in agricultural regions that could potentially be logged to enhance the understanding of the hydrogeology of these regions. To facilitate logging these wells, a modified and miniaturized FEC logging technique was developed and tested in irrigation wells located in the San Joaquin Valley, the southern portion of the Central Valley of California. This technical note describes novel methodology and equipment for performing FEC logging on actively-pumped irrigation wells with limited accessibility.

METHODS

The probes typically used to perform FEC logging have a 3.8 cm diameter and have an inflexible 1.0 - 2.0 m long section. A probe of this size would not fit into most well access pipes and could not bend around the lip where the well casing and access pipe intersect. For our study, a small electrical conductivity probe manufactured by Campbell Scientific (Logan, UT) was used that had a cross-sectional area of 2.5 x 1.9 cm and was 8.9 cm long. We attached to the probe five stainless steel weights that had a 2.5 cm diameter and were 5.0 cm long to reduce the buoyancy of the probe. The probe depth was measured using a depth encoder, which is a device that detects depth measurements and converts them to electrical signals for input into data acquisition systems.

During traditional FEC logging, constant salinity water with salinity lower than the existing wellbore water is injected at the bottom of the well screen simultaneously as the wellbore water is extracted from the top of the wellbore. The less dense, lower salinity water should theoretically move up the wellbore as it displaces the existing water. In an unconsolidated formation, some of the injected water is likely to enter the formation over time, with more water entering the bottom of the formation where the water is injected. Injection of water into the irrigation wells with limited access is a challenge since the small diameter access pipe (3.8 cm) limits the diameter of tubing that can be used in the well. In addition, both the injection and extraction hose must simultaneously fit through the pipe opening. FEC logging is typically performed in wells with diameters in range from 6 - 15 cm. The diameter of the irrigation well casing used in this study is nearly 46 cm, so it would take a long time to replace the borehole water using tubing with a small diameter and a single injection point.

Because replacing the existing well water using a small diameter tube is difficult in these large diameter wells with limited access, we developed a new technique of injecting water using tubing with emitters to provide nearly uniform injection over the length of the well screen. Emitters were originally developed for drip irrigation in agricultural fields, but they have not been used to inject water into wells. Because of the pressure drop along the length of the tubing, pressure-compensating emitters were used to provide a uniform injection rate. The emitters were inserted into 1.9 cm diameter reinforced PVC tubing every 0.3 m over a length of 24 m beginning at the bottom of the hose. Above the 24 m interval, the emitters were spaced at 0.6 m intervals for a total of nearly 39 m of hose with emitters. The total length of the hose was around 90 m. The emitters are rated at 12.5 L/hr for pressures between 10-50 psi, and we verified that the flow rate remained nearly constant as the pressure changed. The emitters maintain a constant flow rate with a flexible membrane that becomes compressed as the pressure increases. A constant flow rate is maintained because the permeability of the membrane decreases with increasing pressure. Our new injection method reduces the time of well water replacement compared to the traditional, single point injection method since the injection occurs over the screened interval and mixes with the existing water over that interval. The existing well water does not have to be entirely replaced as with the single point injection method because FEC logging still works as long as the low salinity water becomes well-mixed with the existing well water and the resulting water salinity has enough contrast with the formation EC.

During the water-replacement part of our well logging tests, constant salinity water with an electrical conductivity between 0 - 500 mS/cm was injected into the wellbore via emitters while the wellbore water was simultaneously extracted from the top. Centrifugal pumps were used to inject and extract water, and the extraction and injection hose had a 1.9 cm diameter. A schematic of our experimental set-up is shown in Figure 1. The results of two tests are presented in this paper. In the first test, the extracted well water was run through de-ionizing filters, and the de-ionized water was then subsequently reinjected into the well. In the second test, water for injection was supplied from a water truck containing water with a conductivity of 500 mS/cm. After the wellbore water was replaced by the de-ionized or constant salinity water, the electrical conductivity (EC) in the well was recorded over time as the water was extracted from the top of the well at a constant rate.

RESULTS

This section presents the results of two tests conducted in irrigation wells in the Central Valley of California (near Los Banos, CA). The goal of these tests was to demonstrate that the modified, miniaturized logging system we developed could be used to conduct FEC logging in the large-diameter irrigation wells. One test was conducted in an abandoned irrigation well that was open at the top because the pump and motor housing had been removed and the other one was conducted in a well with limited access. A small borehole camera was sent down the well to measure the water table, screened intervals, and well depth. Analysis of the FEC profiles presented in this section will be conducted in future work to determine the location, inflow rate, and salinity of the inflow points.

