MANAGEMENT OF IN-SITU RECOVERY (ISR) MINING FLUIDS IN A CLOSED AQUIFER SYSTEM

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ABSTRACT

The Beverley uranium mine, operated by Heathgate Resources (Heathgate), is located on the arid plain between the northern Flinders Ranges and Lake Frome, approximately 550 km North of Adelaide in South Australia. The deposit exists as coffinite mineralisation hosted in permeable sands within the confined, saline Beverley aquifer, some 125m below the ground surface. Uranium is mined using moderately acidic in-situ recovery (ISR) technology which entails circulating oxidizing fluid through the ore body to mobilize the uranium which is then pumped to the surface and recovered. Oxidizing fluid is then re-circulated and as the chloride levels become unmanageable the excess, high chloride, fluids are stored within the mined-out areas of the aquifer.

The demonstrated ability to manage both the mining fluids and the high chloride "disposal stream" within the aquifer system was a critical criterion of permitting and regulatory approval of the mine in the late 1990s. This approval was contingent on Heathgate demonstrating a robust understanding of the hydrogeological structure of the aquifer hosting mineralisation. Studies into the structure of the aquifer, to demonstrate that fluids could be controlled comprised the interpretation of data obtained through a number of hydraulic (pumping) tests.

From a hydrogeological perspective this provided an interesting and unique case. Firstly the aquifer at Beverley was found to be an almost completed bounded aquifer system. Secondly, the very detailed geological and hydraulic data that subsequently emerged during ISR mining provided an excellent validation of the initial, pre-mining, aquifer hydraulic test analysis.

The paper will describe analysis of a series of hydraulic tests, in the Central Beverley ore body, using classical hydrogeological methods, supported through the adaptation of petroleum industry reservoir analysis techniques for hydraulically bounded systems, which demonstrated that the aquifer at Beverley exhibits a response to pumping stress which is consistent with an aquifer system of finite extent, which is completely bounded by lower permeability sediments.

Subsequent very high density drilling, and hydraulic stress analysis during mining of the ore body, continued to support this initial interpretation.

Operation of an ISR mining operation in a hydraulically bounded system presents specific challenges in that a very precise water balance must be maintained to prevent, under or over-pressurising the aquifer during mining.

1. INTRODUCTION

The Beverley uranium mine, operated by Heathgate, is located on the arid plain between the northern Flinders Ranges and Lake Frome, approximately 550 km North of Adelaide in South Australia (Figure 1). The deposit exists as coffinite mineralisation hosted in permeable sands within the confined, saline Beverley aquifer, some 125m below the ground surface. Uranium is mined using moderately acidic in-situ recovery (ISR) technology which entails circulating oxidizing fluid through the ore body to mobilize the uranium which is then pumped to the surface and recovered. Oxidizing fluid is then re-circulated.

Permitting and regulatory approval of the mine in the late 1990s was contingent on Heathgate demonstrating a robust understanding of the hydrogeological structure of the aquifer hosting mineralisation. This was considered vital to provide confidence that the deposit could be mined through ISR methods while maintaining control of oxidizing, radioactive mining fluids, and preventing impact on non-target aquifers. Studies into the structure of the aquifer, involved the interpretation of data obtained through a number of hydraulic (pumping) tests.

From a hydrogeological perspective this provided an interesting and unique case. Firstly the aquifer at Beverley was found to be an almost completed bounded system. This is a scenario rarely studied in detail for typical water supply purposes since, when subjected to prolonged pumping, such a system is quickly dewatered. Secondly, the very detailed geological and hydraulic data that subsequently emerged during ISR mining provided an excellent validation of the initial, pre-mining, aquifer hydraulic test analysis. As a consequence of the existing boundary conditions, solution mining of this bounded aquifer system necessitates very careful attention to the maintenance of a neutral water balance in order to avoid over-pressurization or serious depletion of pressure in the production wellfields (Jeuken et al 2008).

This paper presents the methodology and results of the pumping test analysis, undertaken prior to mining, and compares these results to the subsequent understanding of aquifer structure that emerged during mining. The paper also presents the results of recent hydrogeological investigations on extended ore bodies and the resulting expanded and refined understanding of the hydrogeological system which hosts mineralisation at Beverley.

Figure 1. Location

2. HYDROGEOLOGICAL SETTING

At Beverley, mineralisation is present at a depth of around 120 m, hosted within the Beverley Sand Unit of the Tertiary age Namba Formation. This sand unit occupies an inferred paleodrainage scour in the underlying Alpha Mudstone Unit also of the Namba Formation. The Beverley Sand grades conformably upwards into a silt (Beverley Silt), and then into a locally ubiquitous clay unit (Beverly Clay) which forms the top of the Namba Formation. The Namba Formation is, in turn, overlain by the Quaternary Willawortina Formation comprising alluvial fan deposits deposited during uplift of the nearby Northern Flinders Ranges. This stratigraphic structure is shown in Figure 2.

