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Hydrological measures of success for a pilot bioclogging study at Largs North, South Australia

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Abstract

A field trial of *in situ* bioclogging was carried out at Largs North, Adelaide in South Australia in 1997. Hydrological and chemical data were analysed in this report in order to gauge the success or failure of the bioclogging trial. Bromide tracer analyses indicated spatial distributions of a dense amendment solution in approximate agreement with predictions from previous three-dimensional density coupled injection simulations. Aquifer pumping test analyses indicate significant and simultaneous reductions in hydraulic conductivity and increases in storativity following amendment solution injection. The conductivity and storativity values began to revert to pre-trial values several weeks after the trial ceased. Temporal changes in local aquifer properties determined from pumping test analyses correlate with polysaccharide loads induced in laboratory slurry and column tests under amendment. It is concluded that the bioclogging techniques succeeded in reducing the aquifer hydraulic conductivity, albeit only by less than an order of magnitude and over a short period of time.

Table of Contents

Abstract 1

Table of Contents 2

1. Introduction 3

2. Field Trial - Instrumentation and Execution 4

3. Bromide Tracer Analysis 6

  3.1 Spatial Distributions 7
  3.2 Breakthrough Curves 12

4. Pumping Test Analyses 13

  4.1 Pumping Test 3 14
  4.2 Pumping Test 4 15
  4.3 Pumping Test 5 16
  4.4 Induced Changes in Aquifer Properties 17

5. Conclusions 19

6. Acknowledgements 20

7. References 21

1. Introduction

In 1995 the NATO Committee for Challenges to Modern Society (CCMS) commissioned a pilot study by the Centre for Groundwater Studies on the bioclogging of aquifers for containment and remediation of organic contaminants. Funding for the study was obtained through the industry partners BP Australia Ltd, Minenco, CRA, and the South Australia Environment Protection Authority. The pilot study sought to investigate and demonstrate *in situ* techniques for modifying aquifer hydrological characteristics through microbiological means [Johnston *et al.*, 1996a]. A key goal of the study was to induce a measurable reduction in aquifer hydraulic conductivity by stimulating the indigenous microflora to produce sufficient polysaccharide to clog the aquifer pore spaces.

The pilot study commenced in 1995 with the selection of a suitable test site in metropolitan Adelaide, South Australia. A plot of cleared land in the light industrial district of Largs North, adjoining the Port Adelaide River, was chosen for the field site. This site lies among oil terminals and contains several hydrocarbon plumes in the shallow surficial aquifer [Coffey Partners, 1995]. Extensive field and laboratory activities were undertaken to characterise the test site in terms of hydrogeology, hydrology and geochemistry [Rayner *et al.*, 1996]. Preliminary numerical modelling indicated the need for a detailed understanding of the aquifer hydrological characteristics [Johnston *et al.*, 1996b]. Aquifer pumping tests were carried out in March 1996, yielding firm estimates for hydraulic conductivity and storativity for the surficial aquifer [Trefry, 1996; Trefry and Johnston, 1998].

In concert with extensive laboratory microbial studies of induced polysaccharide production in soil columns and slurries [Johnston *et al.*, 1997], a detailed numerical modelling exercise was carried out in order to design and optimise nutrient delivery pumping strategies for a demonstration phase of the study [Trefry and Johnston, 1996]. This work also identified techniques for determining success conditions, *i.e.* zones of reduced hydraulic conductivity, for the demonstration trial.

Field work for the demonstration trial commenced with the installation of monitoring wells and loggers in March 1997. The nutrient delivery installation and plant was completed in July 1997; the demonstration trial was carried out immediately afterwards. The purpose of this report is to analyse the hydrological and chemical data measured during the field trial in order to determine whether the pilot study goals were achieved. This report considers two issues. Firstly, the fate of the injected amendment solutions is studied through analysis of tracer concentrations in various monitoring wells at the trial site. The resulting breakthrough curves and solute distributions are compared with results predicted from previous density coupled solute transport simulations [Trefry and Johnston, 1996]. Secondly, pumping test drawdown curves and tidal response functions are analysed in order to detect local changes in aquifer hydraulic properties at the trial site using techniques reported previously [Trefry, 1996; Trefry and Johnston, 1996; Trefry and Johnston, 1998].

2. Field Trial - Instrumentation and Execution

The field trial employed a quintuplet amendment delivery scheme [Trefry and Johnston, 1996] with pumping reversal. Figure 2.1 shows a schematic of the pumping well installations, highlighting the linear quintuplet array (wells BC30, BC31, BC32, BC34 and BC35). These wells were screened from just above the ambient water table to approximately 3 m below the water table. This limited depth of screening was chosen to help emplace the amendment solution in the top half of the saturated aquifer, neglecting density effects.

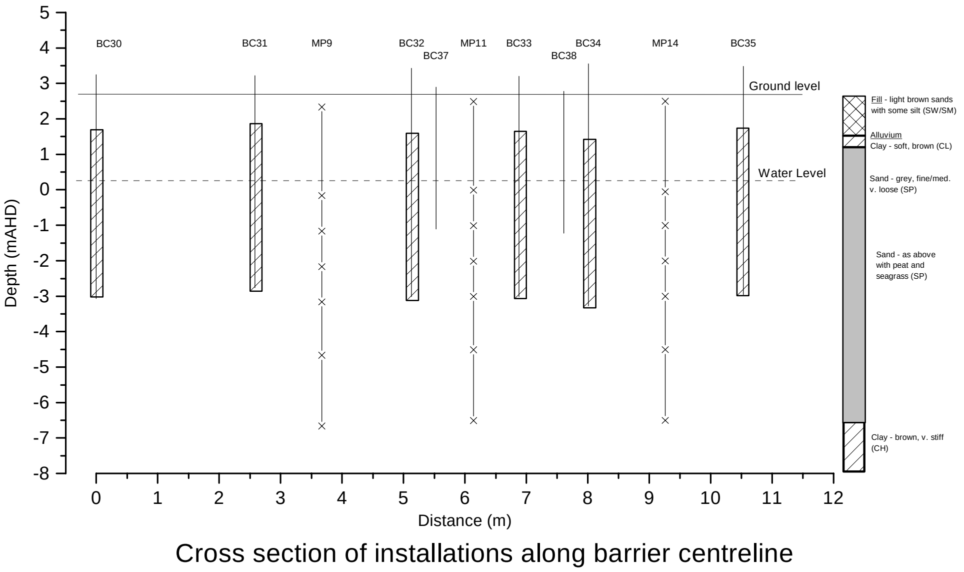

Figure 2.1: Schematic of the amendment injection installation in vertical cross section along the quintuplet axis. Screening intervals are shown for the quintuplet wells (BC30, BC31, BC32, BC34 and BC35) and for the other multiport and monitoring wells.

Figure 2.2 shows a plan view schematic of the installation, highlighting the various multilevel installations (MP8-MP16) used to collect data during the progress of the trial, and the pumping well (BC33) and monitoring wells (BC22 and BC23) employed in the post-injection pumping tests for assessing reductions in hydraulic conductivity. The figure is drawn in transformed coordinates, related to AMG coordinates by a simple translation and rotation.

