Self-potential (SP) response to seawater intrusion in coastal aquifers

D.J. MacAllister[1, 2], M.D. Jackson[1], A.P. Butler[2] and J. Vinogradov[1]
[1]Department of Earth Science and Engineering, Imperial College London, SW7 6AS
[2]Department of Civil and Environmental Engineering, Imperial College London, SW7 6AS

ABSTRACT

Seawater intrusion is a major threat to the sustainability of coastal water supplies. Long-term self-potential (SP) monitoring has been conducted on the South-Coast of the UK in the chalk aquifer, in order to test its application for remote detection of the saline front. Tidal SP fluctuations of c. 2mV have been observed. We attribute tidal SP fluctuations to the exclusion potential, caused by the salinity gradient and the movement of the saline front in the chalk matrix. Furthermore we observe a systematic increase in SP beginning 5 days prior to saline breakthrough; with a maximum magnitude of 300μV at the base of the borehole. We attribute this to the diffusion potential, generated by the local movement of saline water through a fracture logged close to the location of the maximum SP change. These results suggest, for the first time, that SP can provide early warning of seawater intrusion.

INTRODUCTION

Management of abstraction from coastal aquifers is of critical importance to ensure sufficient and sustainable water supplies in coastal areas, but remains a significant challenge. A key reason is that monitoring data, required for such management, are limited (Post, 2005). The most common monitoring strategy is to measure the fluid electrical conductivity (FEC) of the water in monitoring and/or abstraction boreholes. However, spatial resolution is limited by the number and distribution of monitoring boreholes. Measurements at abstraction boreholes can detect the saline front only when it arrives. Therefore monitoring techniques are required that are cheap and non-intrusive, but allow remote detection of saline intrusion.

The self-potential (SP) method comprises the passive measurement of electrical potential at the ground surface and in boreholes. The SP arises to maintain overall electro-neutrality when a separation of electrical charge occurs in response to natural or induced gradients in thermodynamic potential, such as fluid potential (head), and chemical potential (concentration) (Revil, 1999). SP signals are therefore likely in coastal aquifers because gradients in head and concentration are both present. There is evidence from oil and gas reservoir studies that an encroaching saline front may generate a measurable SP signal at an abstraction borehole prior to breakthrough (e.g. Jackson et al., 2012). We test this by conducting a 6 month monitoring program in a borehole located in the coastal UK Chalk aquifer, supplemented by laboratory experiments. We investigate SP signals associated with natural variations in head, and in the location of the saline wedge.

METHOD

Field site

The field site was located near Brighton on the south coast of the UK. The data were acquired from the Saltdean monitoring borehole approximately 1.7km from the coast. This borehole is known to experience seasonally elevated salinity levels to c. 15,000μS/cm (Jones and Robins, 1999). The aquifer unit penetrated by the borehole is the Upper Cretaceous Seaford Chalk, which is the main regional aquifer. The Chalk is a dual porosity aquifer, with matrix porosity in the range 35-47%, but with fractures acting as the primary flowpaths, yielding transmissivities of about 500m^2/day (MacDonald and Allen, 2001) .

Borehole data acquisition

The Saltdean borehole has a water column of c. 30m, is c. 60m deep, has a diameter of c. 1m and is open hole below 15mAOD. The ground level is 30.19mAOD. The borehole monitoring tool, logged with a 5 minute sampling rate, comprised 14 non-polarising electrodes with 2m spacing. The water table fluctuates around 1.01mAOD depending on the tide and in-land freshwater head. The shallowest electrode is located at -0.81mAOD and the deepest electrode is located at -26.81mAOD. Three probes measuring conductivity (FEC), temperature (T) and pressure (P) were also installed at -2.81mAOD, -8.81mAOD and -26.81mAOD. An additional electrode was installed at the surface as a reference electrode.

RESULTS

Borehole monitoring data - referenced against the surface electrode

The head gradually decreased during the monitoring period, and there are fluctuations of varying frequencies around the long-term trend (Fig 1a). Analysis of the head data in the frequency domain using a Fast Fourier Transform (FFT) reveals that the data has semi-diurnal, diurnal and fortnightly frequencies. Consequently, the head data are consistent with semi-diurnal, diurnal, and spring-neap tidal cycles, superimposed on a gradual decrease in head caused by low rainfall during the monitoring period. The variation in head over a semi-diurnal tidal cycle is typically c. 50cm. The FEC in the borehole (Fig 1a) remains low throughout the first three months of the monitoring program, although fluctuating with tides around a mean value of 630µS/cm. Saline water was observed to enter the borehole in late August 2013, reaching a maximum conductivity of 4,000µs/cm by mid-September.