Hydraulically, the Beverley Sand Unit which hosts mineralisation is bounded below by the relatively impermeable Alpha Mudstone, and above by the low permeability Beverley Silt and relatively impermeable Beverley Clay. Lateral hydraulic boundaries comprise the “faces” of the host scour in the Alpha Mudstone, and finer grained overbank deposits outside the main channel system.

Groundwater in the Beverley Sands is saline (TDS 2500 to 13500 mg/L), with very high naturally occurring radionuclides, particularly Radium 226 (average approximately 1000 Bq/L) rendering it unsuitable for uses other than mining. Groundwater quality in the overlying Willawortina Formation is highly variable and is currently used for livestock drinking water at locations greater than 5 kilometers from the ore body .

Mineralisation within the main Beverley paleochannel is present in three main ore zones. Each of these ore zones is hosted within a hydraulically separate unit of the Beverley Aquifer. These zones are North Beverley, Central and South Beverley, and Northeast Beverley (Figure 2). The hydraulic separation between these ore zones is believed to be due to a cut and fill braided stream structure of the paleochannel sediments which results in permeable sand units which are bounded by lower permeability silt and clay beds.

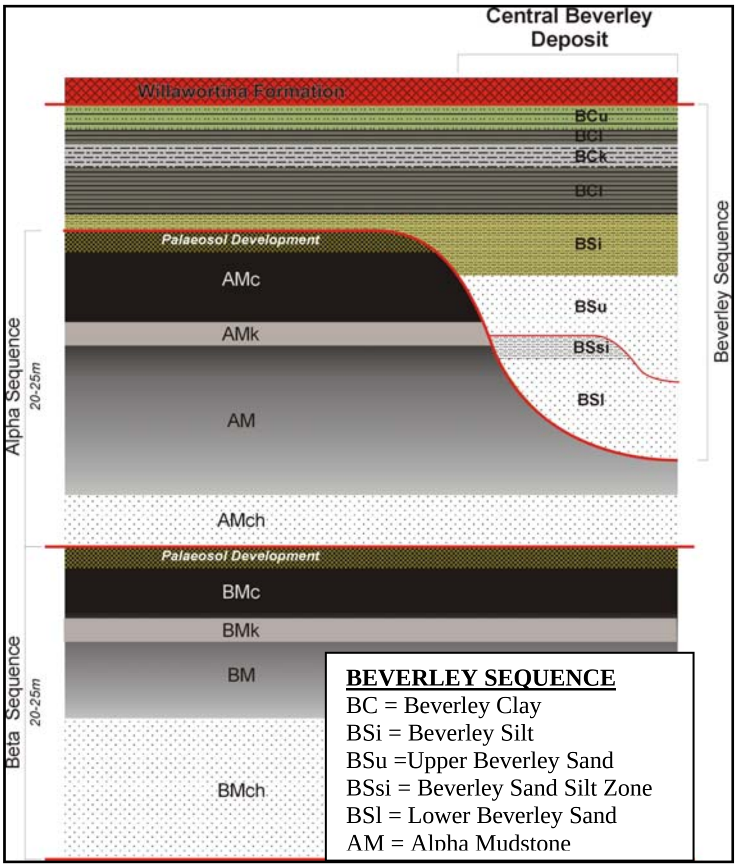

Figure 2. Stratigraphy

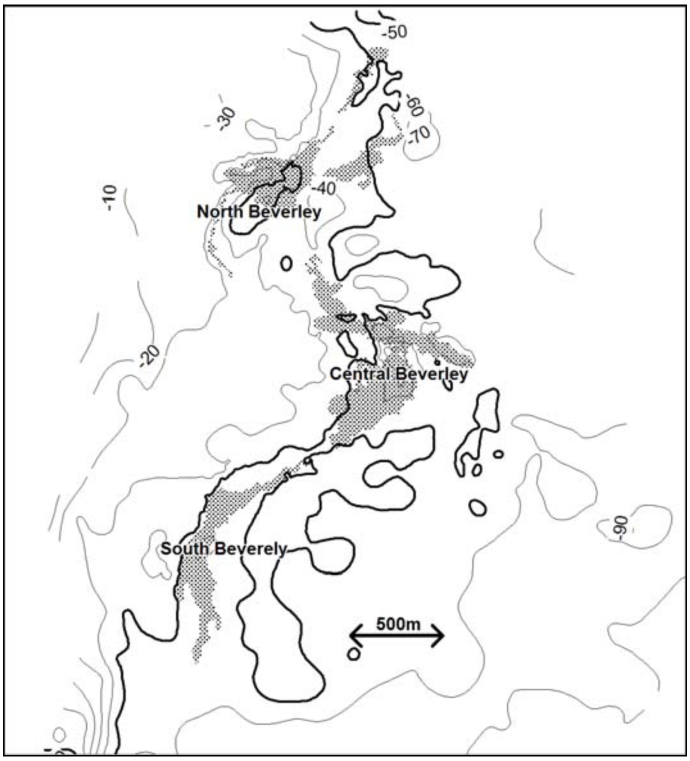

Figure 3. Beverley Ore Zones. Mineralisation extent (Shaded area); Alpha Mudstone surface (10m AHD contour interval) showing paleodrainage scour; 500m grid.