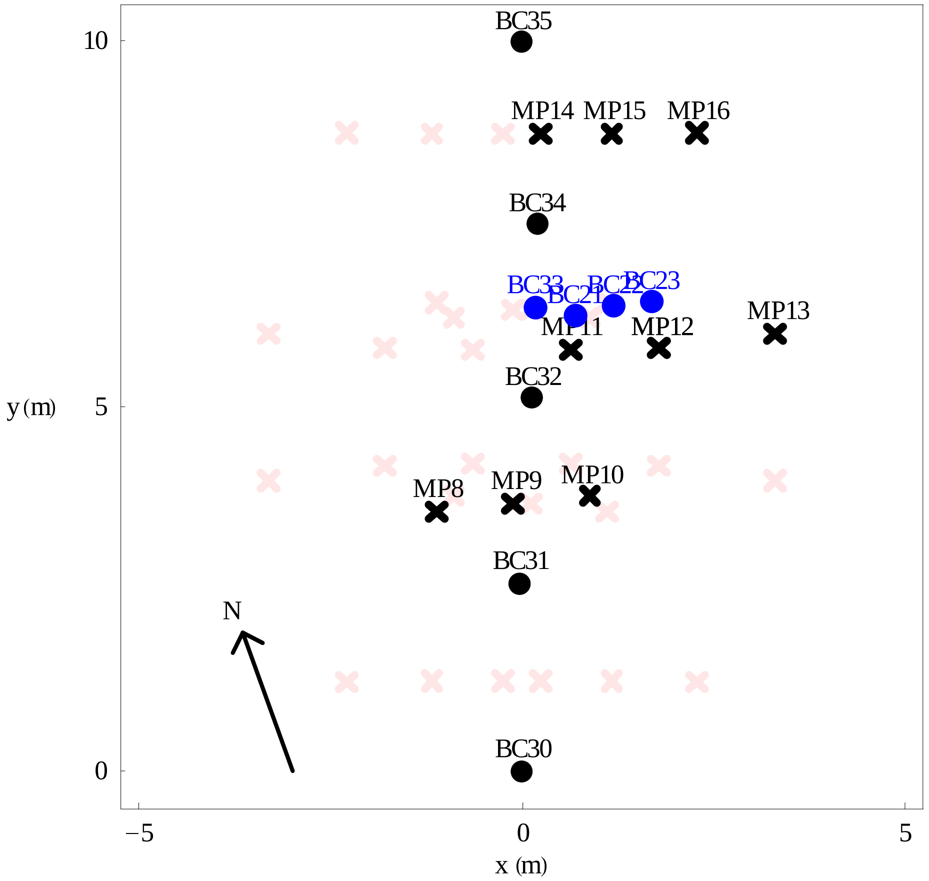

Figure 2.2: Layout of nutrient injection installation in plan projection, showing the quintuplet pumping wells (black dots), the pumping test wells (blue dots), the multi-level sampling wells (black crosses), and the symmetry-generated sampling points (pink crosses, see Section 3). The installation is drawn in transformed (x, y) coordinates; pumping well BC30 is located at the AMG coordinates (271898.23, 6143761.39).

An amendment solution of specific gravity 1.02 containing approximately 90 mg/L bromide as a conservative tracer (see Figure 2.3) was injected into the aquifer using a balanced quintuplet pumping scheme [Trefry and Johnston, 1996]. Details of the field trial are reported separately [Johnston *et al*., 1998]. Variability in the input bromide concentration was due to difficulties in flow metering in the input manifold system. In order to establish a steady flow field, the pumps were run with a balanced total pumping rate of 50 m^3/d of recirculated aquifer water for four hours prior to amendment injection. The initial pumping scheme used injection rates of 25 m^3/d through the centre well and 12.5 m^3/d through each of the outer wells. Extraction rates were 25 m^3/d through the two remaining wells. The amendment injection scheme was then actuated. After 2.2 days the pumping scheme was reversed, so that the center well and outer wells became extraction wells and the remaining wells were used for injection. Magnitudes (but not signs) of pumping rates were maintained for all wells through the pumping reversal. The reversed pumping was maintained for half a day, yielding a total pumping time of 2.7 days.

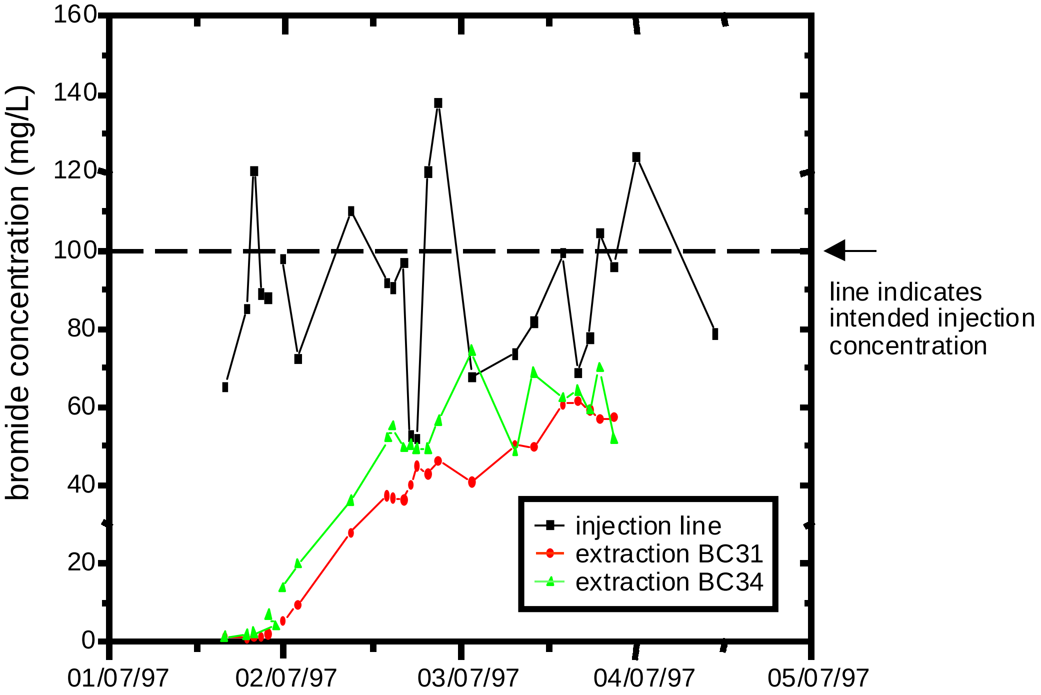

Figure 2.3: Time series of bromide concentration in the injection line (black) and the two extraction bores (red and green) during the first stage of quintuplet pumping, prior to reversal. The approximate mean injection bromide concentration was 90 mg/L, with a peak concentration of 140 mg/L.

3. Bromide Tracer Analysis

The bromide tracer added to the amendment solution is used as a correlator with the amendment nutrients. That is, concentrations of bromide above background levels at a particular position in the aquifer are assumed to indicate the presence of amendment solution. Ignoring sorption processes or the possibility of flow-induced separation of bromide from the remainder of the amendment solution constituents, the concentration of the amendment solution is correlated (proportionate) with the local bromide concentration.

Multi-level sampling ports were used to measure bromide concentrations at various positions in the aquifer near the quintuplet wells, as depicted by black crosses in Figure 2.2. The arrangement of the sampling ports is not symmetric about the quintuplet installation horizontal axes, however for a uniform, homogeneous aquifer the quintuplet wells would generate a largely symmetric amendment distribution in each horizontal plane. If it is assumed that the field aquifer is homogeneous then mirror transformations can be used to generate symmetry-related sampling points (depicted by pink crosses in Figure 2.2) with data equivalent to the data from the true sampling points. This symmetry argument is used merely to simplify the visualisation and analysis of the bromide distributions; the presence of actual symmetric distributions in the field trial is not proven here.

3.1 Spatial Distributions

The following 3D slice diagrams (Figures 3.1 to 3.8) show coloured fringes of bromide concentration at various times through the nutrient injection process. The diagrams are plotted in the transformed coordinates of Figure 2.2. Figure 3.1 shows the tightly confined bromide concentration shortly after the commencement of injection. Succeeding figures show that with time the distribution lengthens along the quintuplet axis (aligned on a north-south axis). Interestingly, the bromide distribution never seemed to penetrate to the bottom of the aquifer (-7.0 m AHD) as was predicted by the numerical modelling [Trefry and Johnston, 1996]. This may imply that aquifer layering inhibited gravity-forced downward migration of the solute. Also, microbial consumption of the nutrient components may lead to a decline in the effective amendment density over time, reducing gravity effects, although this is les likely over the time frames considered.

