Measuring Well Hydraulic Connectivity in Fractured Bedrock using Periodic Slug Tests

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Abstract:

Periodic hydraulic experiments were conducted in a five-spot well cluster completed in a single bedding plane fracture. Tests were performed by using a winch-operated slug (submerged solid cylinder) to create a periodic head disturbance in one well and observing the phase shift and attenuation of the head response in the remaining wells. Transmissivity (T) and storativity (S) were inverted independently from head response. Inverted T decreased and S increased with oscillation period. Estimated S was more variable among well pairs than T , suggesting S may be a better estimator of hydraulic connectivity among closely spaced wells. These estimates highlighted a zone of poor hydraulic connection that was not identified by a constant rate test conducted in the same wells. Periodic slug tests appear to be a practical and effective technique for establishing local scale spatial variability in hydraulic parameters.

1 Introduction

Flow channelization has long been recognized as a hallmark of groundwater flow in fractured bedrock systems [Tsang and Neretnieks, 1998]. The physical nature of the problem is described simply through the cubic law which dictates that water flow rate is related cubically to the local fracture aperture. Prediction of flow in a natural bedrock system is not so simple, however, as the distribution of aperture and its interaction with water flow is highly variable even within a single fracture. Understanding flow in bedrock consequently requires site specific hydraulic characterization to be conducted.

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Typical pumping and slug test configurations are not well suited to bedrock environments. Because of the small water storage in bedrock, the hydraulic radius of influence of a pumping well extends rapidly outward implying that only the earliest drawdown contains local information. Early drawdown is often dominated by well-bore storage and formation damage effects in open boreholes. Slug test responses are weighted more toward local hydraulics but are even more sensitive to borehole influences.

A periodic hydraulic test potentially overcomes some of the limitations of pumping and slug tests. Periodic (also called harmonic, oscillatory, or sinusoidal) tests are conducted by creating an oscillating head in one well and observing the corresponding oscillatory head response in one or more observation wells. Because the head signal is in a constant state of transience, periodic tests highlight the influence of formation storativity on drawdown response. The repeatability of the transience allow initial effects of well bore storage and pump priming to be isolated. Most interestingly, periodic tests are capable of interrogating different portions of the formation without the addition of observations wells. This is because the spatial weighting of hydraulic response to transmissivity (T) and storativity (S) is sensitive to the frequency of the head oscillation [Cardiff *et al.*, 2013; Renner and Messar, 2006]. Periodic tests have also been shown to be more sensitive than constant rate tests to the length of a flow path between an oscillating source and observation well [Fokker *et al.*, 2012]. By conducting periodic tests at varying frequency, different regions of the formation can be tested for hydraulic conductivity and storativity. While this is true for any type of groundwater system, it is particularly effective in bedrock systems because the small storage coefficients means a small head perturbation propagates far from the test well.

Periodic hydraulic testing is by no means a new measurement technique. Periodic hydraulic testing was used in the oil industry as early as 1966 [Black and Kipp, 1981]. During the 1970s it was put to use in oil production wells using alternating periods of flow and shut-in [Hollaender et al., 2002]. The earliest report of periodic tests in the groundwater literature regards the use of naturally occurring periodic oscillations such as earth tides or barometric changes [Black and Kipp, 1981]. These natural periodic influences have the advantage of extending over many kilometers but are generally limited to only a few frequencies (diurnal, seasonal, tidal) and are difficult to isolate due to the complexity of these systems and the mixing of different processes [Rasmussen et al., 2003].

We demonstrate here the use of periodic testing in a single bedding plane fracture at the 10 m scale. In our experiments, head is varied in the test well by oscillating a slug up and down at the level of water in the well. The periodic head response is observed at four observation wells. Because we limit our experiment to a single fracture we highlight aperture variability rather than fracture network connectivity in our experiments. Matrix porosity is negligible so the hydraulics are dictated by the fracture only.

The development of this characterization tool is particularly relevant to geologic fluid circulation systems such as those used in groundwater remediation, petroleum recovery, and geothermal plants. In all of these systems, flow channeling can lead to a short circuiting of the circulation system that may result in inefficient extraction of contaminated groundwater, petroleum reserves, or geothermal heat, respectively. Periodic tests may provide a means for characterizing problematic channeling either before or during operations. Because it is not necessary to extract water or shut down pumps to conduct these tests, they are likely to be much more cost effective than shut-in hydraulic or cross-hole tracer tests.

