

1 **Analysis of flow processes in fractured chalk under pumped and ambient conditions**

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12

13 **Abstract**

14

15 This paper describes an integrated set of different measurements that has been used to study
16 the behavior of groundwater in an observation well in a fractured rock formation, the UK
17 Chalk, under pumped and ambient conditions. Under pumped conditions the response of the
18 open borehole was relatively straightforward with flow mainly concentrated along four
19 discrete flow horizons. Furthermore, excellent correspondence was observed between the
20 three methods of borehole flow velocity measurement: impeller flowmeter, heat-pulse
21 flowmeter and dilution testing. Under ambient conditions the system appeared more
22 complicated. Specifically, in the upper half of the borehole the impeller flowmeter exhibited
23 substantial downward flow, the heat-pulse flowmeter exhibited almost negligible upward
24 flow whilst dilution testing indicated significant dilution. It was concluded that this was due
25 to cross-flow occurring over the upper 29 m. Analysis of drawdown data, recovery data and a
26 Drost analysis of the ambient cross-flow data yielded aquifer transmissivity estimates of
27 $2049 \text{ m}^2\text{d}^{-1}$, $2928 \text{ m}^2\text{d}^{-1}$ and $> 4388 \text{ m}^2\text{d}^{-1}$ respectively. The discrepancy between the
28 drawdown and recovery estimates was attributed to non-linear head-losses associated with
29 turbulence and inertial effects. The difference between the pumping test and Drost results was
30 explained by the flow during the pumping test bypassing this aforementioned 29 m region of
31 rock.

32

33 **Introduction**

34

35 Chalk aquifers represent some of the most important groundwater resources in the UK.
36 Consequently, great effort is incurred in developing catchment scale groundwater models of
37 key water resources sites (see ENTEC, 2003 and references therein). These models routinely
38 use parameters obtained from pumping test analysis (MacDonald and Allen, 2001). However,
39 it is often found that when attempting to simulate the observed ambient (i.e. unpumped)
40 groundwater response, a level of calibration is required (ENTECH, 2003; Rushton et al., 1989).
41 This adjustment of parameter values is due to a range of problems including measurement
42 error and model uncertainty (Liu and Gupta, 2007). However, another problem, not often
43 discussed, is the extent that aquifer parameters derived under locally perturbed (i.e. pumped)
44 conditions are suitable for applying to models that represent the system in the ambient state.

45

46 As part of the UK Natural Environment Research Council (NERC) thematic programme on
47 Lowland CAatchment Research (LOCAR) (Wheater and Peach, 2004) three 100 m deep
48 observation boreholes (PL10A, PL10B, PL10E) were placed around an Environment Agency
49 river augmentation abstraction well at Bottom Barn (BBA) situated in the Berkshire Chalk
50 aquifer, UK (see Figure 1 and Williams et al., 2006). Effort was focused on the
51 characterization of PL10A, which benefited from extensive geophysical logging (caliper,
52 gamma, temperature, televiewer etc.), packer testing, flow logging (using impeller and heat-
53 pulse flow meters) and dilution testing. Of particular interest is that temperature logging, flow
54 logging and dilution testing were undertaken under ambient conditions and again when the
55 BBA (situated 32 m away) was pumping at $5770 \text{ m}^3\text{d}^{-1}$. In what follows it is shown that the
56 pumping of BBA fundamentally changed the observed flow processes within PL10A raising
57 a serious question concerning the application of results obtained from pumping tests in
58 fractured rock aquifers such as the Chalk.

59

60 **Lithostratigraphy**

61

62 Traditionally, the Berkshire Chalk outcrop has been subdivided into the Upper, Middle and
63 Lower Chalk formations (White, 1907). At a meeting of the Geological Society Stratigraphy
64 Commission at the British Geological Survey (BGS) in 1999, a broadly agreed revised Chalk
65 Group stratigraphy was adopted (Rawson et al., 2001), which was based on the more
66 sophisticated lithostratigraphical classification applied by Mortimore (1986) and Robinson

67 (1986). One of the useful markers for applying the new lithostratigraphical classification is a
68 three-metre band, near the base of the Lewes Nodular Chalk (the base of the former Upper
69 Chalk), known as the Chalk Rock (Schurch and Buckley, 2002; Woods and Adiss, 2004).
70 This is because the phosphatized and glauconitized chalk pebble intraclasts, particularly
71 common in the Chalk Rock, give rise to a significant increase in gamma-ray activity (Schurch
72 and Buckley, 2002). Figure 2b shows a gamma-ray log of borehole PL10A where such a
73 gamma-ray peak is present at 27 mAOD.

74

75 Following Schurch and Buckley (2002) and Woods and Adiss (2004), the Lewes Nodular
76 Chalk formation was assumed to be around 20 m thick with its base located at the very
77 bottom of the Chalk Rock gamma-ray perturbation. Therefore, the uncased section of
78 borehole PL10A can be assumed to lie in around 10 m of New Pit Chalk, overlain by 20 m of
79 Lewes Nodular Chalk, overlain by 50 m of Seaford Chalk (see Figure 2 for schematic). The
80 New Pit formation is a firm, smooth-textured marly chalk while the Lewes Nodular is a hard,
81 nodular, gritty chalk, with common flints, marl seams and hardgrounds. The base of the
82 Seaford formation is at the upward change from hard, nodular, gritty chalk to soft, smooth-
83 textured chalk (Woods and Adiss, 2004).