Figure 3.9 shows horizontal slices through the bromide distribution after the completion of amendment injection. The bromide distribution is quasi-rectangular, and is confined largely to the top 4 m of the saturated aquifer. The width of the distribution (at 50 mg/L) is approximately 6 m just beneath the water table (0 m AHD), declining to approximately 4 m at a depth of 2 m AHD, and to 0 m at a depth of 4 m AHD.

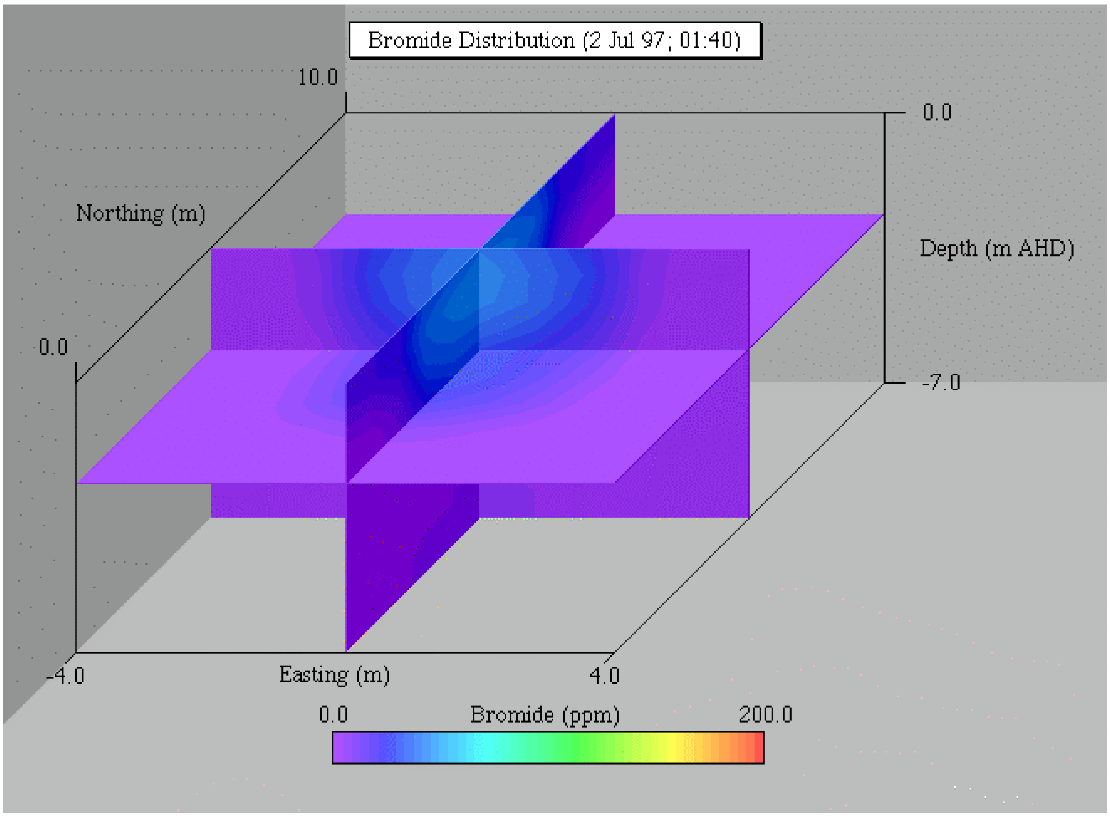

Figure 3.1: Symmetry-generated bromide distribution for 01:40 hrs on 2 July 1997.

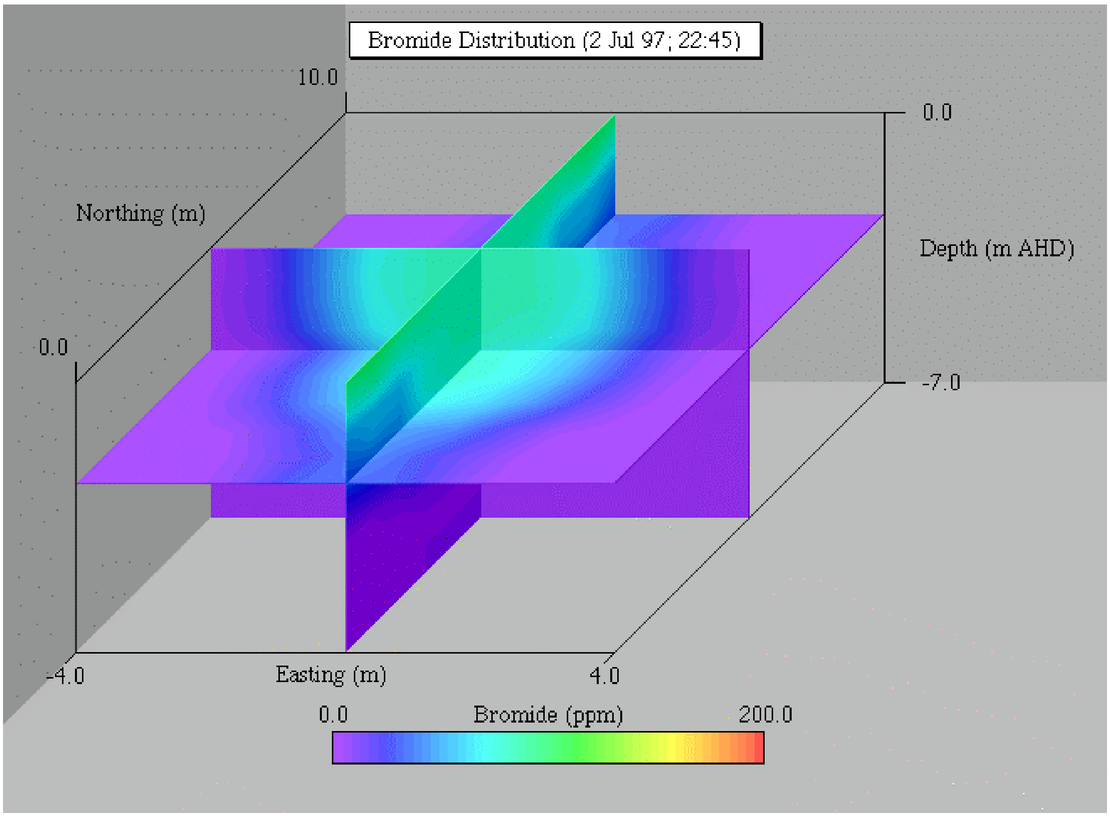

Figure 3.2: Symmetry-generated bromide distribution for 22:45 hrs on 2 July 1997.