FEC Logging in an Open Irrigation Well

The modified FEC technique and equipment were tested in an open irrigation well with screens that began at 37 m below ground surface and continued to the bottom of the well which was approximately at 68 m. The water table in this well was around 8 m below ground surface. De-ionizing filters were used to reduce the salinity of the well water that was extracted. The water extracted from a depth of 9 m was run through the filters and then the de-ionized water was injected into the well via emitters distributed over a depth range of 29 to 68 m. The water was extracted/injected at a rate of 13.6 L/min over a period of 5 hours. Because this was an open well, we were able to send the EC probe into the well while both hoses were in it to monitor the change in EC over time as the de-ionized water was injected. After about an hour, we began to observe a decrease in the EC over the entire screened interval and the EC continued to decrease over time, indicating that the method of injecting water using the small diameter tubing with the emitters was effective in this large diameter well. The EC across the diameter of the well was measured at a particular depth and only small variations in the EC were measured indicating that the de-ionized water had become well-mixed with the existing well water.

After a five hour period of replacing the wellbore water, the injection pump was shut off and only the extraction pump was on at a rate of 18.9 L/min, and the EC profile in the well was logged for the next 3 hours. Figure 2 presents the initial EC profile in the well before water was extracted/injected and the subsequent hourly EC profiles after the water replacement had ceased and water was only extracted. Over the screened interval, the initial EC profile is nearly uniform at 1.35 mS/cm except for a peak near the top of the well screen between 37 to 40 m. After injecting the de-ionized water, the EC decreases to around 0.6 mS/cm between 50 and 67 m and then increases to 0.95 mS/cm between 43 and 50 m. The peak present in the initial profile was still there after the de-ionized water was injected, indicating that flow into the well at that location is higher than in the rest of the well. The peak observed at the top of the well screen propagates up the wellbore over time. Below a depth of 43 m, the FEC profile propagates downward with time most likely because of buoyancy flow.

FEC Logging in a Limited Access Irrigation Well

The miniaturized FEC logging method was also tested in an irrigation well with limited access. The screens in this well began at 35 m and continued to the bottom of the well which was approximately at 48.5 m. In some of the irrigation wells, including the well we logged, a layer of oil was present above the water. The oil is used for lubricating the pump motor and drive shaft, but the excess oil drips into the well and accumulates on the surface of the water. In this well, the top of the oil layer began about 2.3 m below the top of the access pipe intersecting the well. The bottom of the oil layer (which corresponds to the top of the water column) was located around 3.2 m below the access pipe, giving an oil layer that was 0.9 m thick. In order to keep the inside of the conductivity probe where the electrodes are located from contacting the oil layer while the probe was lowered into the well, the openings to the electrodes on the probe were temporarily sealed using foam earplugs and a string was attached to the earplugs to pull them off once the probe got past the oil layer. We verified that the oil did not enter into the probe while it was lowered through the oil layer by monitoring the electrical conductivity, which remained around zero until the earplugs were removed.

We successfully inserted both the injection and extraction tubing through the small access pipe. Water was injected at 22.8 L/min via emitters at depths of 19.5 to 48.5 m and extracted at 16.7 L/min from a depth of 5 m and the pumps were left on for 4 hours. Because the injection water for this test was supplied from a water truck, we were able to inject water at a slightly higher rate than it was extracted to ensure that the formation water was not pulled into the well. In a well with limited access, the EC probe cannot fit through the access pipe if the extraction and injection hose are both already in the well. Therefore, the injection tubing was removed from the well after the pumps were shut off so that the EC probe could be lowered into the well. The EC profile was logged immediately after the lower salinity water had been injected. The extraction pump was turned back on at a rate of 11.4 L/min once the initial log was completed. The initial EC profile before the well water was replaced was not logged for this particular well.

Figure 3 presents the FEC logs at different times. The initial log after replacement of the well water was fairly uniform over the screened interval and had an average EC of 0.95 mS/cm. The small-scale variability in the EC measurements was because of interference with the reel motor and the EC probe which was later corrected by modifying the datalogger program. The EC profile was measured hourly and revealed that the EC increased faster towards the bottom of the well compared to the top of the screened interval. This indicates that the formation at the bottom of the screened interval is more permeable or the EC of the water at the bottom of the well is higher. The observed change in EC over time also demonstrates that the water replacement method was successful in lowering the EC of the water in the wellbore enough to provide contrast with the formation EC.

SUMMARY

These results presented in this note demonstrate that the miniaturized logging system and new method of injecting water can be successfully used to conduct FEC logging in irrigation wells with large diameters and limited access. The use of tubing with emitters reduces the time needed to replace the wellbore water over the screened interval of larger diameter irrigation wells, and the equipment required for the logging is easily transportable and can be developed at a relatively low cost. The miniaturization of the logging equipment and the new method of dispersing water over the well screen also allows hydrogeology studies to be performed on an increased number of existing wells which reduces the need to expend funds on other methods of accessing irrigation wells (e.g. temporarily removing the pump motors) or installing new monitoring wells. An additional use for this method could be for wells with obstructions in slightly off-vertical casing or bends in small-diameter well casing caused by improper installation. A long inflexible probe cannot always move around obstructions and bends whereas the probe/weight configuration used in our study would increase the accessibility into these wells. The miniaturized logging system is a powerful tool for obtaining information on water quality and aquifer properties that would otherwise not be possible for wells that have limited accessibility.