3. CENTRAL BEVERLEY PUMPING TESTS

Overview

Three distinct hydraulic tests were undertaken in the Central Beverley system in 1973, 1997 and 1999 following its discovery in the mid 1960's. Further, in 2005, the removal and re-injection of 6,000 m3 of water over 60 days during mining provided a good quality hydraulic data set where the aquifer was placed under significant prolonged hydraulic stress which in conjunction with the very detailed geological data, obtained during mining, provided a validation of the initial aquifer test analysis.

1973 High Volume Pumping Test

The earliest hydraulic test in 1973 was designed as a trial dewatering exercise. This lasted for two days pumping at a rate of 863 m3/day before the water level in the pumped well approached the pump intake level and the test ceased. A total of 1726 m^3 was discharged in the two days resulting in drawdown in excess of 20 m over a large area of the channel in the Central ore zone. Recovery was very slow, in general less than 50% after 21 days.

Drawdown data from the 1973 high volume pumping test was re-interpreted by Lisdon Associates, in 1999 (Lisdon, 1999b). The aim of this re-interpretation was an assessment of the boundary conditions of this aquifer unit. Petroleum industry methods were used to accomplish this analysis since there are no standard analytical methods in the hydrogeological literature applicable to fully bounded aquifer systems. The analysis of pressure data from the discharging well is an integral part of the well analysis methods applied in the petroleum industry where the equivalent of a fully bounded aquifer system is called a closed reservoir.

Bourdarot (1998) describes analytical methods for both channel and closed reservoirs. In the latter case, methods of estimating the area and shape factor (which is related to the position of the well in the closed reservoir) together with equations describing the theoretical drawdown are presented. These analytical methods were applied to the drawdown data from the well pumped during the 1973 test.

Figure 4 presents a plot of drawdown versus time on a linear scale. The straight line portion of the plot has a slope of 13 m/day and an intercept on the y axis of 13 m.

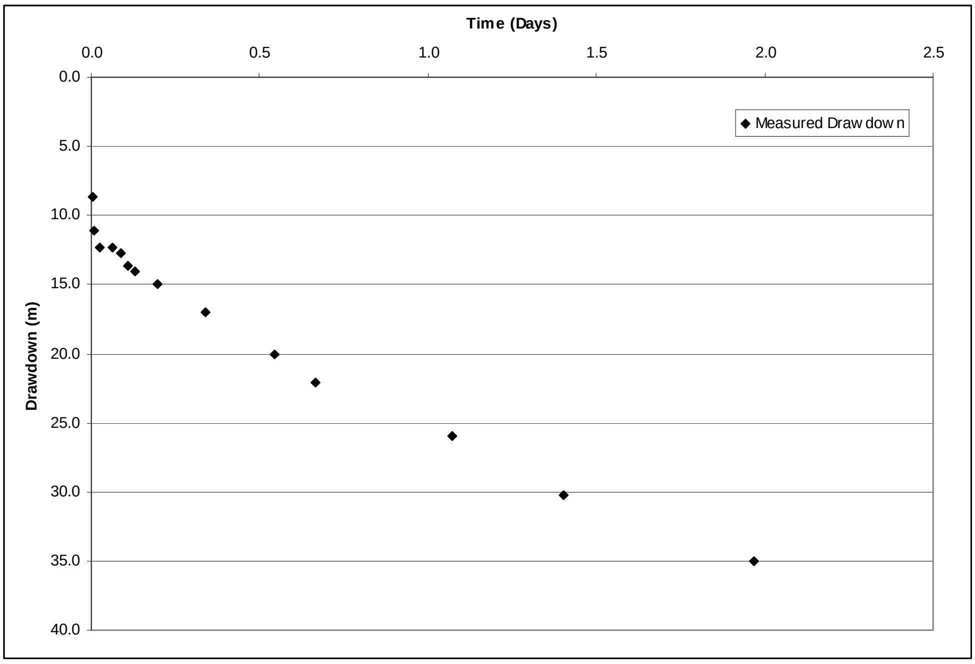

Figure 4. Pumped well drawdown vs time for 1973 pumping test (Linear scale).