84

85 **Fractures**

86

87 To better visualize the physical structure of the aquifer at PL10A, an optical televiewer
88 (OTV) log was obtained. The OTV log provides a 360 degree bitmap image of the entire
89 borehole. Perfectly, planar sub-horizontal features manifest themselves as sine waves, from
90 which the elevation, strike and dip of the fractures that intersect the borehole can be obtained
91 (Paillet and Pedler, 1996). Theoretically, OTV logs can be interpreted automatically using
92 techniques such as the Hough transform (Glossop et al., 1999). However, this requires that
93 the OTV log is still intelligible after translating to a binary image. For the PL10A OTV log,
94 this was not the case. Consequently, a manual technique was adopted. Ideally, this should be
95 a simple case of locating the minimum and maximum points of the intersecting fractures' sine
96 waves. However, for many of the fractures, the absolute location of the peaks and troughs
97 was not clear. Therefore, a MATLAB program was developed to aid a more robust analysis
98 (see Appendix). Figure 2c shows a tadpole plot of borehole PL10A derived from the OTV
99 log. The tadpole body indicates the dip angle and the tail indicates the strike angle (or dip

100 direction) (Williams and Paillet, 2002). It can be seen that there are many sub-horizontal
101 fractures throughout the extent of the borehole.

102

103 **Packer testing**

104

105 The vertical distribution of hydraulic conductivity was measured using a constant head
106 double-packer permeameter. The double-packer permeameter used in borehole PL10A
107 incorporates a pump, to abstract water from the isolated section, and a transducer to measure
108 the pressure within the section (see Price and Williams, 1993 for more detail). Once the
109 section to be tested is isolated by inflating the packers, water is pumped out of the isolated
110 interval at a constant rate, Q [L^3T^{-1}]. The head in the section is monitored using the
111 transducer and pumping continues until a steady-state drawdown is measured, ϕ_0 [L]. In
112 typical UK Chalk boreholes this takes around 20 minutes. The horizontal hydraulic
113 conductivity of the tested section, K [LT^{-1}] is then calculated using (Hvorslev, 1951)
114 $K = QF / \phi_0$ where F [L] is a shape factor dependant on the ratio of horizontal and vertical
115 hydraulic conductivity and the geometry of the packered abstraction system. The appropriate
116 shape factor for the double packer permeameter is given in the form of a simple polynomial
117 approximation by Mathias and Butler (2007). Assuming an isotropic medium, the resulting
118 hydraulic conductivity profile in Figure 2d is obtained. It can be seen that the hydraulic
119 conductivity values span almost five orders of magnitude. Generally there is a linear-log
120 trend with elevation combined with around an order of magnitude of fluctuation. The profile
121 is similar to those obtained at a number of other Chalk boreholes in the UK (Price et al.,
122 1982; Price and Williams, 1993; Allen et al., 1997) and Israel (Nativ et al., 2003).

123

124 **Pumping test analysis**

125

126 As previously stated, the abstraction well, BBA was pumped at $5770 \text{ m}^3\text{d}^{-1}$ for just over a
127 day. Drawdown and recovery (after the cessation of pumping) were continuously monitored
128 using minitrolls in the three observation boreholes and the abstraction well (Figure 3).
129 Following the recommendation of Meier (1998), estimates of effective transmissivities were
130 obtained using Jacob's straight line method on the late time data. Note that recovery data is
131 plotted on a transformed axis (Agarwal, 1980; Samani and Pasandi, 2003) such that it can
132 also be analysed using Jacob's method. The resulting transmissivity estimates are given in

133 Table 1. The mean transmissivity calculated to be $2049 \pm 230 \text{ m}^2\text{d}^{-1}$ from the drawdown
134 phase results and $2928 \pm 229 \text{ m}^2\text{d}^{-1}$ from the recovery. These are well within the national
135 ranges for the Chalk (MacDonald and Allen, 2001), further supporting that this is a relatively
136 typical site.

137

138 The discrepancy between the drawdown and recovery transmissivities is a common
139 occurrence although rarely addressed. Rushton and Chan (1976) showed that the discrepancy
140 between drawdown and recovery data could sometimes be explained by vertical variations in
141 hydraulic conductivity. Rushton and Booth (1976) and Shapiro et al. (1998) suggest that the
142 discrepancy can also be due to non-linear head losses within the well-bore. However, the idea
143 that non-linear head losses only occur within the well-bore is a common misconception
144 dating back to the empirical work of Jacob (1946). In fact, non-linear head losses due to
145 turbulence, microscopic inertia and microscopic drag (Giorgi, 1997) are likely to occur over a
146 large region within the aquifer around the well-bore due to the fast velocities caused by the
147 convergence of flow-lines (Kohl et al., 1997). This is likely to be particularly important in
148 Chalk aquifers where groundwater flow in the saturated zone is often largely confined to a
149 limited number of well connected flow pathways (e.g. Mathias et al., 2007, Hartmann et al.,
150 2007).

151

152 **Flow logging**

153

154 To gain information about which portions of the aquifer are likely to be contributing to this
155 transmissivity, upflow logs were obtained using both impeller and heat-pulse flowmeters.

156

157 Impeller flowmeter measurement involves lowering an impeller down a borehole at a fixed
158 rate and logging the rotation rate of the impeller. The net upflow velocity is obtained from a
159 simple calibration equation, which in turn can be converted to an estimated flow rate by
160 multiplying by the borehole cross-sectional area obtained from caliper log measurements.
161 Note therefore that noise in the flow impeller profiles is partially due to error in the borehole
162 area measurement. The main shortcoming of impeller flowmeters is their lack of sensitivity to
163 low-velocity flow. For smaller flow rates, a heat-pulse flowmeter is more appropriate.

164

165 The heat-pulse flowmeter was originally developed by Dudgeon et al. (1975). An electrical
166 heating grid, located between two thermistors, is heated by a short pulse of electrical current.
167 The heated lens of water is moved towards one of the thermistors by the vertical component
168 of flow in the borehole. The arrival time of the heat-pulse at the thermistor is recorded. If the
169 heat-pulse is detected by the upper one, flow is upwards and vice versa. The flow velocity
170 can then be calculated by dividing the distance between the element and thermistor by the
171 respective travel time. Again, the flow-rate is estimated by multiplying the velocity by the
172 local cross-sectional area from the caliper log. Note that neither the impeller nor heat-pulse
173 flowmeters used in this study were capable of measuring flow across the borehole. The direct
174 measurement of cross-flow requires more sophisticated instrumentation (e.g. James et al.,
175 2006; Su et al., 2006).