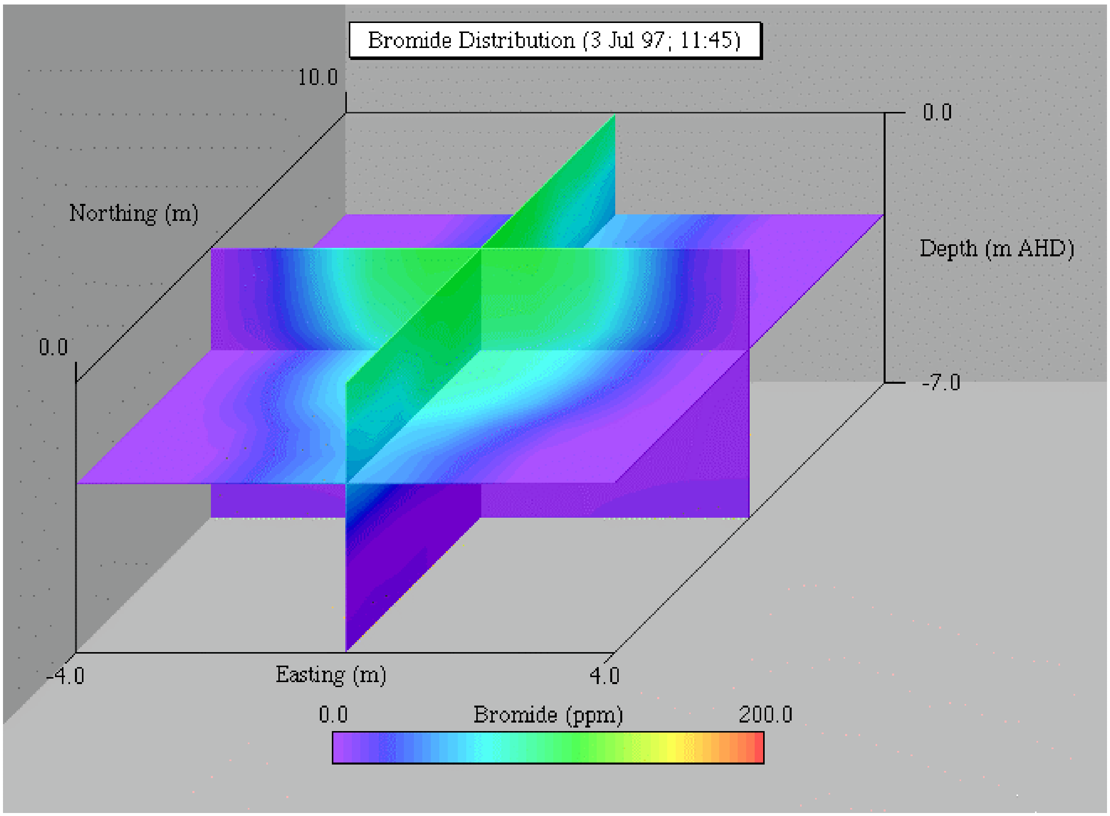

Figure 3.3: Symmetry-generated bromide distribution for 11:45 hrs on 3 July 1997.

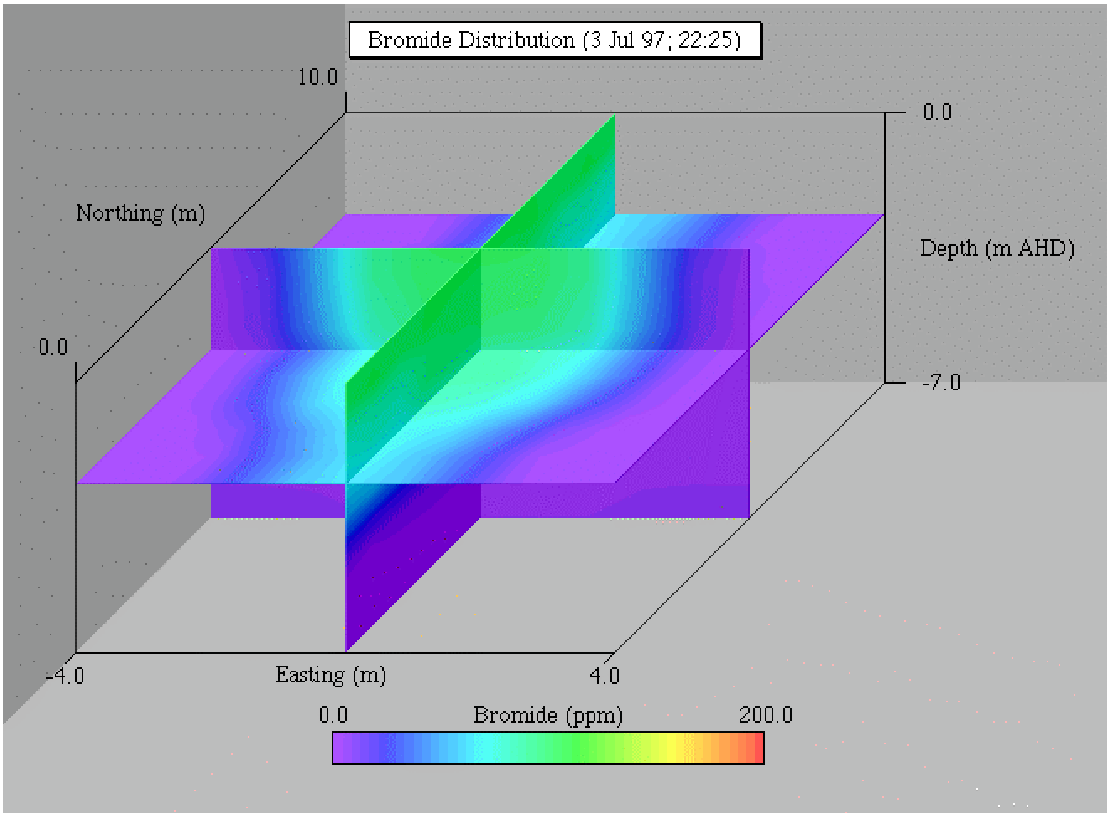

Figure 3.4: Symmetry-generated bromide distribution for 22:25 hrs on 3 July 1997.

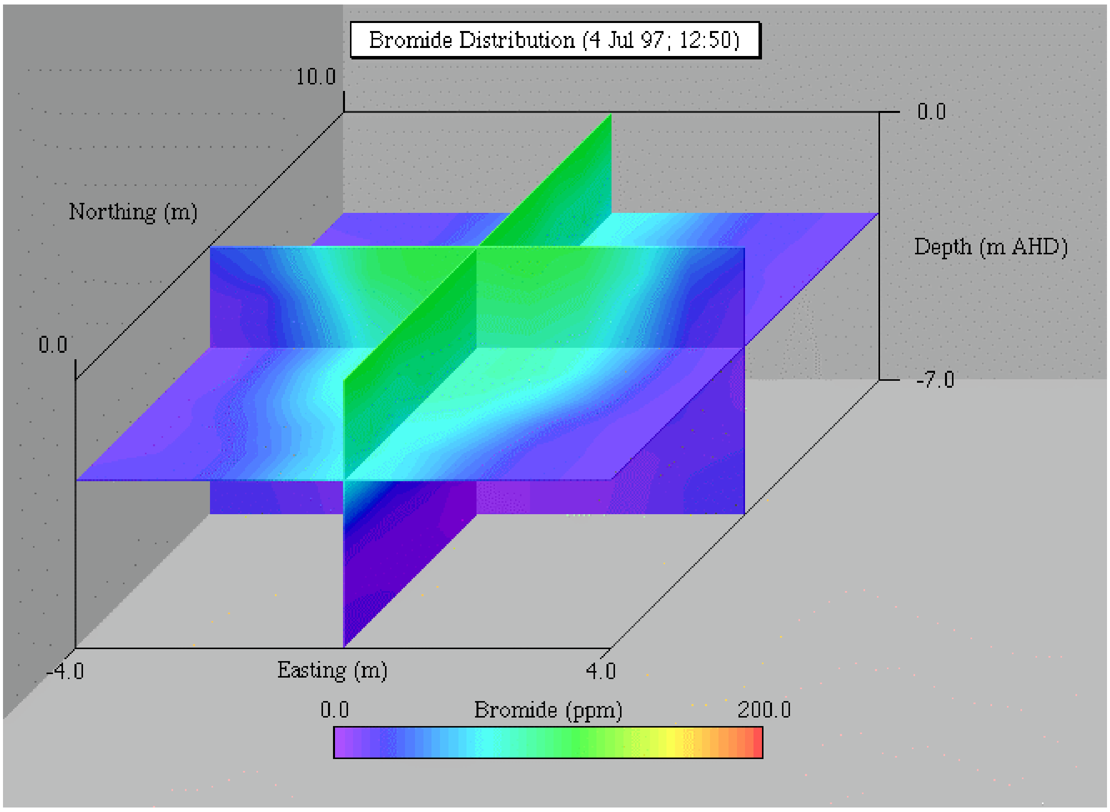

Figure 3.5: Symmetry-generated bromide distribution for 4 July 1997.