2. Methods

2.1 Experimental Site

The Altona Flat Rock Site is located in Clinton County, New York, approximately 25 km northwest of Plattsburgh, New York. It is situated in an exposed pavement of the Cambrian aged Potsdam formation, laid bare by a glacial dam burst at the end of the most recent glacial advance [Rayburn *et al.*, 2007]. The upper Potsdam is highly cemented with silica and thin sections from the site reveal local matrix porosity that is around 1 to 2 percent. Consequently, fractures are the dominant conduit for flow with insignificant flow and storage in the matrix at local scales.

Ground penetrating radar testing revealed a major water-bearing bedding plane fracture (dipping $\sim 3^\circ$) at 7.6 m below ground surface [Becker and Tsoflias, 2010; Talley, 2005; Talley *et al.*, 2005; Tsoflias and Becker, 2008]. A well field was installed at the site in a “five spot” configuration in 2004 (Figure 1).

2.2 Periodic Hydraulic Testing

To create the sinusoidal head signal in the hydraulic source well, a “slug” consisting of a 1.9 cm diameter watertight cylinder was lifted and lowered in the well annulus via a winch operated by a computer controlled stepper motor (Driver: ST10-Si, Motor: HT34-486, Applied Motion Products, Watsonville, CA). A straddle packer system (specially constructed of PVC by RocTest, Lakewood, Colorado) with a 10.2 cm (4 in) inner diameter was used to isolate the hydraulic disturbance to the target fracture. Figure 2 depicts the field setup for the source well during the tests. Pressure transducers were installed to observe the head response in the source and monitoring wells (Druck 1230 Series and a Solinst Levelogger model #3001). The transducers in the monitoring wells were placed within straddle packers (Vanderlans and Sons,

Lodi, California) and routed to a datalogger (CR1000, Campbell Scientific, Logan, Utah) allowing the transducers to be monitored in real-time. The field design assured that all flow occurred in the single bedding plane fracture, i.e. constrained to two dimensions. Three different frequencies were created at each well while all were monitored for head changes.

Interpretation was performed by assuming confined conditions and a formation of infinite extent. The boundary value problem is then

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r} \frac{\partial s}{\partial r} = \frac{1}{D} \frac{\partial s}{\partial t} \quad (1)$$

$$s(r, 0) = 0 \quad (2)$$

$$s(\infty, t) = 0 \quad (3)$$

$$\lim_{r \rightarrow 0} r \frac{\partial s}{\partial r} = -\frac{Q}{2\pi T} \quad (4)$$

where s is the observed drawdown, r is the distance from the center of the pumping well, T is the formation transmissivity, and D is the hydraulic diffusivity. The hydraulic diffusivity is the ratio of the transmissivity to the storativity ($D = T/S$). The flux of water from the well, Q , is the real part of the complex periodic function:

$$Q(t) = Q_0 e^{i\omega t} \quad (5)$$

where i is the complex variable and ω is the frequency of the oscillation.

108 A solution for periodic drawdown was first presented by Black and Kipp [1981] and later by Rasmussen
 109 et al., [2003] who provide a method for T and S to be derived independently from observed drawdown.
 110 The solution for drawdown is

$$111 \quad s(r, t) = \frac{Q}{2\pi T} K_0 \left(r \sqrt{\frac{i\omega}{D}} \right) \quad (6)$$

112 where K_0 is the zero-order modified Bessel function of the second kind . Equation (6) neglects a
 113 period of early time in which the signal has not yet become steady periodic. The amplitude of
 114 the drawdown oscillation in an observation well is

$$115 \quad |s| = \frac{Q_0}{2\pi T} \left| K_0 \left(r \sqrt{\frac{i\omega}{D}} \right) \right| \quad (7)$$

116 and the phase shift between the flux at the test well and the drawdown at the observation well is

$$117 \quad \phi_0 = \phi_s - \phi_Q = \arg \left\{ K_0 \left(r \sqrt{\frac{i\omega}{D}} \right) \right\} \quad (8)$$

118 where ϕ_s is the phase of the drawdown signal and ϕ_Q is the phase of the flux of water at the test
 119 well.