176

177 Figures 4a and 5a show measured upflow profiles for borehole PL10A whilst pumping BBA
178 and under ambient conditions respectively. As the results obtained during pumping are more
179 straightforward to interpret, these are discussed first. It can be observed that there is relatively
180 good correspondence between the impeller and heat-pulse flowmeters. The step changes in
181 the impeller log are indicative of discrete flow horizons. It is apparent that there is an upflow
182 at the base of the borehole, followed by an additional inflow at 27 mAOD, which corresponds
183 to the Chalk Rock (compare Figure 2b). There is a small outflow at 57 mAOD followed by a
184 much larger outflow at 74 mAOD, which is sufficient to change the flow direction. Finally,
185 the impeller and heat-pulse logs suggest that there is an inflow in the vicinity of the water
186 table. This description is further supported by the temperature log in Figure 4b, where
187 inflections can be seen at 27 mAOD and 74 mAOD.

188

189 Under ambient conditions, the picture is more complicated. First, flow rates are generally
190 around a quarter of those for the pumped condition. Second, the impeller flowmeter log in
191 Figure 5a shows an upflow from the base of the hole and an outflow at 57 mAOD that
192 appears to change the flow direction such that there is a substantial downward flow in the
193 upper part of the borehole (the large peak at 63 mAOD is probably due to the flowmeter
194 hitting the side of the borehole). From 57mAOD to 85mAOD the impeller flowmeter results
195 are very variable and always negative. This could be indicative of some downward movement
196 or cross-flow. The temperature log indicates a steep gradient from 57m to 74, confirming
197 very low flows in this interval, but it has a zero gradient above 74mAOD suggesting
198 downward movement perhaps exiting the borehole at 74mAOD. Between 57 and 74 there are

199 only two heat pulse measurements, one positive and similar to those at greater depth, and one
200 of zero at 65m. The higher heat pulse measurements (measuring zero) are found in the region
201 above 74m. It seems likely that the disagreement in these various results is indicative of low
202 vertical flows but significant cross-flow. The distribution of the cross-flow is impossible to
203 estimate but seems likely to be highest at 74mAOD or just above this point, with less
204 significant flow between 57mOAO and 74mAOD.

205

206 **Flow processes within the abstraction well**

207

208 Unfortunately, the pump broke down before the logging team had time to carry out
209 geophysical logging in the abstraction well (BBA). Consequently, it was restarted five days
210 later at a reduced rate of $4750 \text{ m}^3\text{d}^{-1}$. The rate reduction was required for operational reasons
211 and was unfortunate as it made direct comparison with the results from PL10A more
212 problematic. Nevertheless, Figure 6 shows gamma, temperature, fluid electrical conductivity
213 (FEC) and impeller flowmeter logging under pumped and ambient conditions. The gamma
214 log indicates the elevation of the Chalk Rock horizon to be a little higher at 28 mAOD than
215 found in PL10A. The temperature log is relatively flat although there is evidence of warming
216 at 23.6 mAOD where the pump is located. Under ambient conditions, the FEC log shows a
217 distinct step change at 45 mAOD, which is replaced under pumped conditions by three
218 separate changes at 48 mAOD, 61 mAOD and 82 mAOD. These changes are likely to mark
219 the main flowing horizons.

220

221 Figure 6d shows impeller flowmeter data. Under ambient conditions, flow rates are
222 comparable with those observed in PL10A. Under pumped conditions, it appears that
223 $2,000\text{m}^3\text{d}^{-1}$ enters the borehole between 82mAOD and 79mAOD, below which there is a
224 steady increase in down-flow to 61mAOD. At this point a flow of approximately $3600\text{m}^3\text{d}^{-1}$
225 is achieved which is increased to $4750\text{m}^3\text{d}^{-1}$ by 48mAOD. There is considerable uncertainty
226 over this interpretation because the variability in borehole diameter is unknown.
227 Nevertheless, the significant fluctuations about clear trends are believed to be largely due to
228 borehole diameter variability. A caliper log was not available so a constant borehole diameter
229 of 0.762 m was assumed (based on the original completion report). However, as the
230 abstraction borehole was acidized during development to increase the yield (Harker, 1974), it
231 would be reasonable to assume that variations in diameter were accentuated and that active
232 fractures were opened significantly by this process. The acidization process would have

233 depressed the water table considerably and pushed the acid well into the Chalk along open
234 fractures, increasing the permeability greatly.

235

236 **Dilution testing**

237

238 Dilution tests were also performed to complement the logged flow data from PL10A (see
239 Figures 4c and 5c). These involve lowering a fluid electrical conductivity (FEC) probe down
240 the borehole to obtain a measure of background conductivity with depth. A tube is then
241 lowered down to the base of the borehole and filled with a well-mixed saline solution. The
242 tube is then retrieved so as to provide a close to uniform, elevated FEC along the borehole.
243 As water enters and leaves the borehole via natural flow horizons the saline solution is
244 diluted. The rate of dilution is then monitored by subsequent FEC logging. The result is a
245 series of FEC profiles for a range of different times.

246

247 Dilution test data can be inverted to acquire flow rates associated with discrete flow horizons
248 using a dilution test model. Such models generally assume steady-state flow and that the
249 borehole is fully mixed laterally. In this way, solute concentrations within the borehole can be
250 described by a one-dimensional advection dispersion equation subjected to discrete sources
251 and sinks associated with flowing horizons (Tsang et al. 1990).

252

253 Most studies have looked at dilution test model inversions for pumped wells (Tsang et al.
254 1990; Tsang and Doughty, 2003; Evans 1995; Karasaki et al., 2000; Doughty, 2005). This is
255 generally straightforward; providing the pumping rate is large enough, only inflowing
256 features are present. These can be easily located at the beginning of the test as discrete
257 dilution features. However, when the borehole is not directly pumped (as is the case for both
258 ambient and pumped conditions in this paper) the presence of outflowing horizons is likely.
259 Unfortunately, outflow locations are not apparent until later on in the test, by which time the
260 conductivity profiles are generally complex due to the interactions different features
261 (Doughty 2005). Therefore, outflow horizons, and consequently non-pumped wells, are much
262 harder to interpret (Michalski and Klepp, 1990; Williams et al. 2006; Mathias et al., 2007).