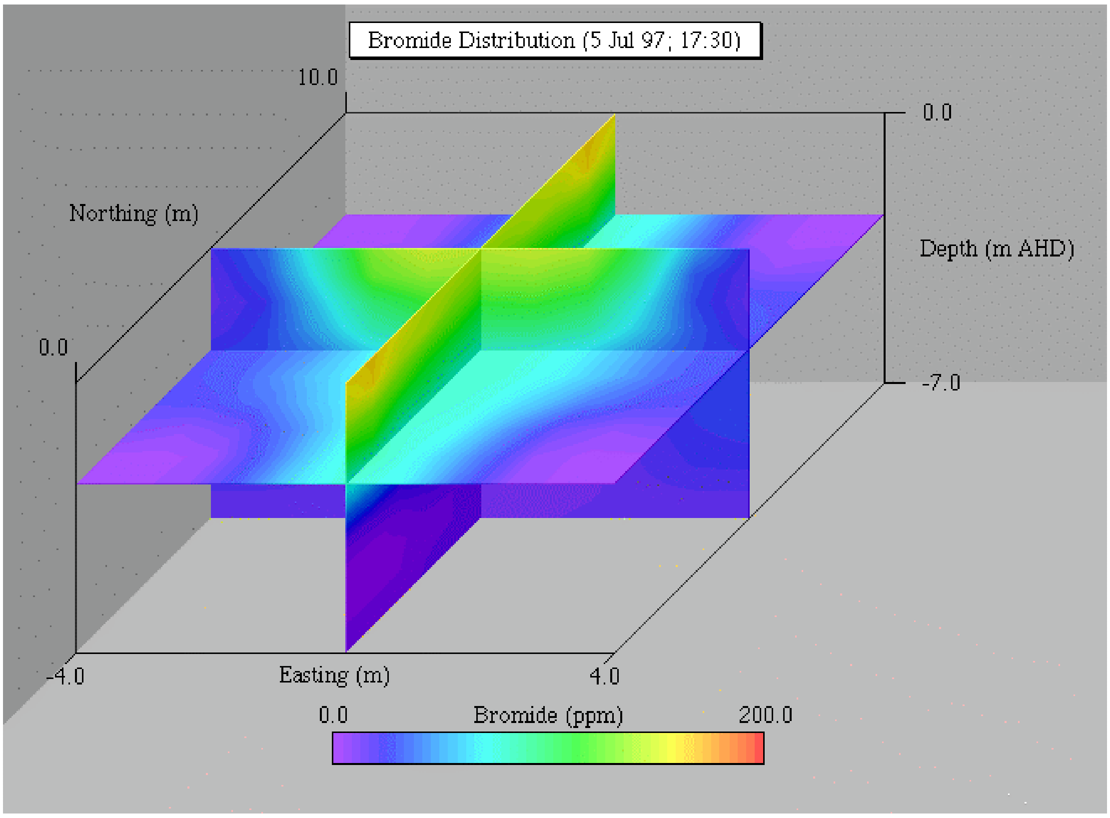

Figure 3.6: Symmetry-generated bromide distribution for 5 July 1997.

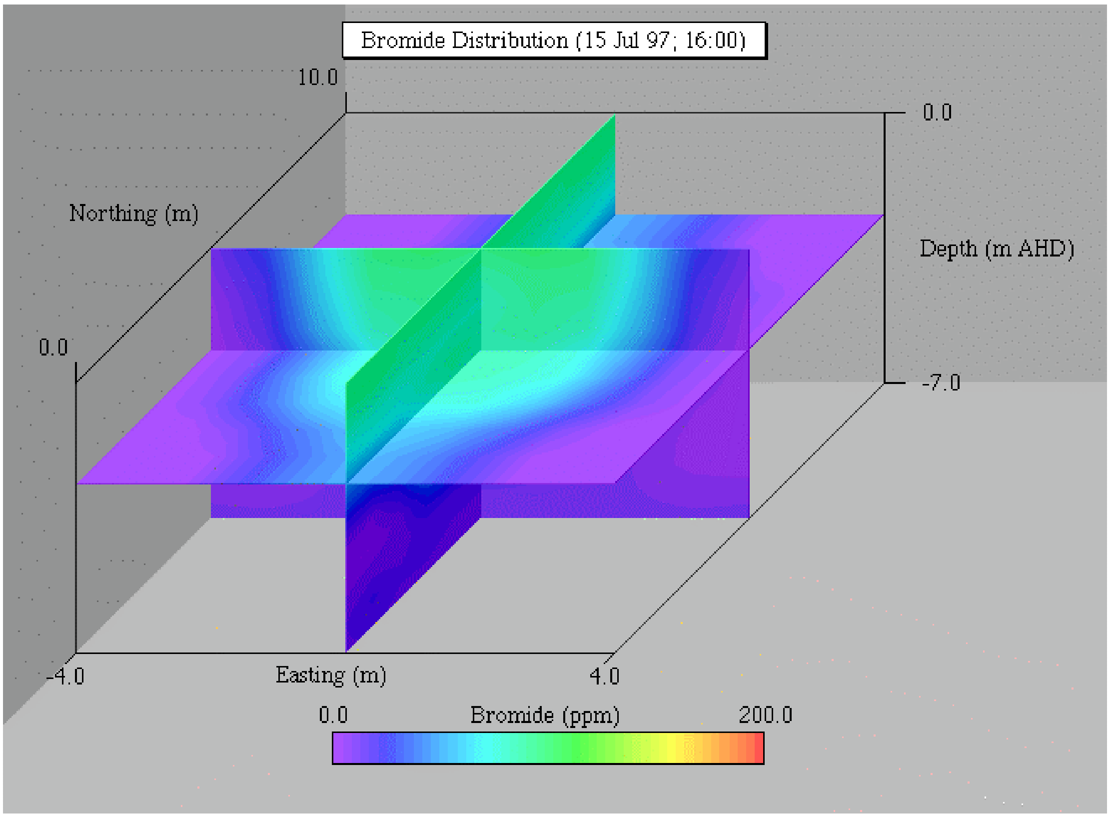

Figure 3.7: Symmetry-generated bromide distribution for 15 July 1997.