120

121 Following Rasmussen et al., [2003], parameters T and D (and therefore $S = T/D$) were obtained
 122 by fitting periodic functions to the measured flux and drawdown data. At the test well, the
 123 oscillating flux is fit with the cosine function

$$124 \quad Q(t) = Q_0 \cos(\omega t - \phi_Q) = Q_1 \cos \omega t + Q_2 \sin \omega t \quad (9)$$

125 where Q_0 is the amplitude, ω the frequency, and ϕ_Q this phase of the flux signal at the test well.

126 The coefficients Q_1 and Q_2 represent $Q_0 \cos \phi_Q$ and $Q_0 \sin \phi_Q$, respectively. Likewise, the
127 drawdown at the observation well is fit with the function

$$128 \quad s(t) = s_1 \cos \omega t + s_2 \sin \omega t \quad (10)$$

129 where the coefficients s_1 and s_2 represent $s_0 \cos \phi_s$ and $s_0 \sin \phi_s$, respectively, and s_0 is the
130 amplitude of the drawdown. After fitting the functions (9) and (10) to the flux and drawdown
131 signals, respectively, the phase lag, ϕ_0 , is found from

$$132 \quad \phi_0 = \arctan\left(\frac{s_2}{s_1}\right) - \arctan\left(\frac{Q_2}{Q_1}\right) \quad (11)$$

133 The magnitude of the drawdown, s_0 , is found by normalizing the modulus of the drawdown
134 signal to the modulus of the flux signal as

$$135 \quad s_0 = \frac{|s|}{|Q|} = \frac{\sqrt{s_1^2 + s_2^2}}{\sqrt{Q_1^2 + Q_2^2}}. \quad (12)$$

136 To facilitate the inversion of D from ϕ_0 in equation (8), we use a fifth order logarithmic
137 polynomial [Rasmussen *et al.*, 2003]:

$$138 \quad \ln\left(\frac{\omega r^2}{D}\right) = \sum_{j=0}^5 c_j (\ln \phi_0)^j \quad (13)$$

139 where $c_j = (-0.12665, 2.8642, -0.47779, 0.16586, -0.076402, 0.03089)$. Transmissivity is
140 obtained by solving (7) for transmissivity and substituting (12):

$$T = \frac{\left| K_0 \left(r \sqrt{\frac{i\omega}{D}} \right) \right|}{2\pi s_0} \quad (14)$$

To determine flux in and out of the test well due to the oscillation of the slug (9), the volume of water gained or lost from the test well must be calculated from the slug displacement and water rise and fall in the well. The slug displacement was controlled through programmed movements in the stepper motor and the water level in the well was measured with a pressure transducer. The difference between slug volume displacement and the water volume change within the well is the volume of water gained or lost by the formation. To determine the flow rate this difference is fit to a sinusoidal signal

$$V(t) = A \sin \left(\frac{2\pi t}{P} - \phi \right) \quad (15)$$

where A is the amplitude, P is the period of the oscillation, and ϕ is the phase lag. The derivative of Equation (15) with respect to time is, therefore, the flow rate into and out of the fracture:

$$Q(t) = A \left(\frac{2\pi}{P} \right) \cos \left(\frac{2\pi t}{P} - \phi \right). \quad (16)$$

The process of extracting the flux is illustrated for well 404 in Figure 3. The flow rate precedes the observed change in head by a slight phase shift [Renner and Messar, 2006].

2.3 Constant Rate Pumping Test

A constant-rate pump test was conducted as a comparison to the periodic slug tests. A submersible pump was used to withdraw water at a rate of 3.3 L/min from the packer isolated

fracture in well 404. Straddle packers were installed across the target fracture in each monitoring well and pressure transducers (Leveloggers, Solinst, Waterloo, Canada) were deployed to monitor the drawdown.

3 Results

3.1 Periodic Hydraulic Tests

During three different slug oscillation periods head response in the monitoring wells equidistant from the test well, 404, differ from 404 in both amplitude and phase (Figures 4, 5, and 6). Well 204 displays a modest attenuation of the amplitude and minor phase lag, while well 104 shows a significant attenuation and phase lag. Wells 304 and 504 show a nearly identical response in between that of 204 and 104. The relationships between the signals are independent of the frequency of the test; however, the amplitude increases with decreasing period as the displaced water has less time to enter the formation. This results in an increased head in the wellbore and higher flowrates in the formation (Figure 7). The inability to create a flowrate with the same amplitude, regardless of frequency, is a limitation of our field set-up that could be overcome by the use of slugs of different volumes. The amplitudes in the observation wells range from about 0.1 to 0.2 meters. The greatest attenuation and phase lag of the input signal was observed at well 104. Past experience with slug and tracer testing at the site confirms that this well is poorly connected hydraulically to the remainder of the well field [Becker and Tsoflias, 2010; J. Talley *et al.*, 2005].