263

264 *Pumped conditions*

265

266 Note that the pumped condition did not involve pumping PL10A, but a neighboring
267 abstraction well 35 m away (BBA). Nevertheless, from the analysis of the flowmeter and
268 temperature data, inflows appear to occur at 10 mAOD and 27 mAOD, and outflows at
269 57 mAOD and 74 mAOD. By inspection of the dilution test data, an additional inflow
270 probably exists at 79 mAOD. Using a model similar to that of Tsang et al. (1990), Mathias et
271 al. (2007) obtained the set of calibrated inflows and outflows listed in the flow chart to the
272 right of the dilution test data (Figure 4c). The comparison between the resulting simulated
273 and observed upflow and salt concentration data is very convincing (see Figures 4a and c).

274

275 From these results it is clear that water table observations made in PL10A whilst pumping do
276 not necessarily reflect the overall aquifer response. Rather, they represent the integrated
277 response of the four discrete flow horizons and the upflow from the base of the borehole.

278

279 *Ambient conditions*

280

281 The dilution test performed under ambient conditions is much harder to interpret (Figure 5c).
282 There is definitely an upflow from the base most of which leaves the borehole at 57 mAOD.
283 The difficulty arises in the upper region of the borehole (> 57 mAOD). At a glance, it appears
284 that there are two major inflows at 74 mAOD and 79 mAOD, which push the salt down to the
285 outflow at 57 mAOD. However, this conflicts with the heat-pulse flowmeter and temperature
286 data (compare Figures 5a and b), which suggest that there is very low vertical flow in this
287 region. Furthermore, although salt arising from the bottom of the hole initially looks as
288 though it does not pass the 57 mAOD horizon, the final profile recorded after 587 min shows
289 some passing (subsequent testing has shown that this feature is repeatable). This implies that
290 the vertical flow above 57 mAOD is very small in an upward direction, this is confirmed by
291 the heat pulse measurement at 59mAOD, but which is in complete contrast to the impeller
292 flowmeter data. Therefore, it is assumed that the dilution taking place in the upper region is
293 due to a complex distribution of cross-flow, which is not measured by the impeller or heat-
294 pulse flowmeters.

295

296 Due to the number of degrees of freedom, it is difficult to delineate the vertical distribution of
297 cross-flow using the aforementioned dilution test model. However, an estimate of the total
298 cross-flow, Q_c [L^3T^{-1}] in that region can be obtained using the analytical solution of Drost et
299 al. (1968)

300

$$301 \quad \frac{\bar{c} - \bar{c}_0}{\bar{c}_i - \bar{c}_0} = \exp\left(-\frac{Vt}{Q_c}\right) \quad (1)$$

302

303 where \bar{c} [ML⁻³], \bar{c}_0 [ML⁻³] and \bar{c}_i [ML⁻³] are the mean current, mean background and mean
304 initial salt concentrations respectively, V [L³] is volume of borehole under consideration and t
305 [T] is time after tracer injection.

306

307 Figure 7 shows a plot of mean concentration against time in borehole PL10A for
308 $z > 57$ mAOD under ambient conditions. Interestingly it does not converge on to the mean
309 background value, \bar{c}_0 during the time studied. This is because salt is moving up (albeit at a
310 very slow rate) past the 57 mAOD horizon. Therefore, when fitting the Drost et al. (1968)
311 formula, the \bar{c}_0 parameter should be considered unknown.

312

313 If \bar{c}_0 and \bar{c}_i are known, equation (1) can be fitted to the data using linear regression (by
314 applying a log_e transformation to the concentration data). However, because this is not the
315 case, a non-linear method is required. Specifically, the RMSE (root mean squared error)

316

$$317 \quad \text{RMSE} = \sqrt{\frac{1}{N} \sum_{n=1}^N (\bar{c}_n - \bar{c}_{obs,n})^2} \quad (2)$$

318

319 was minimized using a simplex search method available with MATLAB called
320 FMINSEARCH. N [-] is the number of data samples, \bar{c}_n [ML⁻³] and $\bar{c}_{obs,n}$ [ML⁻³] are the n^{th}
321 modelled and observed concentration values.

322

323 A plot of the calibrated curve alongside the data is shown in Figure 6. The final parameter
324 and RMSE values were $Q_c / V = 0.015 \text{ min}^{-1}$, $\bar{c}_0 = 0.48 \text{ kg m}^{-3}$ and $\text{RMSE} = 0.02 \text{ kg m}^{-3}$. The
325 \bar{c}_i was estimated by averaging the 2 to 8 minutes profile. From the calliper log, the volume of
326 this portion of the borehole was calculated to be $V = 0.97 \text{ m}^3$. Therefore, the estimated value
327 of total cross-flow was found to be $Q_c = 22 \text{ m}^3 \text{ d}^{-1}$.