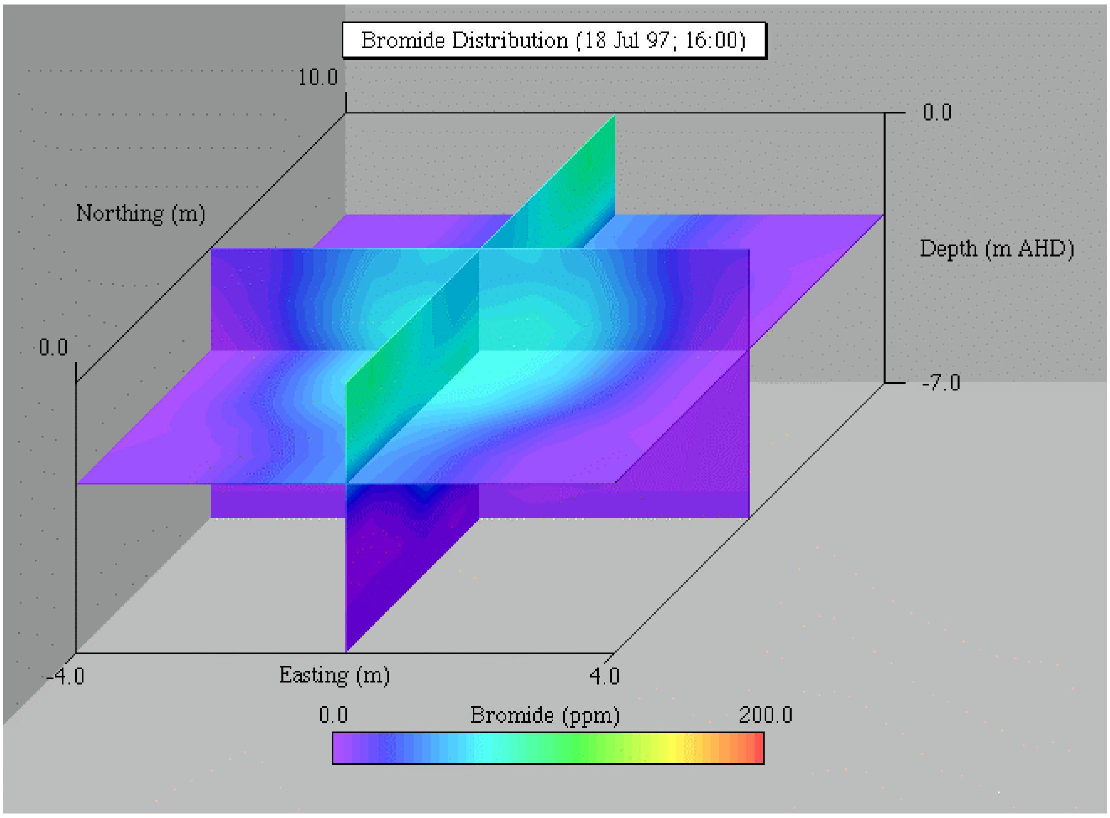

Figure 3.8: Symmetry-generated bromide distribution for 18 July 1997.

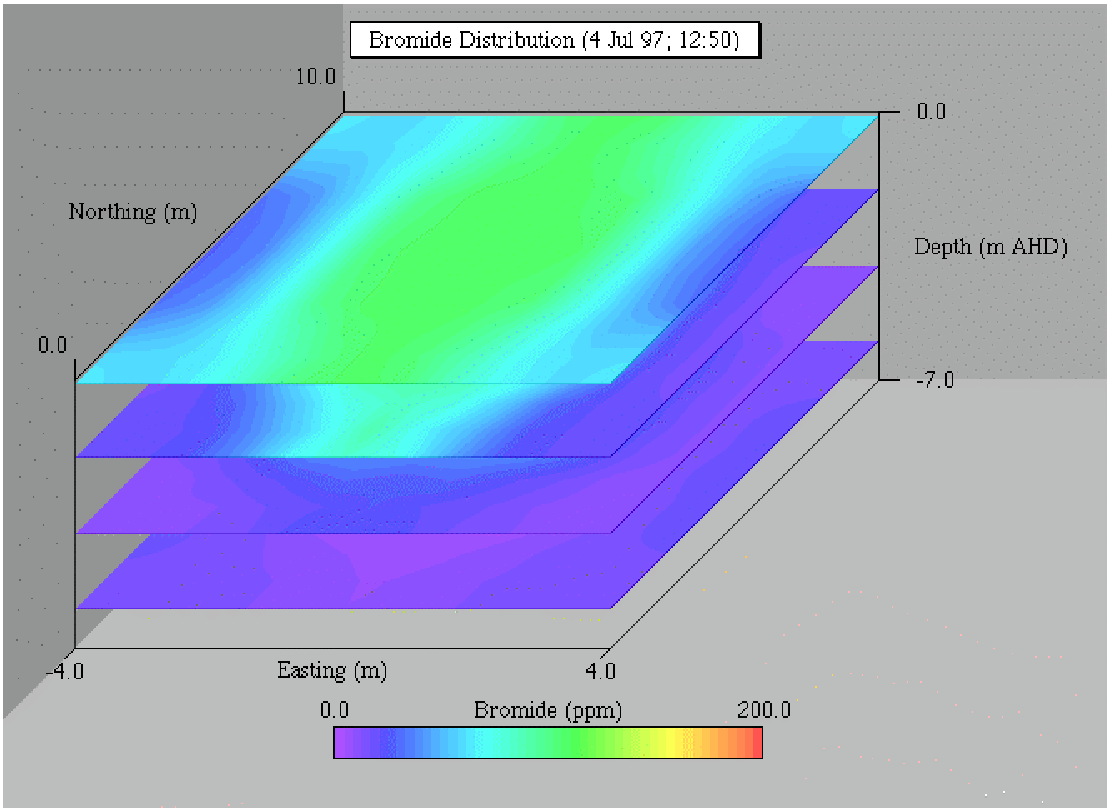

Figure 3.9: Horizontal projection of bromide distribution at the cessation of pumping.

Overall, the distributions show that by the cessation of pumping of 4 July 1997 the amendment solution had been delivered to a quasi-rectangular zone in the upper half of the saturated thickness of the aquifer. At times 1-2 weeks after the cessation of pumping, the peak concentrations in the bromide distributions are declining slowly, and the distributions as beginning to fragment (Figures 3.7 and 3.8).

3.2 Breakthrough Curves

It is possible to compare explicit breakthrough curves for the bromide tracer at some of the monitoring wells with the simulated results from the modelling work of Trefry and Johnston (1996). The comparison must be qualified by the fact that density coupled transport simulations were only carried out for triplet amendment schemes (rather than the quintuplet scheme actually performed in the field) and that breakthrough curves were only calculated for selected wells at the water table. The best well for comparison is MP10, for which both simulated (triplet) and measured (quintuplet) breakthrough curves are available. Figure 3.10 compares the measured (at two depths) and calculated breakthrough curves, using normalised bromide concentrations. The measured breakthrough curves were normalised to the maximum bromide concentration observed 17 days after pumping commencement (not shown in Figure 3.10). The variability of the measured breakthrough curves is high, significantly larger than the effect of changing the injected amendment density. Thus it is not possible to gauge the presence of density effects in the breakthrough curves. However, overall the measured distributions agree at least qualitatively with the modelling predictions of Trefry and Johnston (1996), apart from the reduced gravity effects seen in the field data.

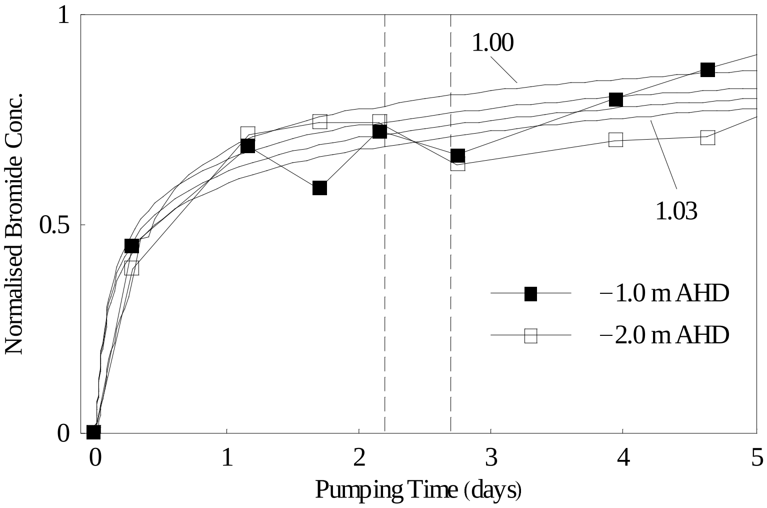

Figure 3.10: Measured and modelled bromide breakthrough curves for the MP10 well. Measurements (empty and filled boxes) were taken at two depths in the MP10 well. Modelled results for a triplet installation are drawn as smooth curves, representing amendment solutions of specific gravity ranging from 1.00 to 1.03 in equal steps. The dashed lines indicate pumping reversal (2.2 days) and cessation (2.7 days). The modelled results are calculated for continuous pumping over five days.