Using well 104 as the test well resulted in highly attenuated and shifted signals at the monitoring wells (Figure 8). The experimental setup was as described previously, except that the straddle

system and slug was moved from well 404 to 104. Well 404 was fitted with the same straddle system used in the other observation wells. These results were expected due to the poor hydraulic communication between well 104 and the remainder of the well field.

Figure 9 presents all estimates of hydraulic diffusivity based upon responses to head oscillations in well 404. The estimates of hydraulic diffusivity range over two orders-of-magnitude among well pairs. Well 204 had the greatest estimated hydraulic diffusivity and 104 the smallest. With only a few exceptions we find good reciprocity between well pairs which demonstrates that the analysis is repeatable. The hydraulic diffusivity estimates made based upon responses to head oscillations at all wells within the well field range from $0.52 \text{ m}^2/\text{sec}$ to $190 \text{ m}^2/\text{sec}$ (Table 1).

3.2. Constant Rate Test

For comparison to the periodic tests, constant rate pumping tests were performed at well 404(Figure 10). Hydraulic diffusivity was determined for all four observation wells by fitting a Theis curve to the drawdown, ignoring the first few minutes of drawdown. Hydraulic diffusivity estimated from each of the four observation well responses was estimated to be one to two orders of magnitude less than those estimated by the periodic tests. The relationship between each well pair is consistent amongst each test. The periodic tests appear to be more sensitive to well connectivity than the constant rate tests (Figure 11).

4. Discussion

Estimates of hydraulic diffusivity obtained from the periodic tests (Figure 9) vary by more than an order of magnitude even though all measurements were made in the same bedding plane fracture. The range in hydraulic diffusivity is due primarily to the variation in estimated storativity (Figure 12) rather than transmissivity (Figure 13). Prior theoretical studies have

shown that diffusivity tends to be representative of the hydraulic connection among closely spaced wells and may also be a strong predictor of tracer transport [*Knudby and Carrera*, 2006].

Periodic test estimates of hydraulic diffusivity generally decreased as oscillation period increased for all monitoring wells (Table 1). *Renner and Messar* [2006] observed a similar relationship in sinusoidal periodic hydraulic tests conducted in fractured sandstone bedrock. In their tests, wells were hydraulically connected through a series of fractures, rather than a single fracture. These authors suggested that estimated storativity increased with oscillation period as water had more time to exchange between a “backbone” of more direct water flow and the surrounding fracture void space.

Cardiff et al. [2013] arrived at a different interpretation of *Renner and Messar’s* [2006] experiments using numerical simulations of periodic hydraulic tests. They used adjoint methods to show that the sensitivity of observed drawdown to the hydraulic diffusivity changes spatially as period changes. The authors reasoned that the different parameter estimates obtained at different frequencies by *Renner and Messar* [2006], as well as by ourselves in a preliminary study [*Becker and Gultinan*, 2009], reflect differences in the sensitivity of oscillatory tests at different frequencies to aquifer heterogeneity. For example, well bore damage or negative skin might cause a local increase in estimated T that would lead to an observed decrease in estimated T (and D) at longer oscillation periods as greater radial distances from the source well were interrogated.

We do not favor this interpretation. First, *Ahn and Horne* (2011) demonstrated that skin (negative or positive) has no effect on sinusoidal periodic pressure signals observed in response to an oscillating source. Also, we see most of the variability with period occurs in estimates of

storativity, which is not considered in wellbore skin. Similarly, a damage zone would likely have little influence on storativity unless it was highly broken. We have seen no evidence of such broken zones in our downhole camera logging. Lastly, both skin and damage zone would be highly local and as discussed below, the influence of these tests extends many meters away from the oscillating well. In any case, we consider the cause of the consistent trend in estimates of D with oscillation period to be an open question that deserves further analysis. Recent development of numerical methods that solve the oscillating problem in the frequency domain [Cardiff et al., 2013; Fokker et al., 2013; Fokker et al., 2012; Fokker and Verga, 2011, Vinci et al., 2014] will be a helpful tool in this regard.