328

329 **Implications for transmissivity**

330

331 The above calculated value of cross-flow, in conjunction with the local hydraulic gradient,
332 can be used to calculate an additional estimate of aquifer transmissivity that is independent of
333 the perturbation caused by pumping BBA. From the water level elevations in PL10A, PL10B
334 and PL10E prior to pumping BBA, the local hydraulic gradient, J_x [-] was estimated to be
335 $1/(224 \pm 53)$ (error is based on 0.5 cm error on water level elevations). An estimate of the
336 regional groundwater flow, q [$L^3T^{-1}L^{-1}$] can be obtained from $q = Q_c / (\alpha D)$ where D [L] is
337 the borehole diameter and α [-] is a dimensionless borehole factor. Assuming that the well is
338 perfectly circular and the aquifer is isotropic and homogenous, Bidaux and Tsang (1991)
339 calculated that $\alpha = 2$. From the caliper log (Figure 2a) the average diameter of PL10A over
340 the region $57 \text{ mAOD} < z < 86 \text{ mAOD}$ was 0.206 m. It follows that an estimate of the regional
341 groundwater flow around PL10A is $22 / (2 \times 0.206) = 53.4 \text{ m}^3 \text{ d}^{-1} \text{ m}^{-1}$. Applying Darcy's Law
342 then leads to a transmissivity estimate of $11,945 \pm 974 \text{ m}^2 \text{ d}^{-1}$, an order of magnitude larger
343 than the values obtained from the pumping test analysis (in Figure 3) and outside the national
344 statistical distributions presented by MacDonald and Allen (2001). However, for a well
345 developed borehole Bidaux and Tsang (1991) suggest that α might be more around 5, which
346 leads to a more realistic transmissivity value of $4778 \pm 390 \text{ m}^2 \text{ d}^{-1}$.

347

348 Given the difference in flow distributions in PL10A under pumped and ambient conditions,
349 the discrepancy in transmissivity estimates is not surprising. Under pumped conditions, flow
350 was concentrated in just four discrete horizons where as under ambient conditions flow
351 appeared to be distributed over a region of around 29 m thickness, but it seems likely that
352 most cross-flow occurs above 79mAOD. However, if this was really the case, it is expected
353 that the integrated value of the packer test results should also be of the order $5000 \text{ m}^2 \text{ d}^{-1}$. The
354 packer test data in Figure 2d would therefore suggest that there must be features above those
355 measured of significantly greater permeability. Unfortunately it was not possible to observe
356 these as the borehole at this elevation was too wide for the packers.

357

358 **Conclusions**

359

360 This integrated study has revealed significant new insights into the behavior of groundwater
361 flow and head in an observation and abstraction borehole in the UK fractured Chalk aquifer
362 under pumped and ambient conditions. Under pumped conditions the system behaves in a

363 relatively straightforward manner flow being mainly concentrated in four discrete flow
364 horizons. Furthermore, excellent correspondence was observed between the three methods of
365 borehole flow velocity measurement: impeller flowmeter, heat-pulse flowmeter and dilution
366 test inversion. Under ambient conditions the system appears much more complicated.
367 Specifically, in the upper half of the borehole the impeller flowmeter suggested a substantial
368 downward flow, the heat-pulse flowmeter suggested a close to negligible upward flow whilst
369 the dilution testing provided evidence of significant dilution. It was concluded that this was
370 due to the significant cross-flow occurring over a region of 29 m thickness. Analysis of
371 drawdown data, recovery data and a Drost analysis of the ambient crossflow data yielded
372 aquifer transmissivity estimates of $2049 \text{ m}^2\text{d}^{-1}$, $2928 \text{ m}^2\text{d}^{-1}$ and $> 4388 \text{ m}^2\text{d}^{-1}$ respectively.
373 The discrepancy between the drawdown and recovery estimates is assumed to be caused by
374 non-linear head-losses associated with turbulence and inertial effects. The difference between
375 the pumping test and Drost results was then explained by the groundwater flow during
376 pumping bypassing this aforementioned 29 m region of aquifer.

377

378 Changes in observation well flow profiles induced by pumping in another well are primarily
379 thought to occur due to changes in the head distribution of the large-scale flowpaths (Le
380 Borgne et al., 2006). Previously, this phenomenon has been exploited to identify and
381 characterize those features that are directly connected to the abstraction well (Williams and
382 Paillet. 2002; Le Borgne et al., 2006). However, in many instances, aquifer parameters are
383 sought for modeling groundwater or catchment behavior away from the presence of
384 abstraction wells. These might, for example, be to evaluate water resources, minimum
385 environmental stream flows or responses to extreme events (droughts and floods), This
386 emphasises the great care that must be taken in the extrapolation of pumping test results to
387 ambient flow conditions. The marked change in flow pathways also implies that similar
388 caution is required when applying transport parameters obtained during pumping to such
389 conditions.

390

391 **Appendix – Details of the strike and dip program**

392

393 A fracture is identified from a visual inspection of the OTV bitmap image. The user then
394 selects three points anywhere along the fracture intersect: (θ_1, z_1) , (θ_2, z_2) and (θ_3, z_3) , where
395 $0 < \theta < 2\pi$ (i.e. North = 0 and South = π) and z [L] is elevation. The program then
396 superimposes the sine wave

397

$$398 \quad z = \Delta z \sin(\theta + \alpha) + z_0 \quad (3)$$

399

400 where

401

$$402 \quad \Delta z = a \sec(\alpha) \quad (4)$$

$$403 \quad \tan(\alpha) = -b / a \quad (5)$$

$$404 \quad z_0 = \frac{z_3 \sin(\theta_1 - \theta_2) + z_2 \sin(\theta_3 - \theta_1) + z_1 \sin(\theta_2 - \theta_3)}{\sin(\theta_1 - \theta_2) + \sin(\theta_3 - \theta_1) + \sin(\theta_2 - \theta_3)} \quad (6)$$

405

406 and

407

$$408 \quad a = \frac{(z_3 - z_2) \cos(\theta_1) + (z_1 - z_3) \cos(\theta_2) + (z_2 - z_1) \cos(\theta_3)}{\sin(\theta_1 - \theta_2) + \sin(\theta_3 - \theta_1) + \sin(\theta_2 - \theta_3)} \quad (7)$$

$$409 \quad b = \frac{(z_3 - z_2) \sin(\theta_1) + (z_1 - z_3) \sin(\theta_2) + (z_2 - z_1) \sin(\theta_3)}{\sin(\theta_1 - \theta_2) + \sin(\theta_3 - \theta_1) + \sin(\theta_2 - \theta_3)} \quad (8)$$

