Monitoring of a tracer experiment with electrical resistivity at Haslemoen, Hedmark county, Norway

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Introduction

Studies have shown that surface resistivity measurements can be used to monitor groundwater flow. The data have been used in determining various parameters of importance to hydrogeologists, such as natural groundwater flow directions and bulk groundwater velocities (White 1988, Karous et al. 1993), and the direction of maximum transmissivity (Bevc & Morrison 1991). The method involves injection of a conductive tracer into an aquifer, and monitoring the tracer movement over time with surface electrodes.

The opportunity unexpectedly arose to test low-volume injection of a conductive tracer at Haslemoen in the county of Hedmark. The experiment was part of a tracer test conducted by the Norwegian Water Resources and Energy Administration (NVE). The purpose of the tracer test from NVE's standpoint was to optimise parameters for future tracer studies and not to conduct a geophysical experiment. Therefore, from a geophysical point of view, the test was not optimum. However, as a test of the resistivity monitoring method, the results are useful.

Site description

In the test area, the sediment thickness is about 30 m. For the purposes of this experiment, the sediments of the upper 10 m, where the injection occurs, are of greatest importance. This section consists predominantly of a medium-grained sand interpreted to have been deposited by a braided river system (Riis 1992). From Schlumberger vertical electrical soundings, the resistivity of this unit is estimated to be 8800 Ωm above the groundwater table and 2800 Ωm below (Morris et al. 1993).

At the time and location of the experiment, the depth to the groundwater table was approximately 2.5 m. The groundwater table inclines to the south in the area with a gradient of approximately 3 m/km. Permeability of the aquifer in the test area ranges from around 1.1×10^{-2} cm/s to 5.8×10^{-2} cm/s (Nordal 1986).

Method

Electrode Configuration

A charged potential or mise-à-la-masse configuration was used to monitor saltwater movement. The metal casing of the injection well served as the near current electrode, while the far electrode was placed 900 m to the north. The influence of the far electrode in the measurement area was negligible. Two non-polarising $Cu/CuSO_4$ electrodes were used for the potential difference measurements. Potential differences were measured in a radial pattern. Positions for potential electrode placement were 1, 2, 4, 8, 12, 16, 20 and 30 metres in eight directions away from the injection well (Fig. 1).

Experimental Procedure

The experiment took place from May 1 to May 5, 1991. Twelve kg of NaCl mixed with 700 l of water (σ = 4.6 S/m) were injected over a period of one hour into the saturated zone through a fil-

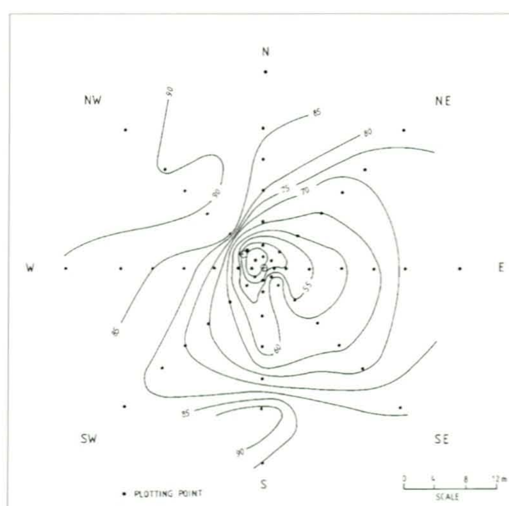

Fig 1. Normalised apparent resistivity for the measurements made 17-18 hours after injection.

ter extending from 4.3 to 5.2 m in a well. Because the formation has low permeability, pumping was commenced 3.5 hours prior to injection at a well located 3 m northwest of the injection well. The filter in the pumping well was located between 4.1 to 5.0 m. Pumping was sustained throughout the experiment, starting with 70 l/min and lowering to 55 l/min at the end of the experiment. Conductivity of the pumped water and the pumping rate were recorded at frequent intervals. The output water from pumping was released into an open ditch 18 m south of the injection well.

Monopolar 200 mA square current pulses were used for all measurements. Current 'on-time' was 2 seconds while 'off-time' was 6 seconds. Prior to each time measurement, the potential grid was leveled to 'infinity' to an electrode located 450 m southwest of the near current electrode. Possible self-potential field was compensated before reading the effect of current pulses. It took approximately one hour to measure the potential values for the entire array.