A common estimate of the range of impact from a hydraulic test in a confined formation is the hydraulic radius or, in the case of oscillatory tests, penetration depth. Both are given by, or proportional to, $1.5\sqrt{D\tau}$, where τ is the characteristic time of penetration [e.g. Renner and Messar, 2006]. In periodic tests, τ is assumed to be the period of oscillation while in constant rate tests τ is taken to be the time since pumping began. In our tests, period of oscillation was between 1 and 4 minutes, while the pumping test was conducted over a period of 10's of minutes or more. This difference in characteristic times suggests that pumping tests interrogated a much larger area than the periodic tests.

Because transmissivity is derived from the late time slope of the pumping test drawdown, the lack of sensitivity to well position in pumping tests is expected. The radius of influence (depth of penetration) for periodic tests ranged between 4 m and 161 m with an average of 61 m (calculated from Table 1). These measures suggest that even the periodic tests influenced an

area much larger than the well field. In retrospect, we should have run our experiments at shorter periods (0.5 to 4 min) to focus on interwell distances.

The reader should also be aware that we are inverting radially symmetric one-dimensional representations of flow in a fracture that is certainly heterogeneous with respect to aperture and, therefore, transmissivity. In a previous article we inverted constant rate pumping tests in an attempt to estimate a variable field of both T and S [Castagna *et al.*, 2011]. We found that a graphical Cooper-Jacob (one-dimensional radially symmetric) analyses of individual pump tests suggested an almost spatially homogeneous transmissivity field (nearly constant late time slope) and a spatially heterogeneous storativity field (variable intercept), while a Bayesian stochastic inversion suggested that both T and S are spatially heterogeneous. A negative correlation between T and S was observed in our inversion as was also observed in a similar inversion by Illman *et al.* [2009] at the Mizunami Underground Research Laboratory. Although Equation 7 suggests that estimated T and S can be separated during the inversion, it remains to be seen how periodic hydraulic tests are able to estimate a correlated stochastic T and S field.

None of the analyses mentioned thus far account for hydromechanical dilation of the fracture aperture. Decreasing the period of head oscillation provides less time for water to move into the formation resulting in larger amplitude waves with greater hydraulic force to dilate fractures. This dilation could explain the decrease in transmissivity with period shown in Figure 13. Other researchers have performed single well experiments in which aperture dilation has been measured by extensimeters in response to repeated slug testing [Svenson *et al.*, 2008]. The use of coupled extensimeter measurements perhaps in concert with tilt meter measurements [Vasco *et al.*, 2001], would help constrain the interpretation of periodic testing in bedrock.

5. Conclusions

Periodic hydraulic experiments were conducted by oscillating a slug in a wellbore isolated at a saturated bedrock fracture. A periodic solution of the standard Theis problem was used to extract transmissivity and storativity from observed amplitude and phase relationships between the tested well and an observation well. Storativity estimates, and to a lesser extent transmissivity estimates, varied distinctly among some well pairs in the five tested wells. The ratio of estimated transmissivity to estimated storativity (hydraulic diffusivity) has been suggested as a predictor of hydraulic and transport connectivity in heterogeneous groundwater systems [Knudby and Carrera, 2006]. The connectivity estimated in these periodic hydraulic tests agrees with tracer experiments and ground penetrating radar imaging conducted in the same well field [Becker and Tsoflias, 2010].

For problems that require local estimations of hydraulic connectivity among wells, periodic slug tests appear to be an attractive tool. Aside from the localization of the hydraulic stress field, they require no net extraction of water. A mass neutral test is beneficial in contaminated environments where extracted water must be tested and/or treated. Advances in the sensitivity of pressure transducers and the fact that only sensor precision and not accuracy is required to interpret periodic tests, suggest that they may be useful in near well porous as well as fractured bedrock systems [Bakhos et al., 2014]. An oscillating signal with a slug connected to a computer controlled winch is relatively straightforward and produces excellent signal to noise ratio of head perturbations. Consequently, it may be worth considering periodic slug tests in closely spaced wells completed in formations of small storativity.

Periodic tests were repeated for oscillation periods that varied between one and four minutes. Thus measured, the apparent transmissivity decreased and the storativity increased with

oscillation period. Past researchers have observed this same relationship from periodic pumping tests in fractured bedrock and interpreted it as a result of flow interaction between a “backbone” of flow in channels and surrounding stagnant zones [Renner and Messar, 2006]. A relationship between oscillation period and estimated hydraulic transmissivity has been observed also in single pulse tests [Nakao *et al.*, 2005].