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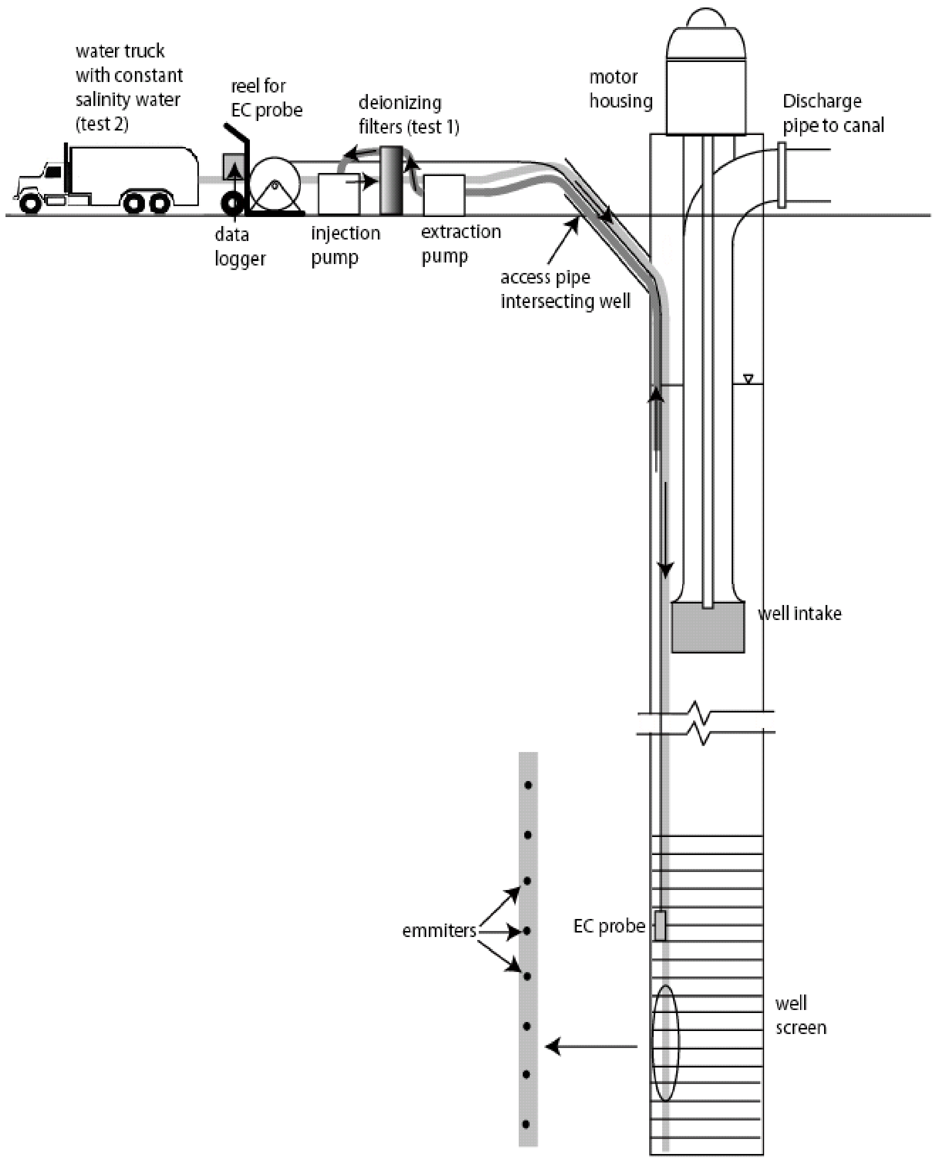

Figure 1. Schematic of the modified FEC logging apparatus for a large-diameter irrigation well with limited access (not to scale).