410

411 The three points can then be moved independently, and the sine wave automatically corrects
412 itself to fit them. The user can keep moving the points until an appropriate visual fit between
413 the sine wave and the fracture intersect is achieved (see Figure 8). The final values of (θ_1, z_1) ,
414 (θ_2, z_2) and (θ_3, z_3) are subsequently stored. The strike and dip of the fracture can then be
415 obtained from

416

$$417 \quad \text{strike} = \begin{cases} \pi / 2 - \alpha, & \Delta z < 0 \\ 3\pi / 2 - \alpha, & \Delta z \geq 0 \end{cases} \quad (9)$$

$$418 \quad \text{dip} = \arctan(2 |\Delta z| / D) \quad (10)$$

419

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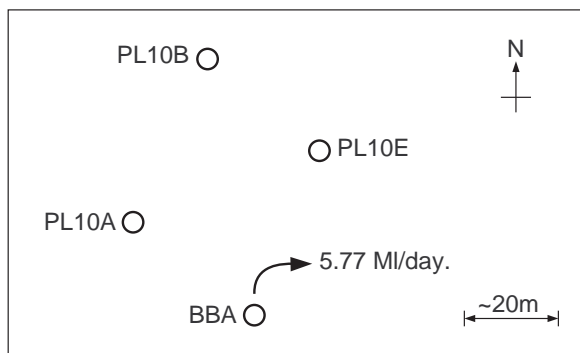
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518 **Table 1** Transmissivity data obtained from Jacob analysis (see Figure 3)

519

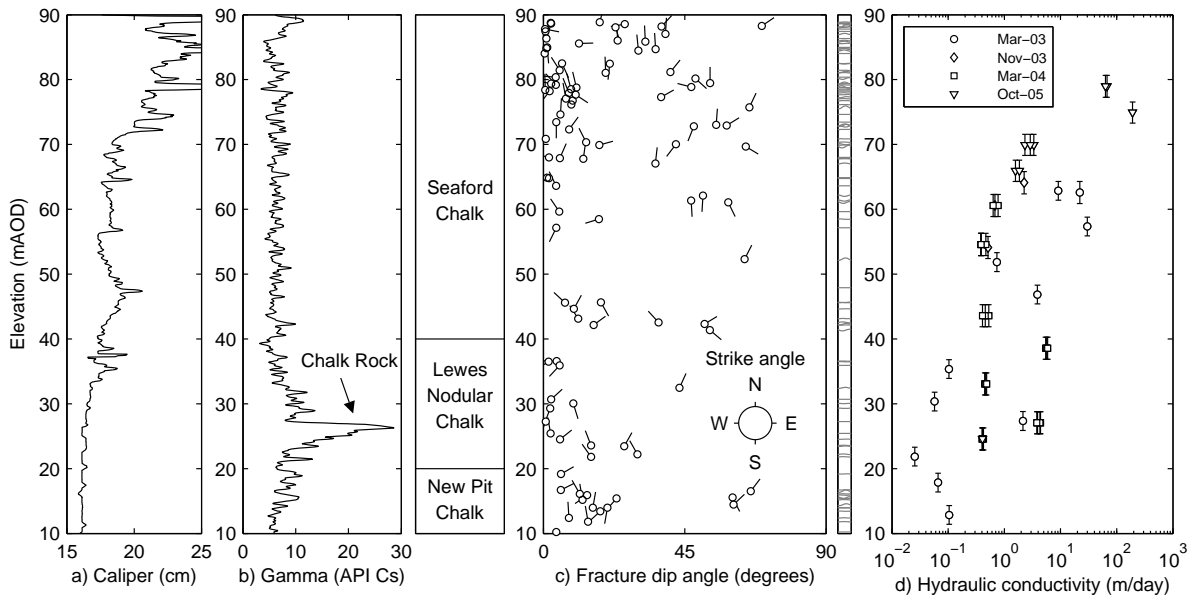
520 Borehole	Drawdown	Recovery
521 BBA	1782 m ² /day	2933 m ² /day
522 PL10A	2328 m ² /day	3076 m ² /day
523 PL10B	2219 m ² /day	3147 m ² /day
524 PL10E	866 m ² /day	2555 m ² /day
525 Mean	2049 m ² /day	2928 m ² /day
526 Standard deviation	230 m ² /day	229 m ² /day