More recent synthetic simulations [Cardiff *et al.*, 2013] show that varying source periodicity changes the sensitivity of head oscillations in observation wells to distributed hydraulic parameters, suggesting our observations may be the result of structured heterogeneity (e.g. open apertures or cross-cutting fractures) in the vicinity of the well field. This analysis may turn out to be a generalization of the “backbone” conceptualization of flow. Not considered in these analyses or our own is that hydromechanical effects can cause non-linear relationships between head and storage [Cappa *et al.*, 2008; Rutqvist and Stephansson, 2003; Svenson *et al.*, 2008].

For comparison, a constant rate pumping test was conducted in the same well field and analyzed by fitting a Theis curve to the drawdown. The periodic tests appear to be more sensitive to the hydraulic connectivity among well pairs. The trend in hydraulic diffusivity estimated from the periodic tests appears to approach that estimated from the steady rate tests as the oscillation frequency decreases (Figure 11), as would be expected according to the analyses of Cardiff *et al.* [2013].

Research to date, including this work, suggests that the period-dependency of apparent (i.e. homogenous equivalent) hydraulic parameters is a result of heterogeneous flow and storage in the formation. Thus, periodic hydraulic testing may provide a means to characterizing flow channeling in bedrock fractures and fracture networks. In our estimation, the full potential of

periodic testing for bedrock is as of yet untapped due to a lack of theoretical understanding. To date, theoretical models have been based upon near homogeneous hydraulic parameters and/or linear hydromechanical properties, while fractured bedrock rarely exhibits either quality in response to hydraulic stresses. Given the impact of flow channeling on groundwater, geothermal, and petroleum problems, the use of periodic hydraulic tests in bedrock systems deserves further investigation.

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Figure 1

Figure 1. Site well configuration.

Figure 2

Figure 2. Schematic of the experimental design of the hydraulic source well.

Figure 3

Figure 3. An example of the extraction of flow in and out of the test well: well 404 with a slug oscillation period of 242.6 seconds.

Figure 4

Figure 4. Periodic test at well 404. Period – 242.6 seconds.

Figure 5

Figure 5. Periodic test at well 404. Period - 121.4 seconds.

Figure 6

Figure 6. Periodic test at well 404. Period – 60.7 seconds.

Figure 7

Figure 7. Flow rates during tests conducted at Well 404. Calculated flow rates ignore an initial transient period at the start of each test.

Figure 8

Figure 8. Periodic tests at well 104. Period – 112.4 seconds. Note the change of scale for the monitoring well drawdown.

Figure 9

Figure 9. Calculated hydraulic diffusivity during the well 404 tests.

Figure 10

Figure 10. Drawdown (points) at well 104 in response to pumping well 404. A Theis drawdown curve is displayed for comparison (solid line; $T = 8.2 \text{ E-}5 \text{ m}^2/\text{min}$; $S = 2.2 \text{ E-}4$).

Figure 11

Figure 11. A comparison of hydraulic diffusivity estimates from the constant rate test and periodic tests at well 404.

Figure 12

Figure 12. Calculated storativity from the well 404 tests.

Figure 13

Figure 13. Calculated transmissivity from the well 404 tests.

Table

Tested Well	Period (seconds)	Hydraulic Diffusivity Estimated at Observation Well				
		(m ² /s)				
		104	204	304	404	504
104	56.2	--	9.85	8.51	6.99	11.56
	112.4	--	3.58	2.88	2.13	4.58
	242.6	--	0.96	0.79	0.52	1.43
204	60.7	4.17	--	39.67	22.15	15.24
	121.4	4.2	--	50.32	48.75	17.72
	242.6	2.01	--	14.65	10.87	6.29
304	56.2	9.26	168.15	--	106.62	152.81
	112.4	5.2	67.6	--	30.61	37.39
	224.6	2.23	18.58	--	6.72	8.88
404	60.7	4.59	189.75	71.49	--	32.34
	121.4	2.59	48.18	19.05	--	11.49
	242.6	1.34	16.45	6.57	--	4.99
504	56.2	15.24	56.84	166.32	58.65	--
	112.4	7	17.35	29.55	12.4	--
	224.6	3.68	7.47	10.29	5.06	--

Table 1. Estimates of hydraulic diffusivity obtained from periodic tests conducted in the Altona well field.