4. Pumping Test Analyses

A total of five pumping tests were performed at the Largs North test site over the duration of the bioclogging study. The first two tests, performed using well BC11 in 1996, were used to determine local aquifer hydraulic conductivity and storativity. Full descriptions of this work are contained elsewhere [Trefry, 1996; Rayner *et al.*, 1996; Trefry and Johnston, 1998]. After the design of the field trial instrumentation [Trefry and Johnston, 1996], and the installation of the pumping quintuplet centred on BC32, it was decided to perform a validating pumping test prior to amendment injection. This pumping test was designated Pumping Test 3 and was carried out in well BC33 (see Figure 2.2), a location expected to lie inside the polysaccharide curtain induced by the intended amendment injection. The remaining Pumping Tests were conducted at BC33 shortly after the cessation of amendment injection (Pumping Test 4), and approximately ten days later still (Pumping Test 5). The effects of the amendment injection on the aquifer matrix can be assessed by comparing estimates of local hydrological properties derived from these three tests. In the following sections Theis analyses are performed on drawdown data from selected monitoring wells for each of the last three pumping tests. Presented well data is selected on the basis of completeness and continuity of water levels throughout the duration of the tests. Unfortunately, data coverage was not consistent for the three pumping tests.

The transient drawdowns, s, were analysed in terms of the standard Theis solution for confined aquifers [Kruseman and de Ridder, 1994, p.61-62]

$$s = \frac{Q}{4\pi KD} W\left(\frac{r^2 S}{4KDt}\right) \tag{4.1}$$

where $W(u) = -Ei(-u)$ is the usual well function, D is the aquifer thickness, and r is the radial distance of the drawdown point from the pumping well. This approximation can be justified for unconfined and semi-confined aquifers (as in the current case) if the pumping times are short and the induced drawdowns are small [Kruseman and de Ridder, 1994, p.100]. In the following sections Theis analyses will be applied to measured drawdowns to determine aquifer hydraulic conductivity, K, and storativity, S, as functions of time over the final three pumping tests.

4.1 Pumping Test 3

Pumping Test 3 was carried out on 23 March 1997. It had a pumped duration of six hours, with constant discharge rate $Q = 28.8$ m^3/d through well BC33. Figure 4.1 shows measured and fitted type curves for wells BC22 and BC23. The Theis analysis indicates values for K ranging from 7.5 to 8.5 m/d and a consistent estimate for S of approximately 0.0023, in welcome agreement with earlier findings [Trefry, 1996; Trefry and Johnston, 1998]. These values represent the pre-clogging properties of the aquifer, against which results from Pumping Tests 4 and 5 will be compared to deduce changes due to the effects of bioclogging.

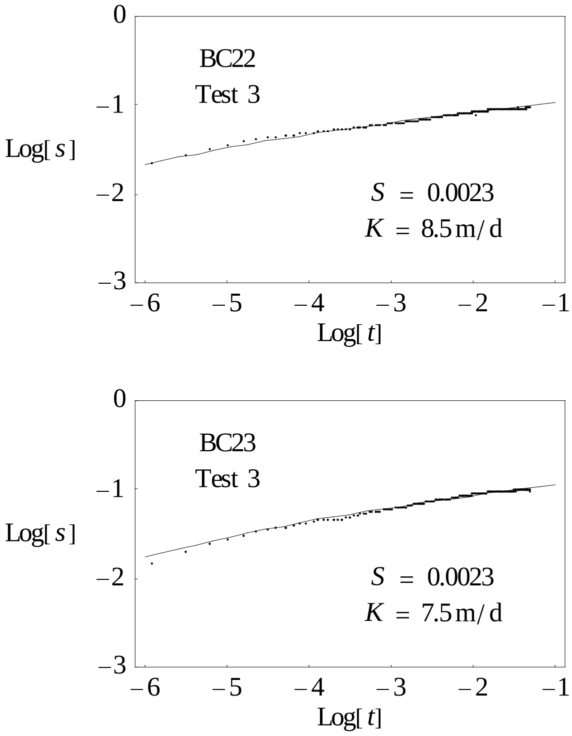

Figure 4.1 Measured drawdowns (dots) and fitted Theis curves (solid curve) for monitoring wells BC22 and BC23 for Pumping Test 3.

4.2 Pumping Test 4

Pumping Test 3 was carried out on 9 July 1997, five days after the cessation of amendment injection. It had a pumped duration of five hours, with constant discharge rate *Q* = 5.96 m^3/d through well BC33. The sustainable discharge rate was limited by dewatering in the pumping well; by this time significant volumes of gas (mostly hydrogen and CO_2) were exiting the saturated zone in the vicinity of the quintuplet installation. Figure 4.2 shows measured and fitted type curves for wells BC21 and BC22. The Theis analysis indicates values for *K* of approximately 2 m/d and for *S* ranging from 0.03 to 0.06. The high value for storativity may indicate enhanced compressibility, possibly due to large amounts of gas entrapped in the aquifer (see section 4.4 and details in Johnston *et al.* (1998)).

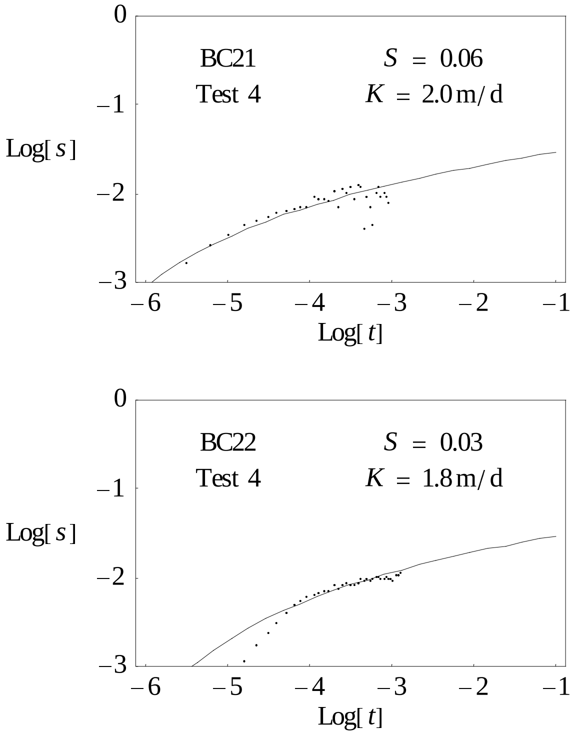

Figure 4.2 Measured drawdowns (dots) and fitted Theis curves (solid curve) for monitoring wells BC21 and BC22 for Pumping Test 4.

4.3 Pumping Test 5

Pumping Test 5 was carried out on 27 July 1997, over three weeks after the cessation of pumping. Test 5 had a pumped duration of six hours, with constant discharge rate Q = 12.3 m^3/d through well BC33. By this stage gas production in the aquifer had declined, permitting higher pumping rates for the test. Figure 4.3 shows measured and fitted type curves for wells BC21, BC22 and BC23. The Theis analysis indicates values for K ranging from 3.5 to 9 m/d and for S ranging from 0.005 to 0.02. The Theis solution fits the BC21 drawdown data best. The data for BC22 and BC23 are less well described by the Theis solution with significant elastic responses at early times (*e.g.* BC22), possibly reflecting continued disturbance of the soil matrix at these points by gas evolution from microbial activity. One value of K (for BC21, closest to the quintuplet axis) is significantly smaller than the other two; one value of S (for BC23, furthest from the quintuplet axis) is significantly larger than the other two. This may indicate that clogging was maintained close to the quintuplet axis, whilst gas production continued toward the outer fringes of the clogged zone, although such inferences should be treated with caution.