The area enclosed within the aquifer boundaries is calculated from the equation below. For a storativity value of 1.82 x 10^{-4} (Calculated from early time data from the 1973 test at a observation well 31.6 m from the pumped well) this equates to a drainage area of 364,750 m^2.

$$dQ.t/dHt = \mathbf{S} \times A$$

Where: $dQ.t$ = the volume of water removed from the system
dH_t = the change in aquifer pressure
S = storativity
A = area of bounded aquifer.

Figure 5 plots drawdown over time for the 1973 test with time on a logarithmic scale. A series of straight line segments represents increasing rates of drawdown as aquifer boundaries are encountered. In the Bouradot method of analysis, the initial slope of the semilog plot is important. Unfortunately this slope is obscured by minor boundary effects in the pumped well drawdown data therefore a theoretical slope value based on estimated aquifer hydraulic properties was applied in the analysis.

The theoretical slope is given by:

$$m = 1.151 \times Q/T$$

and by using a Transmissivity (T) = 300m^2/day a slope of 3.3m/log cycle is obtained.

A Shape Factor (Ca) can now be calculated:

$$Ca = 2.2458 \times 10^{-[((pi-po)/m)-\log(A/r2w)-0.87\ S]}$$

Where: pi – po = intercept of straight line on linear plot (13 m)
S = "skin" assumed to be -3 due to prior development of the well screened interval.

The resulting Shape Factor of 21.48 is interpreted from Table 11.1 (Bouradot 1998) to represent a well location which is off centre in a square shaped aquifer, or centrally placed in a rectangular aquifer with one side approximately twice the length of the other.

It is now possible to calculate the theoretical drawdown versus time from the following equation:

$$pi - pwf = (Q \times t / S \times A) + 1.151 \times Q/T\ [\log(A/r^2_w) + \log 2.2458/Ca) + 0.87\ S]$$

Where: **S** = Storage Coefficient
S = "skin"
t = time in days
T = Transmissivity

The resulting theoretical drawdown is shown on Figure 5 together with the observed drawdown. For values of time greater than 0.1 day the shape of the theoretical curve is very similar to the observed data, but at smaller values of time the theoretical drawdown is too large. This is most likely because the theoretical curve represents a simple, single fully bounded sand unit whilst the observed data come from a complex system of lenticular sands within the enclosing aquifer boundaries.

1997 Pumping Test

Subsequent aquifer testing in 1997 (Lisdon Associates, 1997) had two objectives; to define the aquifer parameters for use in the design of a Field Leach Trial (FLT), and to assess the potential for leakage from the overlying Willawortina Formation aquifer through abandoned exploration holes. A two day test pumping at 345 m^3/day was employed to assess aquifer parameters. Drawdown in the order of 1.5 to 2 m was developed after two days and recovery was again slow. A one day test pumping at 160 m^3/day from an upper sand unit of the Beverley Aquifer, at a location close to an old abandoned drillhole, developed drawdown up to 3 m in the upper sand unit. The Vandenberg Leaky Strip Analysis (Vandenberg 1977) was applied to data from the first test to infer a total aquifer transmissivity of 270 m^2/day, Storativity of 4.5 $\times 10^{-4}$, and a strip aquifer of limited extent with a width of approximately 250 m (Type curve matches are presented as Figure 6, modelled aquifer parameters are summarised in Table 1). Neither test produced concomitant drawdown in the overlying Willawortina Formation aquifer, indicating that the Beverley Clay is an effective confining layer, and that swelling of the clay appears to seal old drillholes, thus preventing inter-aquifer leakage via this pathway.