The SP data (Fig 1b) shows no obvious long-term trend, but there are fluctuations of varying frequencies, similar to the head data. A FFT of the SP data reveals semi-diurnal and diurnal frequencies. The SP is therefore recording the tidal signature. The variation in SP over a tidal cycle is c. 2mV, and is anti-correlated with head. The SP also becomes less positive with depth, with a range of c. 5mV from the top to the base of the borehole (Fig 1b).

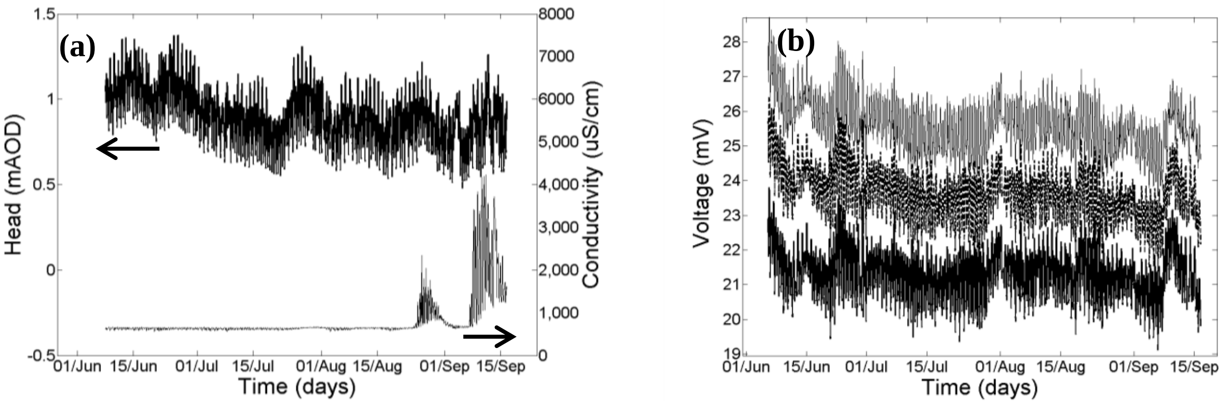

Figure 1 (a) Head and conductivity measured in the borehole. (b) The voltage measured in the borehole at -26.81mAOD, -14.81mAOD and -2.81mAOD. There is a gradient with depth with the voltage decreasing at the shallower electrodes.

Borehole electrode response to temperature and salinity variations

The SP clearly exhibits a tidal signature. However, the borehole FEC and temperature also display tidal signatures, and variations in both of these can affect the electrode response. Temperature fluctuations contribute a maximum of c. 150µV. Conductivity fluctuation induce a voltage change of c. 50µV. Hence it is clear that the conductivity and temperature variations in the borehole do not significantly affect the performance of the electrodes, suggesting that the tidal SP response is caused by sources within the aquifer.

Borehole monitoring data - referenced against a borehole electrode

The SP referenced against the surface electrode does not yield any obvious long-term trend, so we analysed the difference in voltages measured in the borehole to examine if there is evidence of the SP responding to the long-term movement of the saline water in the aquifer prior to breakthrough (Fig 2). To do this, we reference the borehole electrode voltages against the borehole electrode at -2.81mAOD which remained in a stable low conductivity environment throughout the monitoring period (Fig 2a). After filtering out the semi-diurnal SP we observe a systematic increase in the SP starting c. 5 days before breakthrough (Fig 2b). This is observed throughout the array, but the magnitude decreases up the borehole, from c. 300µV at -26.81mAOD (Fig 2b) to c. 50µV at -4.81mAOD.

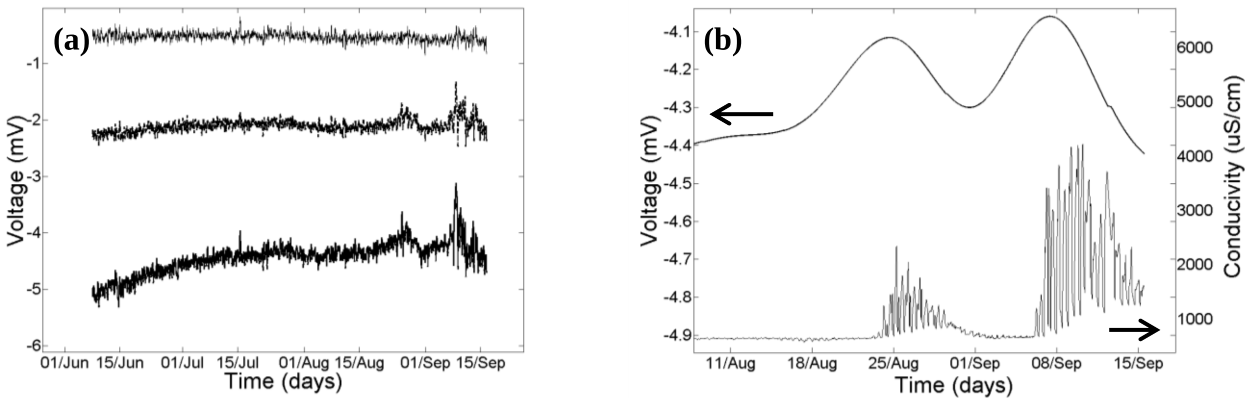

Figure 2 (a) Voltage at -26.81mAOD, -14.81mAOD and -4.81mAOD and referenced against the electrode at -2.81mAOD. (b) Filtered voltage and FEC at -26.81mAOD showing an increase in voltage prior to breakthrough of saline water.

