Catfield Fen - Pumping Test and Radial Flow Analysis

1. Introduction

A number of pumping tests on different groundwater abstraction sources have been undertaken in the Ludham-Catfield area over the last 30 years. These tests have been undertaken at the time of licensing the sources, or in the case of the Anglian Water Services (AWS) Ludham source, during the course of the AMP3 investigation to support work under the Restoring Sustainable Abstraction (RSA) programme. The aims of this Technical Note are:

- To evaluate the pumping tests, to review any previous analysis and assess if they are suitable for re-analysis;
- To re-analyse the pumping tests to confirm the conceptual understanding of the aquifer system in the vicinity of the abstraction and to assess aquifer parameters;
- To use the pumping test results to suggest potential refinements to the Northern East Anglia Chalk (NEAC) regional groundwater model aimed at further improving the calibration of the NEAC model.

The pumping tests were analysed using the AquiferWin32 package and a radial flow model using the RADMOD pre-processor for MODFLOW.

This Technical Note aims to describe the analysis of pumping tests undertaken in the Catfield area using AquiferWin32 and a radial flow model using the RADMOD pre-processor for MODFLOW.

2. Pumping Tests

Over the course of the last 30 years, several pumping tests have been undertaken in the Ludham-Catfield area.

Details of the pumping tests which were reviewed as part of the present work are summarised in Appendix A. The main tests of interest to this study are:

Site	Date of Test	Duration	Pumping Rate (m³/d)
AWS Ludham	23 to 30 September 2003	7 days	2.5 Ml/d*
	15 August to 14 November 2002	91 days	0.84 Ml/d*
Alston – Plumsgate Road	15 to 26 July 1985	11 day	1.327 Ml/d
	12 to 14 August 1985	2 day	1.133 Ml/d
Alston – Ludham Road	28 September to 5 October 1987	7 day	0.855 Ml/d

*Abstraction rate from the test borehole with an abstraction of about 1.5 Ml/d from a second borehole. This abstraction was maintained prior to, during and following the test.

Figure 1 shows a map of the Catfield area with pumping test sources and observation boreholes used for analysis. The most recent tests, carried out in 2002 and 2003 on the site of the AWS Ludham source, provide the most coherent data and were therefore the main source of information for deriving aquifer properties. These two pumping tests were conducted by pumping at a constant rate from one of the supply boreholes and then undertaking the constant rate pumping test at a second borehole. The additional discharge was pumped to waste via an over ground pipe – to the sewage works in 2002 and to the River Ant in 2003. The tests were conducted in this way to allow a baseload abstraction of about 1.5 Ml/d to continue to pump into supply. The disturbance of the aquifer system was then achieved by increasing the abstraction beyond this quantity.

The total quantities of abstraction pumped from the AWS Ludham source during the 2002 and 2003 tests were therefore:

- 2002 - 2.36 Ml/d;
- 2003 - 4.05 Ml/d.

These quantities are significantly greater than the current annual licensed quantity of 1.4 Ml/d. The groundwater level responses observed during the pumping test should not therefore be interpreted as indicating the current level of drawdown or impact on the aquifer system in the vicinity of the source.

The initial analysis for the AWS Ludham tests was originally carried out by Atkins using the HSI analysis package P-TEST. The results of the analysis are included in Appendix A. Atkins/HSI (2003) also used a radial flow model which provided the initial basis for the model described in Section 3.2.

2.1 Quality of Pumping Test Data

The data from some of the older (1985-1992) pumping tests on the Alston and Overton sources is of varying quality due to problems during the tests such as fluctuations in pumping rate, heavy rainfall and incomplete data records. Analysis of the data, described in Section 3, was only undertaken for tests where the data were considered to be reasonable (see comments in Appendix A) and in most cases was limited to the recovery test data. These tests include AWS Ludham (2002 and 2003), Alston Plumsgate Road (1985) and Alston Ludham Road (1987).