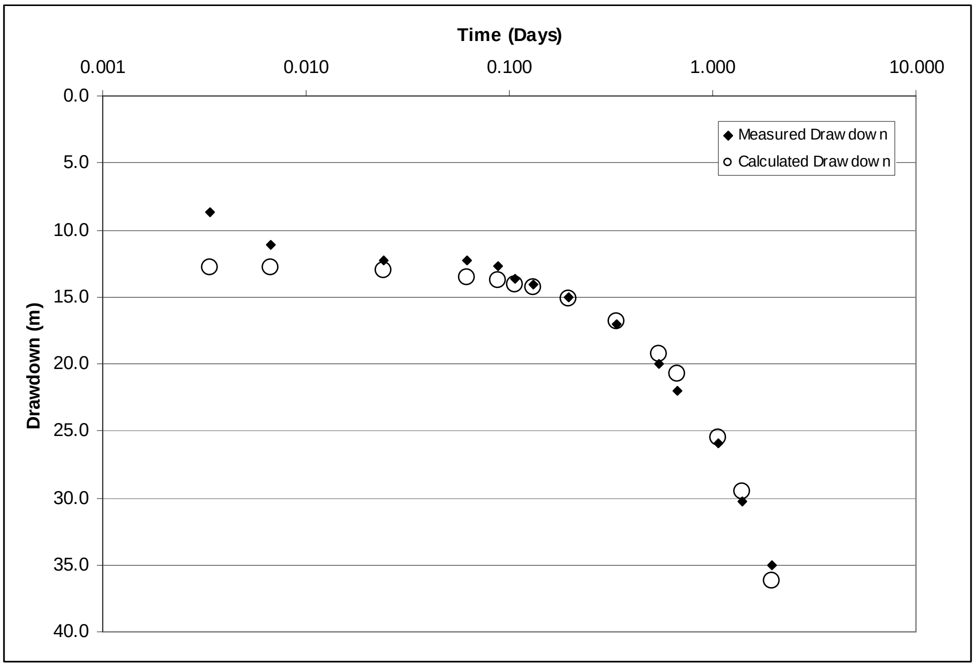

Figure 5. 1973 pumping test in Central Beverley observed and calculated drawdown (Log - linear scale).

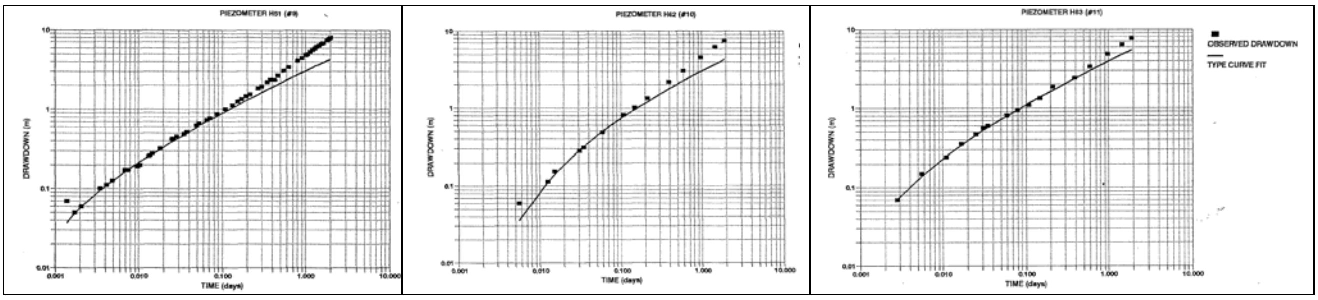

Figure 6. Vandenberg Leaky Strip curve match for drawdown of 1997 Central Beverley Pumping Tests (Log - log scales)

Table 1. Modelled aquifer parameters for 1997 pumping test in Central Beverley.
Flow rate was 345 m^3/day

Peizometer	radius (m)	Tranmissivity (m^2/day)	Storativity	Leakance (m)	Strip Width (m)
#9	46.8	272	0.00042	3446	165
#10	106.3	330	0.00035	750	275
#11	54.9	227	0.0001	508	250

1999 Pumping Test

The third test in Central Beverly was undertaken in 1999 (Lisdon Associates 1999) with the aim of confirming boundary conditions of the aquifer hosting the Central Beverley Ore Zone in response to regulatory uncertainty regarding the bounded nature of the aquifer. The test was designed to apply the maximum attainable stress on the aquifer. A discharge rate of 432 m^3 per day was maintained for 5 days during which 2160 m^3 of water were extracted. Drawdown was monitored at 10 wells (Figure 7) located in the Central and South Beverley Aquifer. Drawdown is shown in Figure 8 and Figure 9. The data show that peizometers located close to the pumped well approach a common drawdown and a rate of drawdown that approaches a slope of 1:1 on a log-log scale. This is a characteristic response of pumping from a closed system where the removal of water results in a linear reduction in pressure. Peizometers located to the south of the Pumped well, RM5, H32c, and RM7 exhibit a muted response. This infers the presence of a low permeability constriction in the aquifer between the central ore body and the southern ore body . Peizometer RM4 exhibits an anomalously muted response to pumping and is inferred to be located outside the paleochannel.

The model that emerges from the analysis of the three pumping tests prior to mine development commencing in 2000 is that of a completely bounded system comprising a main aquifer unit with an area of approximately 350,000 m^2 with a shape which is roughly square or at most elongated to a rectangle with one side twice the length of another. To the south a hydraulic constriction leads to a strip aquifer which is bounded at some point further to the south (Figure 7).