DISCUSSION

Tidal SP and vertical gradient

There are two likely SP source mechanisms for the c. 2mV tidal response. The first is the streaming potential, which arises as a result of head gradients. The second is the exclusion-diffusion potential arising as a result of the concentration gradient (e.g. Revil, 1999).

Laboratory measurements of the streaming potential coupling coefficient (Jaafar et al., 2009) yield values of -521µV/mH_2O and -17µV/mH_2O for samples of Seaford Chalk saturated with groundwater and seawater, respectively. Consequently, we conclude that a streaming potential source cannot be solely responsible for observed tidal SP response. Indeed, the laboratory value of the streaming potential coupling coefficient suggests that the c. 50cm tidal head variations contribute only c. 260µV of the observed 2mV SP response. The exclusion potential arising in response to the concentration gradient associated with saline intrusion is the most likely SP source mechanism. To date, no measurements are available of the exclusion potential in chalk. However, the negative surface charge interpreted from streaming potential measurements is consistent with exclusion of negative ions from the rock pore space and an excess of positive charge migrating down the concentration gradient (Revil, 1999). Thus, on a regional scale the movement of the saline water through the matrix generates an exclusion potential. The SP becomes less positive as the saline front approaches the monitoring location, which explains why the SP is anti-correlated with head, and may also explain the 5mV gradient: the saline front is closer to the base of the borehole.

Seasonal SP variations with borehole electrode referencing

The SP is observed to become more positive c. 5 days prior to saline breakthrough, when referenced against the borehole electrode. There is evidence that the saline water enters the borehole through a fracture at the base (Jones and Robins, 1999). We suggest that the diffusion potential (opposite sign to the exclusion potential) is the dominant SP source within the fractures on a local scale. This explains the positive change in voltage observed prior to saline breakthrough. This suggests that the change in voltage is related to the position of the saline front. However further work, most likely constrained inversion, is required to estimate the position of the front relative to the borehole and how changes in voltage are related to its position over time. It is clear, however, that SP appears to systematically change pre-breakthrough providing early (c. 5 days) warning of saline intrusion.

CONCLUSIONS

A 6 month program to measure SP in a monitoring borehole in the UK south-coast Chalk aquifer has revealed a c. 2mV tidal signature, consistent with the observed variations in head. The magnitude of the tidal SP response cannot be explained solely by streaming potentials. Instead, we argue that the SP measured at the borehole primarily reflects the exclusion potential established across the salinity front in the matrix. Furthermore a systematic increase in SP prior to saline breakthrough appears to be consistent with a local diffusion potential in the fractures. The increase in SP appears to provide early warning of the advancing saline front c. 5 days before breakthrough. Our results provide the first field evidence that borehole SP measurements can be used to remotely monitor saline intrusion.

REFERENCS

Jaafar, M.Z., Vinogradov, J. and Jackson, M.D., 2009. Measurement of streaming potential coupling coefficient in sandstones saturated with high salinity NaCl brine. *Geophysical Research Letters,* 36**,** L21306, doi:10.1029/2009GL040549.

Jackson, M.D., Gulamali, M.Y., Leinov, E., Saunders, J.H. and Vinogradov, J., 2012. Spontaneous Potentials in Hydrocarbon Reservoirs During Waterflooding: Application to Water-Front Monitoring. *SPE Journal,* 17**,** 53-69.

Jones, H.K. and Robins, N.S., 1999. The Chalk Aquifer of the South Downs. *British Geological Survey,* Keyworth, Nottingham.

MacDonald, A.M. and Allen, D.J., 2001. Aquifer properties of the Chalk of England. *Quarterly Journal of Engineering Geology and Hydrogeology,* 34**,** 371-384.

Post, V.E.A., 2005. Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? *Hydrogeology Journal,* 13**,** 120-123.

Revil, A., 1999. Ionic Diffusivity Electrical Conductivity Membrane and Thermoelectric Potentials in Colloids and Granular Porous Media: A Unified Model. *Journal of Colloid and Interface Science,* 212**,** 503-522.

Contact Information: Donald John MacAllister, Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, United Kingdom. E-mail: d.macallister11@imperial.ac. uk