527



528

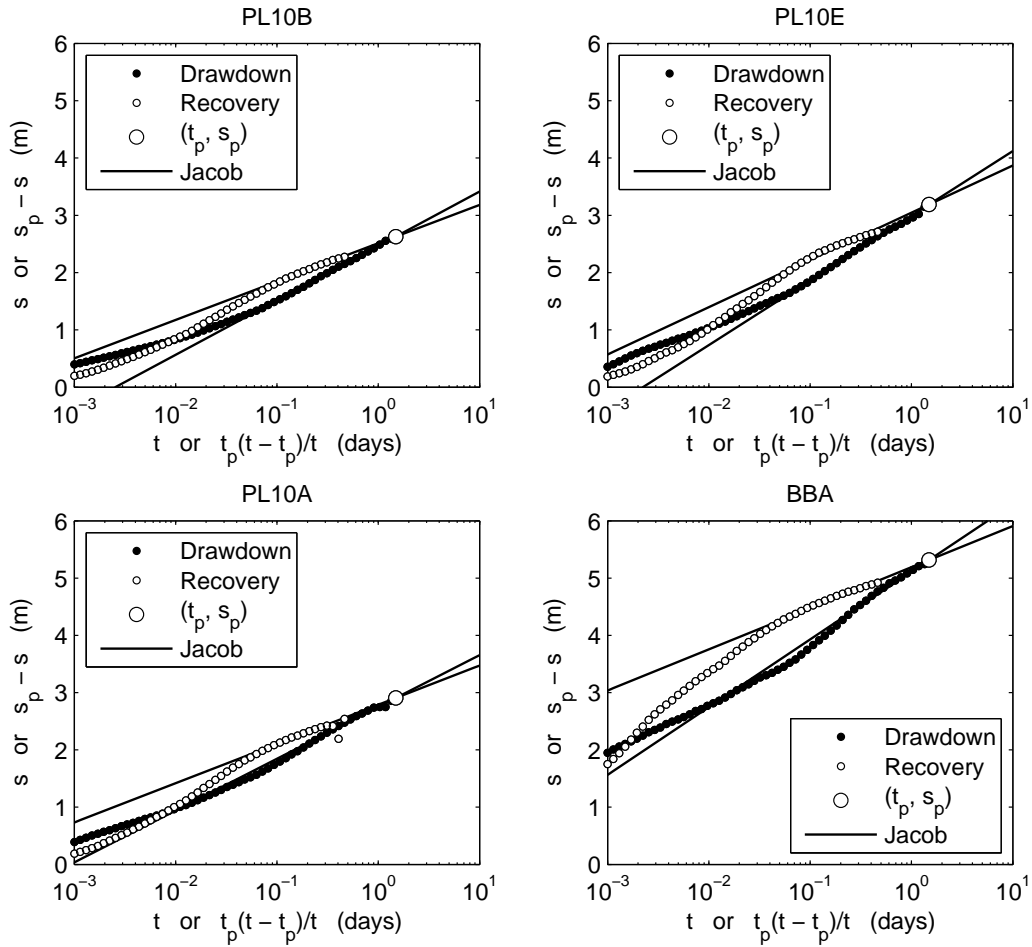
529 **Figure 1** Site layout



530

531 **Figure 2** Stratigraphy, fracturing and hydraulic conductivity distributions for borehole
 532 PL10A. Subplot (a) shows the variation of borehole diameter with elevation. Subplot (b)
 533 shows a natural gamma log along with the stratigraphy inferred from it. Subplot (c) is a
 534 tadpole plot, derived from the televiewer log (see sketch to the right), showing the dip
 535 (tadpole body) and strike (tadpole tail) of the fractures. Subplot (d) shows the hydraulic
 536 conductivity distribution measured from the constant head double packer permeameter tests.
 537 These were taken at different dates as detailed in the legend. The error bars represent the
 538 length of isolated interval (≈ 3 m).

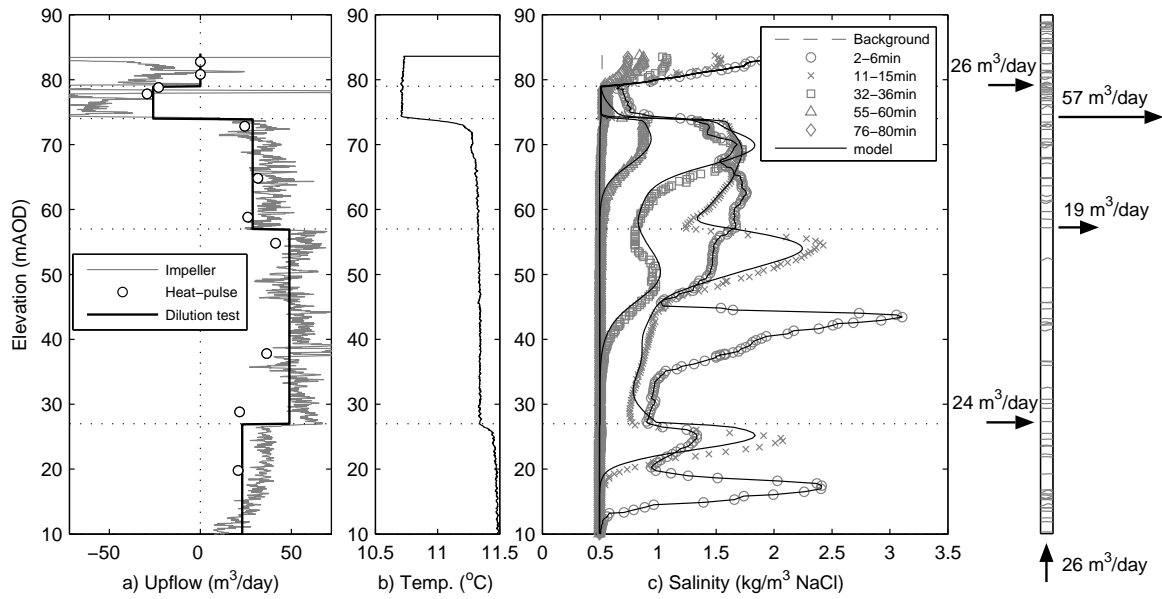
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541 **Figure 3** Plots of drawdown and recovery for BBA, PL10A, PL10B and PL10E whilst
 542 pumping BBA at 5.77 ML/day. Note that t_p and s_p refers to the time the pump was switched
 543 off and the corresponding drawdown. For drawdown s is plotted against t where as for
 544 recovery $s_p - s$ is plotted against $t_p(t - t_p)/t$.