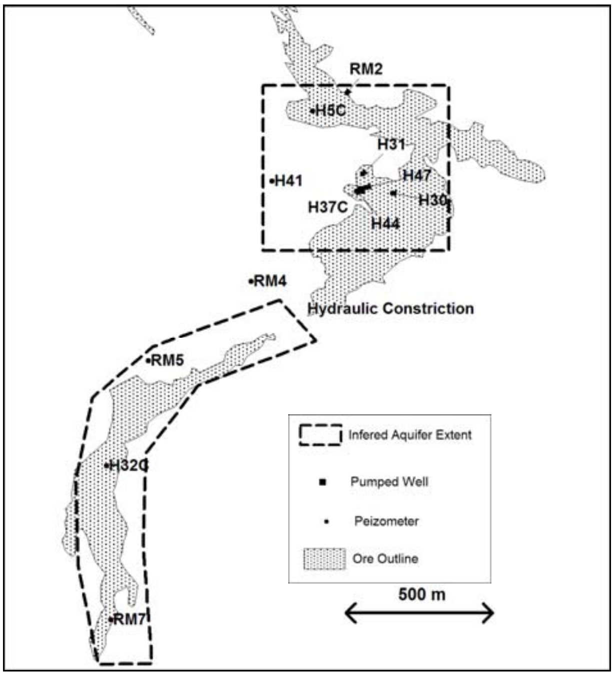

Figure 7. 1999 Pumping test peizometer array and inferred aquifer extent

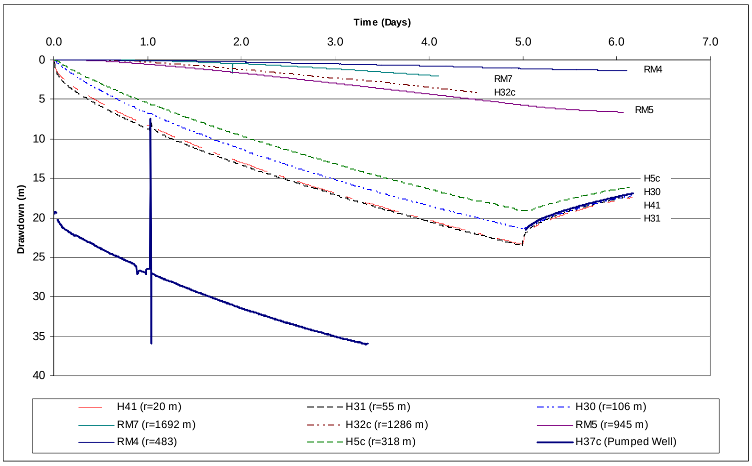

Figure 8. 1999 Pumping Test Drawdown Data (Linear scale).

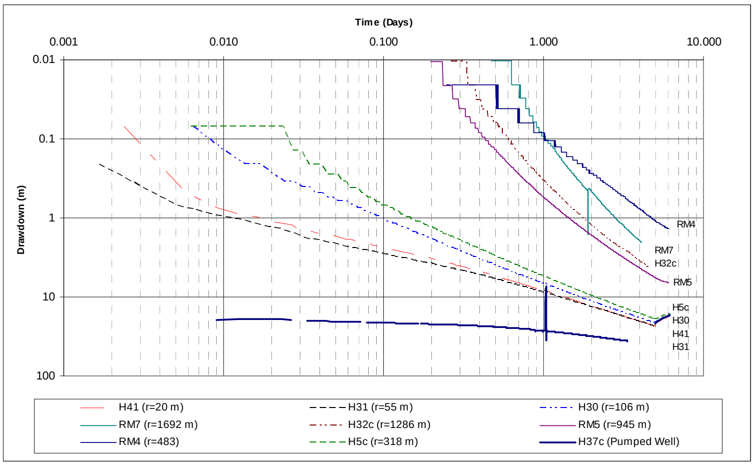

Figure 9. 1999 Pumping Test Drawdown Data (Log – log scale).

4. CONEPTUAL HYDROGEOLOGICAL MODEL VALIDATION USING HIGH DENSITY GEOLOGICAL DATA AND NUMERICAL MODELLING OF THE 2005 HYDRAULIC STRESS EVENT

In 2005 following five years of mining, very high resolution drilling had been completed to delineate the ore body and define the paleochannel aquifer geometry (The very high drillhole density and the inferred paleochannel aquifer extent is shown in Figure 10). In addition a good quality hydraulic data set describing the Central and South Beverley aquifer response to hydraulic stress was obtained when there was over-extraction of approximately 6000kL from the aquifer over a period of 11 days while a large pond on site was filled, followed by a period of re-injection of approximately 6000 kL as the aquifer water balance was restored. Significant, prolonged, hydraulic stress was placed on the aquifer and large variations in monitored aquifer water levels over time were measured at wells throughout the aquifer. A numerical model (Aquaterra, 2007), configured utilizing the very detailed geological data available in 2005, was employed to assess this response to hydraulic stress. This detailed data set provides a unique opportunity to validate the initial aquifer testing interpretation.