The AWS Ludham pumping tests were analysed using both AquiferWin 32 and RADMOD as these tests include water level data from a number of observation boreholes. Analysis of the

Alston Plumsgate Road and Alston Ludham Road tests was undertaken using AquiferWin32 for the recovery data only (Section 3.1) as it was not possible to analyse the constant rate test due to variations in pumping rate. It was also considered that there would be limited benefit in analysing the test data using a radial flow model as there were limited observation borehole data.

3. Analysis of Pumping Tests

3.1 AquiferWin32

The pumping test data described in Section 2 were collated and reassessed using AquiferWin32. Methods of analysis included Cooper&Jacob (1964) (Straight Line Method), Hantush (1946) and the Theis recovery method. These methods are described in Kruseman and de Ridder (1990).

The Hantush 1964 method is considered to be most appropriate to the test conditions, as it takes leaky conditions and partially penetrating wells into account. The results of the reassessment are summarised in Appendix A and example matches are shown in Appendices B to D.

The transmissivity values derived from the AWS Ludham tests typically ranged between 600 and 1 000 m^2/d with a storage coefficient between 0.00005 and 0.0008 indicating confined conditions. Transmissivity values for the Alston Plumsgate Road test ranged from 250 to 760 m^2/d and a single transmissivity value of about 450m^2/d was obtained for the Alston Ludham Road test.

The test data for the Alston Ludham Road test did not allow a storage coefficient to be calculated. Previous test analysis for the Alston Plumsgate Road test provided a wide range of results and a value of 0.25 was used for drawdown predictions.

Lower confidence should be attached to the data for the Alston Ludham Road and Alston Plumsgate Road tests, compared to the AWS Ludham test, as the analysis is mainly based on the recovery data and observation borehole data are only available for Alston Plumsgate Road (see comments in Appendix A).

This re-analysis confirms the conclusions from previous analysis by the Environment Agency.

The values derived from these test are consistent with the aquifer properties for the Crag in Norfolk and with values used in the NEAC Model.

3.2 Radial Flow Model

A radial flow model was used to simulate the pumping tests of the AWS Ludham source. Given the limited observation data for the Alston Ludham Road and Alston Plumsgate Road sources it was considered that there would be limited benefit in using this model to simulate the pumping tests for these boreholes.

The radial flow model was set up with a radius of 10 kilometres and comprises 236 cells. The size of cell increased from the centre of the model to the edge of the model. The pumping borehole was placed at the centre of the model and a constant head boundary with a value of

59 m was assigned at the boundary (outermost cell), 10 km from the abstraction. For a constant head boundary, the head remains fixed and, therefore the boundary, can act as a source of water for the abstraction, which is why this boundary has been set at distance.

The complex geology of the Ludham-Catfield area was depicted by 6 model layers with varying hydrogeological properties (see Table 1), based on the conceptual model outlined in Catfield Fen Impact Assessment (Atkins/HSI 2003) as well as geological cross sections and borehole logs (Catfield Fen Investigation, AMEC 2012).

A comparison of the hydrogeological section through the Fen and the model structure of the radial flow model is shown in Appendix E.

The model assumes a surface aquitard representing the uppermost layer of peat and the locally underlying estuarine clays of the Ludham-Catfield Fen area. This confining layer (Layer 1) is required in order for drawdown predictions in the shallow Crag (Layer 2) to be generated, as no response is predicted for this layer when the overlying confining layer is removed. The effect of this assumption is that groundwater is not drawn from the unconfined storage in the shallow Crag. If this larger storage is used, the model predicts that the drawdown in water levels in the upper layers is less than 0.001 m.

Table 1 Model Structure – Radial Flow Model

Layer	Thickness (m)	T (m^2/d)	Kh (m/d)	Kv (m/d)	S	Sy
1	2		1.00E-03	1.00E-03	6.00E-02	0.03
2	11	200	18.2	18.2	3.00E-04	0.25
3	3		8.00E-04	8.00E-04	1.50E-05	0.03
4	15	200	13.3	13.3	1.00E-05	0.25
5	9		4.00E-03	4.00E-03	6.00E-06	0.03
6	20	620	31	31	1.00E-04	0.2