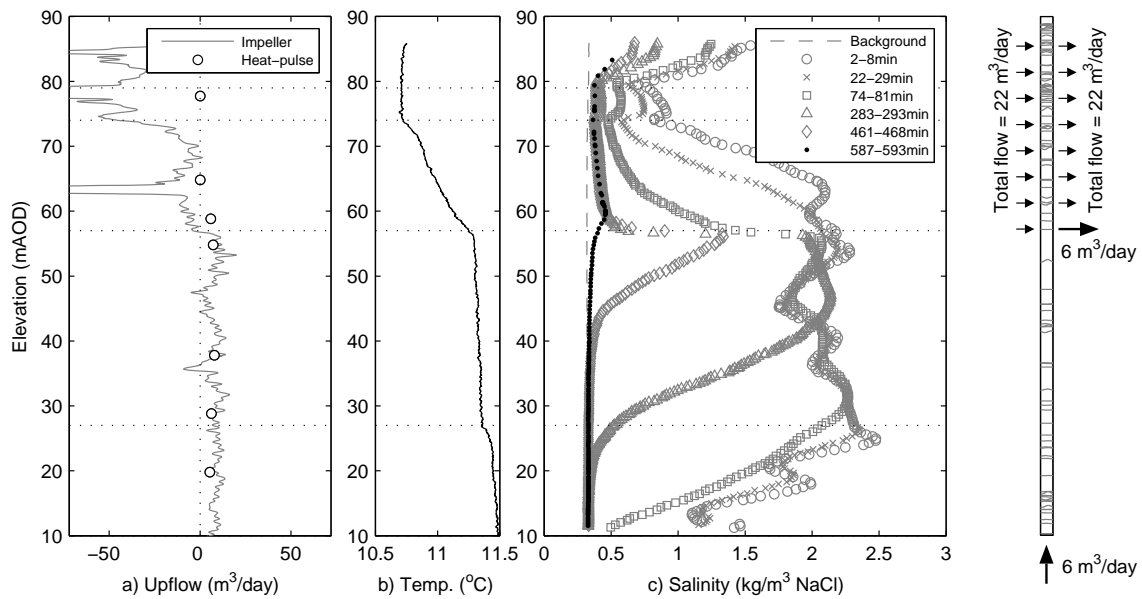
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547 **Figure 4** Flow logging, temperature logging and dilution testing in PL10A whilst pumping
 548 the Bottom Barn abstraction well (≈ 35 m away).

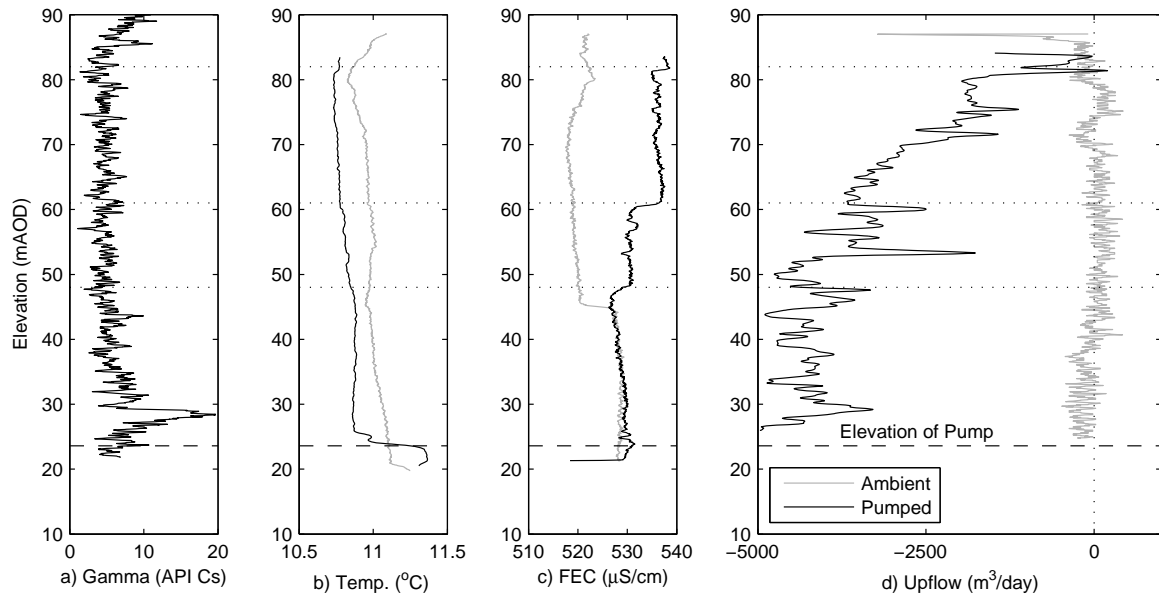
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551 **Figure 5** Flow logging, temperature logging and dilution testing in PL10A under ambient
 552 conditions.

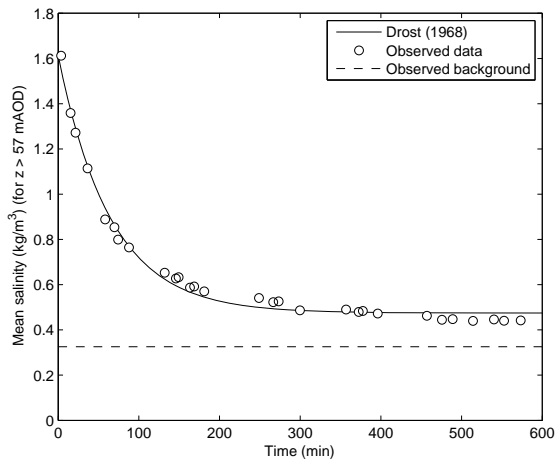
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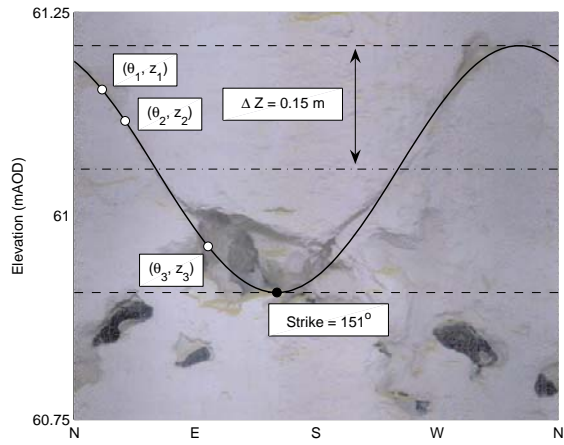
555 **Figure 6** Gamma, temperature, fluid electrical conductivity and impeller flowmeter logging
 556 in BBA. Note that this logging was undertaken 5 days after the previously discussed pumping
 557 test and the BBA was pumped at a reduced rate of 4750 m³/day.

558



559

560 **Figure 7** Plot of mean concentration against time in borehole PL10A for $z > 57$ mAOD under
 561 ambient conditions.



562

563 **Figure 8** An example of a sine wave fit to a fracture in borehole PL10A.