The numerical model setup was very simple, comprising two layers, representing the Beverly Silt and the Beverley Sand units varying layer thickness as per geological interpretation. Model Parameters are summarised in Table 2. The model was first calibrated to drawdown data from the 1999 pumping test (Figure 12 presents calibration data). The model was then validated using data from the 2005 stress period. Hydraulic stress was modelled as net extraction and injection from nine wellfields. Cumulative pumped volumes are shown in Figure 12 and calibration plots in Figure 13. The calibration plots show a very close match between observed water levels and modelled water levels.

The range of head variation within the central ore zone of more than 60 m created by the extraction of ~6ML over 11 days followed by injection of a similar volume over ~15 days illustrates the high sensitivity of the bounded aquifer system to changes in the water balance.

This validation using current data continues to support the initial interpretation from early pumping tests; that the aquifer hosting mineralisation at Central Beverley is hosted within a fully bounded aquifer comprising a large central region and an elongated southern channel, separated by a hydraulic constriction.

Table 1. Model setup

Layer 1 (Beverley Silt)	K = 1 x 10^{-3} m/day	S = 1.5 x 10^{-5}
Layer 2 (Lateral silt / Clay)	K = 1 x 10^{-4} m/day	S = 1.5 x 10^{-5}
Layer 2 (paleochannel Sands)	K = 4 m/day	S = 1.5 x 10^{-5}
Boundary Conditions	Extraction and subsequent injection from 9 well Fields	

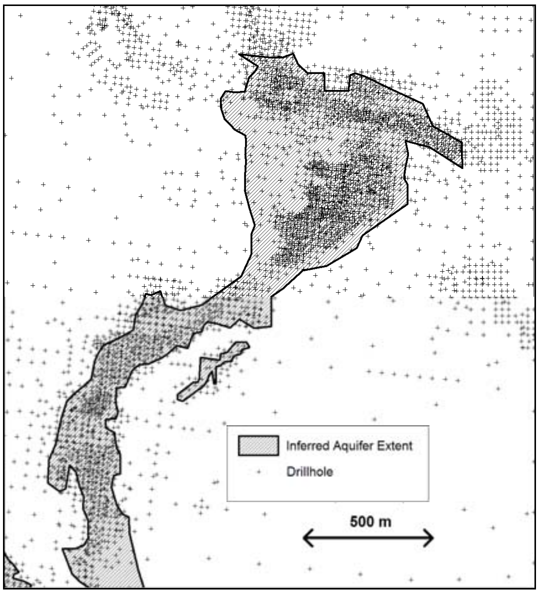

Figure 10. Inferred Central Beverley paleochannel aquifer extent and drillhole locations

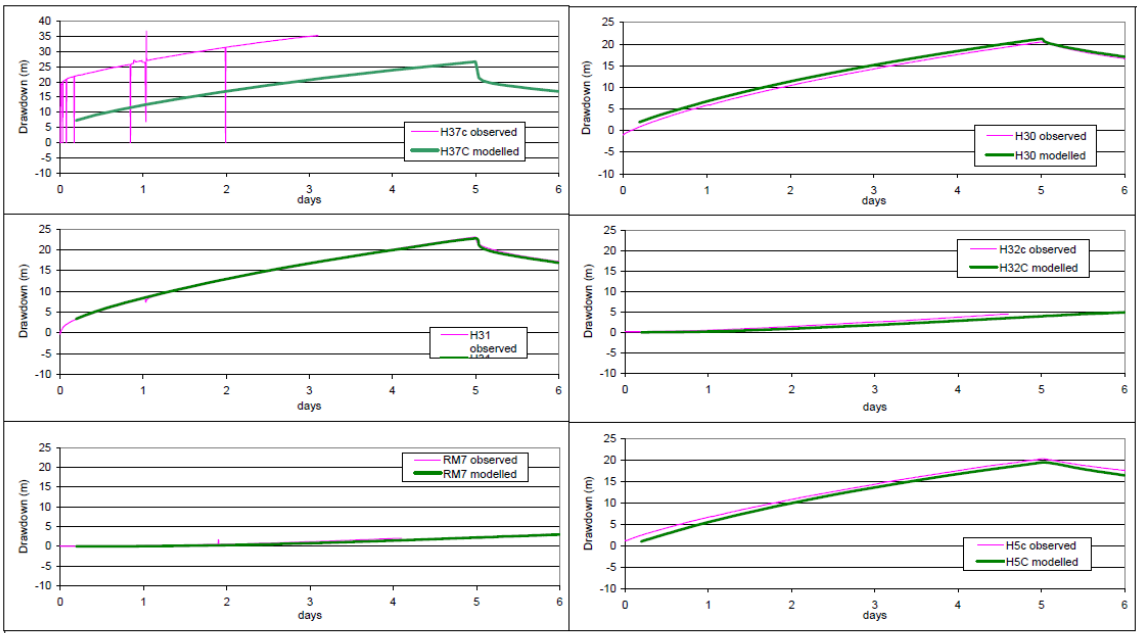

Figure 11. Calibration data from 1999 pumping test numerical model calibration (Aquaterra, 2007).