Results and discussion

Potential differences were measured for the entire array eight times in a 70 hour period. The electric current was not measured correctly for the initial (preinjection) measurement. Therefore, these data could not be used in the interpretation. The conductivity of the pumped water was measured frequently throughout the experiment. Approximately 40 hours after injection, the conductivity had returned to its initial background level.

Establishing 'background' values

In the interpretation of the data, it is important to have reliable estimates of the 'background' resistivity. Since the preinjection resistivity measurements had to be rejected, it was necessary to select alternative 'background' values. Potential differences measured 67-68 hours after injection, well after the conductivity of the pumped water had returned to its initial value, were chosen as reference or 'background' values, with which earlier measurements could be normalised. At this time, approximately 60% of the tracer had been pumped out of the aquifer. The assumption is then that, by this time, the remaining saltwater was sufficiently diluted. For geophysical purposes, the formation water could be regarded as having returned to its original composition.

Determining groundwater flow directions

The direction of tracer movement can best be determined by contouring the apparent resistivity values normalised with respect to background values (Fig. 1). The asymmetric pattern with the steep gradient to the northwest indicates that pumping in that direction has the greatest effect on flow. Even though a large portion of the saltwater was removed, there is a steep northwest gradient as a result of the artificial barrier created by pumping. It is also possible to determine the natural direction of groundwater flow to the southeast through an examination of normalised apparent resistivity as a function of time.

Determining groundwater flow velocity

The dimensions, both in time and space, of this

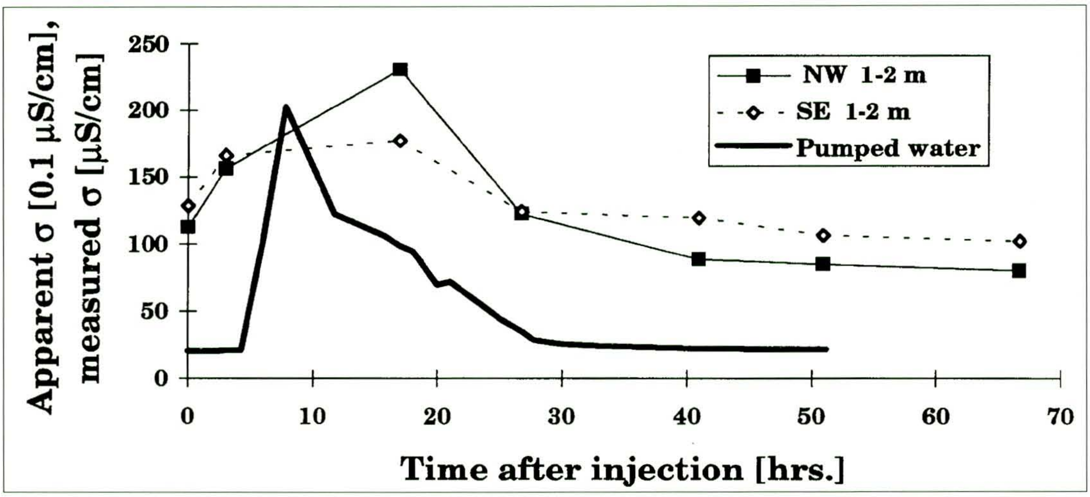

Fig. 2. Apparent conductivity calculated from the potential differences measured 1-2 m from the injection well compared to the conductivity of the outpumped water.

experiment were limited, and make it difficult to determine a velocity. The distance between the wells was such that the second resistivity survey (conducted 3-4 hours after injection) was completed approximately at the time of tracer breakthrough. This is illustrated by comparing values of calculated apparent conductivity ($=1/\rho_a$) with measured conductivity of the pumped water (Fig. 2). The measured conductivity of the pumped water was greatest 7 hrs. and 40 min. after saltwater injection. The apparent conductivity may have reached a maximum some time before that. However, the frequency of potential measurements was not high enough to detect such a maximum.

Conclusions

In a small-scale tracer experiment the artificial direction of flow towards the pumping well was recognised. Through an examination of normalised apparent resistivity as a function of time, it was also possible to determine the natural direction of groundwater flow. With increased sampling in time, and greater distances of plume movement, it should be possible to determine the groundwater flow velocity.

In a similar experiment in the future, the injection and pumping wells should be in a line parallel to natural flow, with much larger spacing between them. In order to obtain more frequent observations, it is recommended to measure potential differences with an automatic system.

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