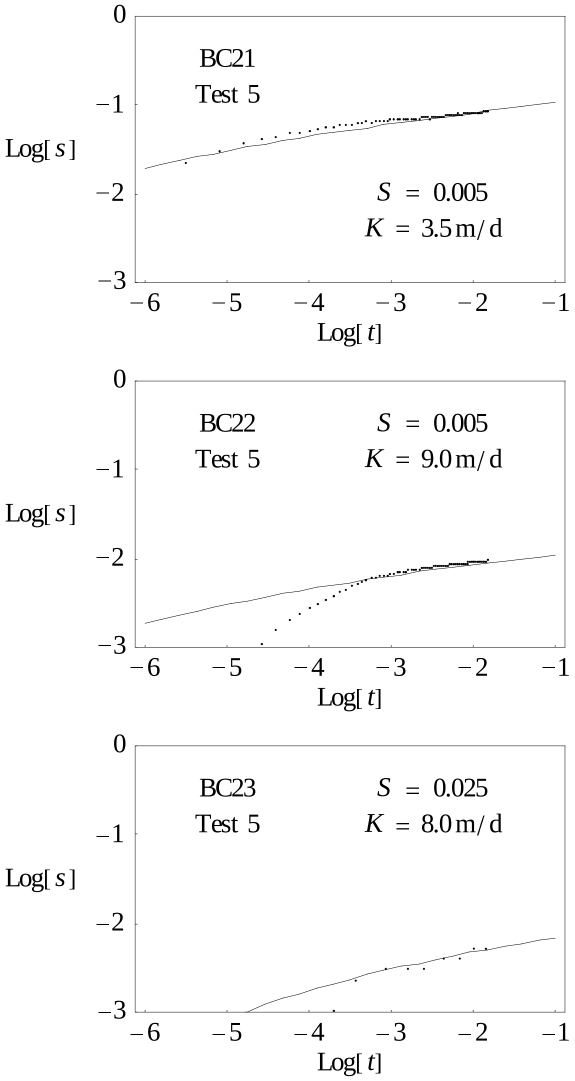

Figure 4.3 Measured drawdowns (dots) and fitted Theis curves (solid curve) for monitoring wells BC21, BC22 and BC23 for Pumping Test 5.

4.4 Induced Changes in Aquifer Properties

The results of the Theis analyses for Pumping Tests 3, 4 and 5 are summarised in Figure 4.4. The Figure shows plots of local *K* and *S* versus time. Time is measured from the onset of amendment injection. The duration of the amendment injection is also indicated by a shaded bar. *K* and *S* results from Pumping Test 3 are shown at time zero, although that test was performed approximately one hundred days before the trial. It is assumed that the aquifer properties remained constant until amendment was introduced. It is seen that *K* declines from the ambient value by a factor of approximately five immediately after the amendment injection. At the same time, *S* increases by an approximate factor of twenty. Eighteen days later, *K* has increased to approximately half the ambient value, albeit with a large spread of values, and *S* has declined to somewhere between two and ten times the ambient value.

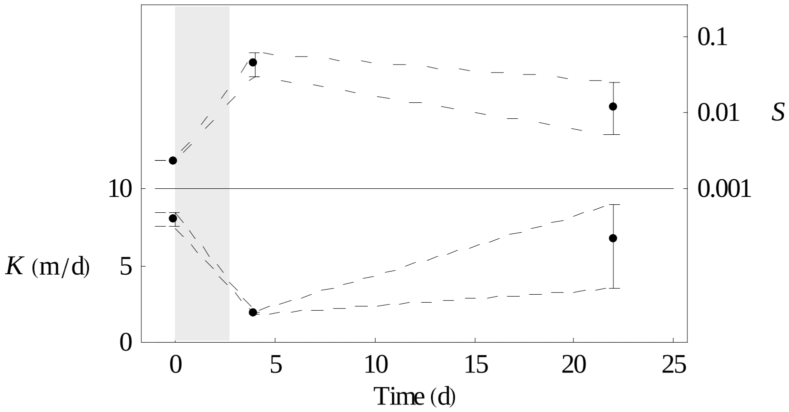

Figure 4.4 Time evolution of hydraulic conductivity, *K*, and storativity, *S*, for the amendment zone, as calculated from Theis pumping analyses. Plotted are bands of *K* (lower) and *S* (upper) values for the three pumping tests. Dashed lines are drawn between pumping tests to aid the eye. Value bounds are based on absolute ranges of Theis estimates. Time is measured from the onset of amendment injection (see text).

During the running of the field trial, significant gas production was observed in the amendment injection zone. The gas was largely composed of hydrogen, with a significant nitrogen fraction. Gas production continued in the aquifer for approximately two weeks after the amendment injection. Thus Pumping Test 4 was carried out during a period of strong gas production in the amended phase. The presence of gas in the saturated zone would lead to increased storage compressibility, hence providing an explanation for the greatly elevated storativity necessary to fit Theis curves to the measured drawdowns. At the same time, entrapped gas would tend to lessen hydraulic conductivity through increased surface tension effects between the gas and liquid phases. However these effects are expected to be small and would be unlikely to account fully for the fivefold reduction in *K*. Therefore the evidence supports the conclusion that injection of the amendment solution led, via biochemical processes, to measurable changes in *K* (decreases, mainly due to clogging effects) and *S* (increases, mainly due to gas production).

Information on the longevity of the changes induced in K and S is provided by the results of Pumping Test 5. Although the Theis analyses yielded more variable results than for the previous Pumping Tests, it is possible to state that K has increased significantly during the eighteen days elapsed from Pumping Test 4. The variability may indicate that the microbial activity is spatially dependent, *i.e*. that the production/metabolism of polysaccharides is proceeding at different rates in different parts of the amendment delivery zone. No direct evidence for this statement is presented here. Another explanation may be that the mechanics of the gas production created more disturbance to the soil matrix in some regions of the delivery zone than in others. Nevertheless, all K values able to be estimated from the drawdown data for Pumping Test 5 were elevated over the values found for Pumping Test 4. Estimates of S were also variable, possibly highlighting different stages of gas production in the delivery zone. Again, the estimated S values were all lower than for Pumping Test 4.

These results show that the maximum reduction in K was likely to have occurred close to the cessation of amendment injection. Certainly, by the time of Pumping Test 4 significant reductions in K were evident. This agrees with results from laboratory column and slurry tests, where peak polysaccharide production was observed two to four days after amendment injection. The laboratory tests also showed slow declines in polysaccharide concentrations after the peak value was obtained. The concentrations declined on a time scale of a week or so to trace levels after several weeks. This correlates well with the results of Pumping Test 5, which shows K and S reverting towards ambient values more than two weeks after the amendment injection.

5. Conclusions

Previous modelling studies established well layouts and pumping regimes for a bioclogging field trial. The field trial was carried out in July 1997 according to the model output parameter values. Bromide tracers indicated that the injected amendment solution was delivered to a zone of the aquifer with similar dimensions to those predicted by earlier numerical simulations. The major difference was that the bromide distributions were shallow, penetrating only to 3-4 m below the water table. This was in contrast to the theoretical predictions of full saturated depth (to 7 m) penetration by the dense amendment. The bromide measurements show that an amendment zone of approximate width 6 m (defined by the 50% bromide concentration contour) and depth 4 m was created after 2.7 days of pumping, in approximate agreement with expectations for the actual amendment density of approximately 1020 kg m^{-3}. Plots of the bromide distributions showed that by several weeks after the cessation of pumping the distributions had stabilised, possibly even reducing slightly in concentration.

Success criteria for the trial involved significant and measurable reductions in K arising from induced polysaccharide distributions in the amendment zone. Using techniques developed and modelled in earlier work, three Pumping Tests were carried out in the amendment zone - one prior to amendment injection, one immediately after amendment injection, and a final test eighteen days later. Theis analyses applied to pumping drawdowns measured in the amendment zone for these tests indicated rapid reductions in K and increases in S shortly after amendment injection. By the time of the final test, these values had begun to revert towards their ambient values. The time dependence correlated well with prior laboratory studies of polysaccharide production and longevity in amended slurries and columns.

It is concluded that the bioclogging field trial was successful in using a nutrient amendment solution to induce *in situ* a polysaccharide biobarrier in a sandy surficial aquifer. The biobarrier generated a measured fivefold reduction in conductivity, before increasing to ambient values over a time span of several weeks. Whilst a greater reduction in conductivity was desirable, the measured reduction was nonetheless significant.

6. Acknowledgements

This work was supported by BP Australia Ltd, CRA, Minenco, and South Australia Environment Protection Authority. David Briegel is acknowledged for assistance during the field trial.

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