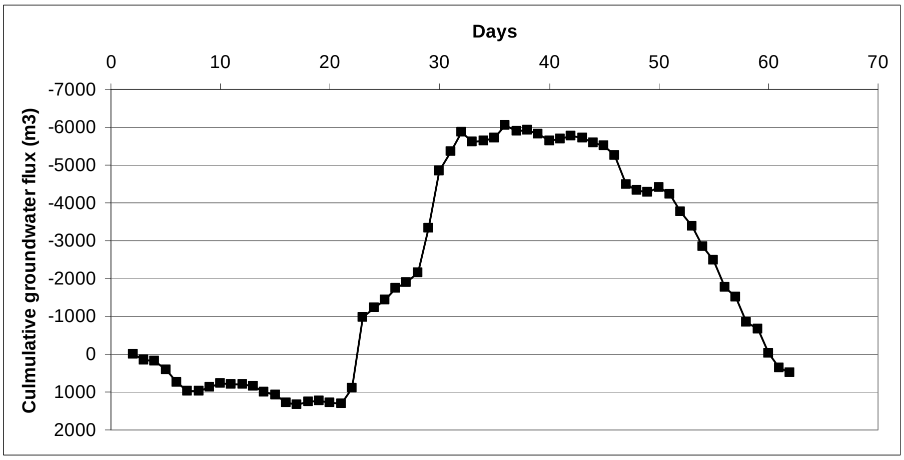

Figure 12. Cumulative pumped volume during 2005 stress event
(negative values represent extraction)

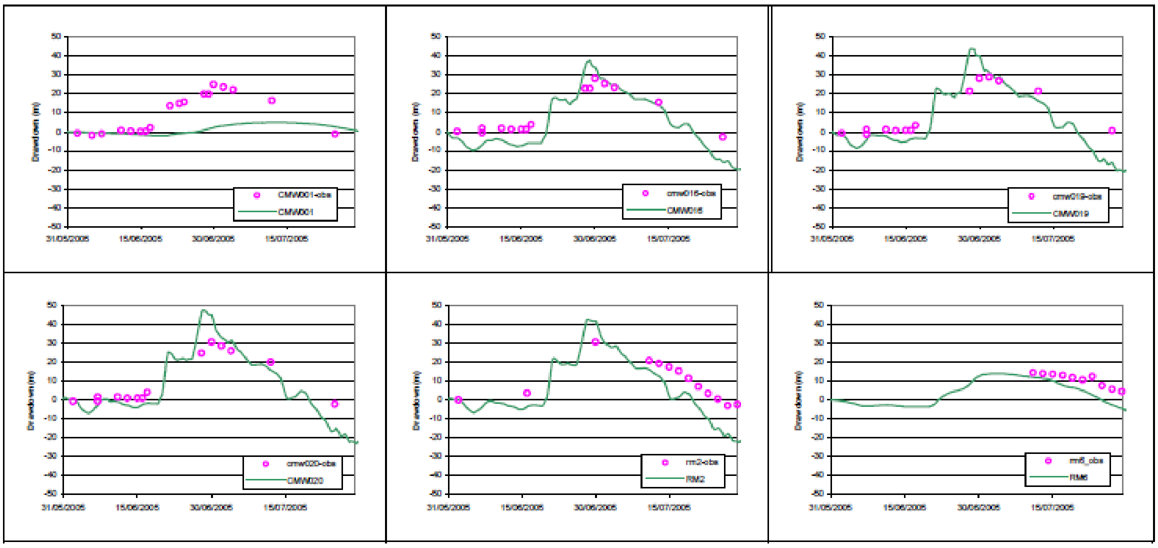

Figure 13. Calibration data from 2005 stress event numerical model validation (Aquaterra, 2007).

5. CONCLUSIONS

The regulatory and operational requirement to demonstrate a strong understanding of the hydrogeological structure of the aquifer hosting mineralisation at Central Beverley prior to mining and subsequent requirement to maintain a neutral water balance motivated an exhaustive process of pump testing and analysis to provide a robust conceptual hydrogeological model of the deposit. The uniquely bounded hydrogeological structure at Beverley required the application of oil reservoir analysis methods to drawdown data from these pumping tests. Subsequent detailed drilling, hydraulic stress modelling has continued to confirm the initial analytical analysis of pumping test data. This demonstrates the potential power of analytical methods of analysis, to provide useful conceptual models at an early stage of project development.

6. REFERENCES

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