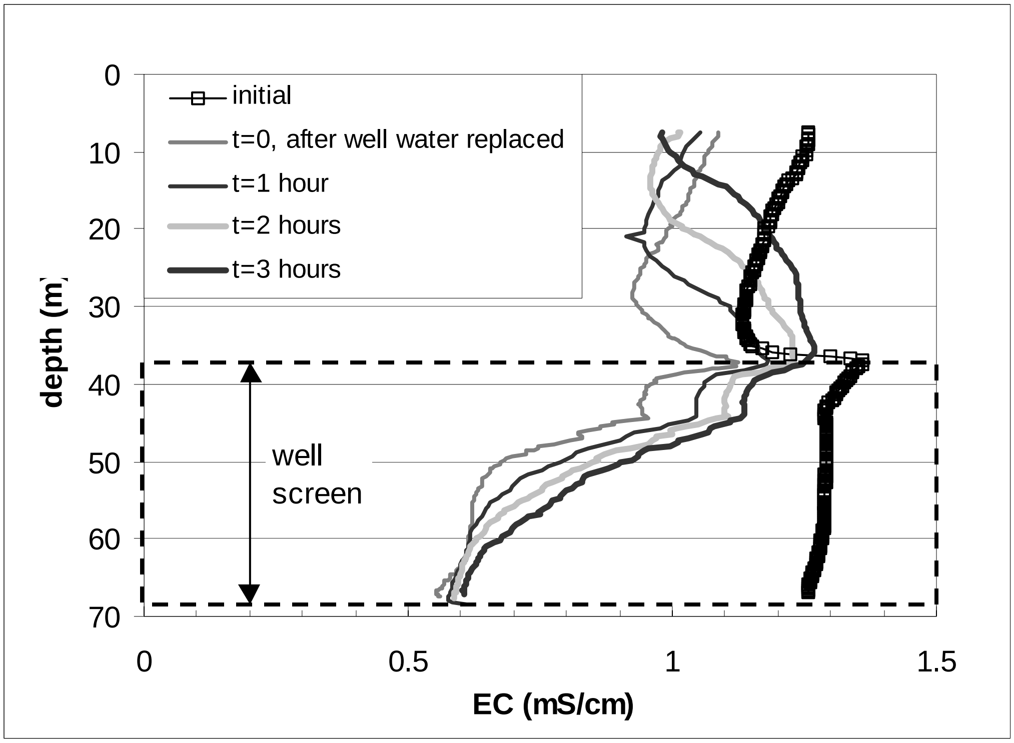

Figure 2. FEC profile prior to water replacement and hourly profiles after the well water had been replaced in an open well.

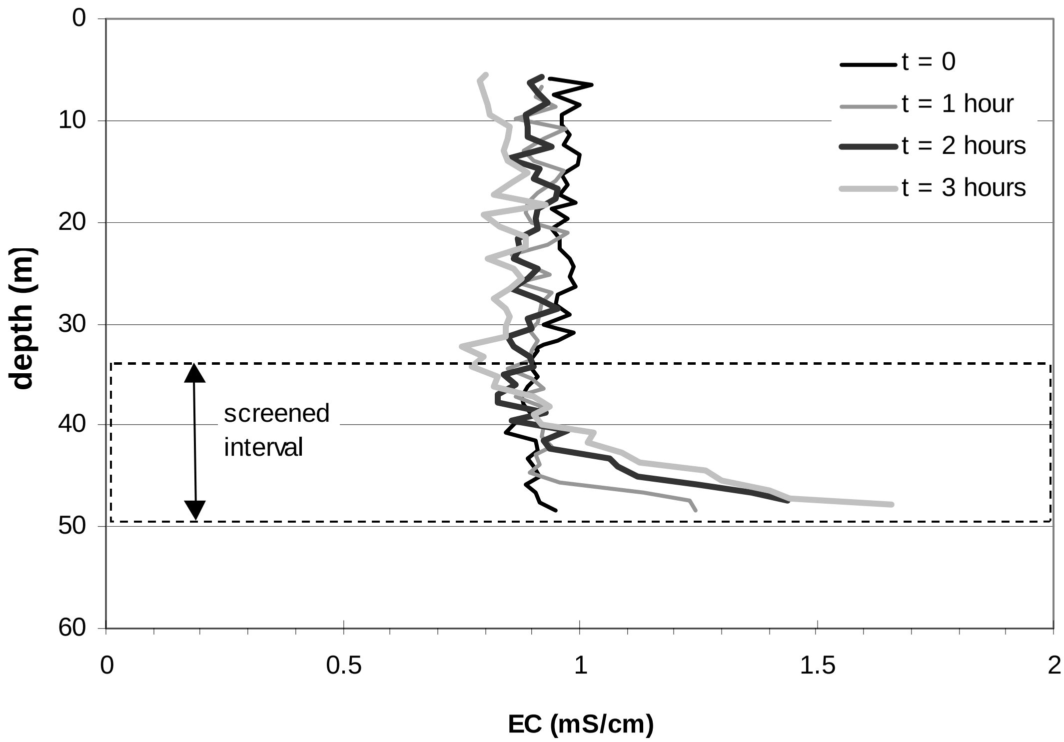

Figure 3. Hourly FEC profiles after the well water had been replaced in a well with limited access.