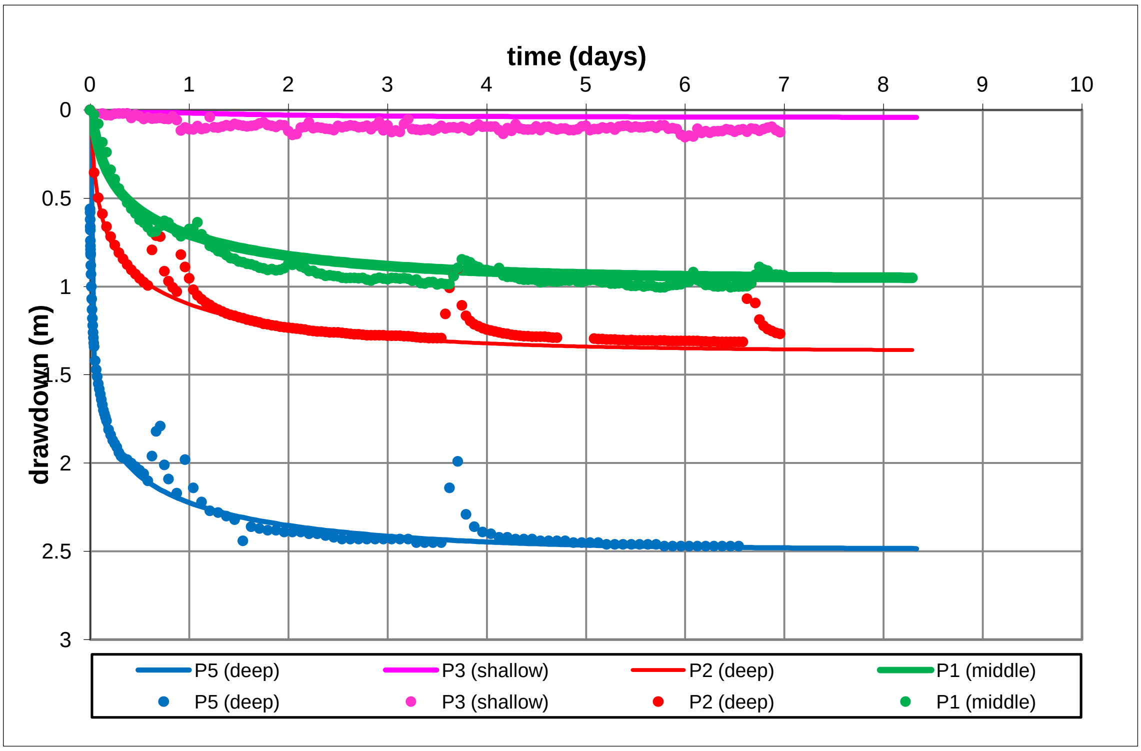
T = transmissivity, Kh = horizontal hydraulic conductivity, Kv = vertical hydraulic conductivity, S = storage coefficient, Sy = specific yield.

The model was mainly built around and calibrated using data from the AWS Ludham 91 day and 7 day pumping tests in 2002 and 2003 respectively.

The groundwater abstraction was taken from layer six, the lowest of the 3 modelled aquifers and is therefore consistent with borehole construction records.

Values for hydrogeological properties of the model were taken from the reassessed pumping test results and distributed across the model layers to correspond with water level behaviour during the pumping tests. The result of model calibration is shown in Figure 2, with lines showing the modelled values and dotted lines marking observed values. The test was calibrated against observed drawdown in boreholes located 75 m (P5) and 450 m (P1, P2, P3) from the abstraction. Data records from observation boreholes located at greater distances (e.g. NTG3270P4) were obscured by either rainfall or technical problems (see comments in Appendix A) and could therefore not be taken into account for calibration.

Figure 2 Modelled vs. Observed Drawdown – Pumping Test 2003 (7days)



The model shows a good agreement to the observed drawdowns and model parameters are comparable to the results from analysis of the pumping tests using AquiferWin32.

Table 2 shows predicted drawdowns calculated with the radial flow model after continuous pumping for 7 days. Presented in Table 2 are also the observed drawdown values for the 7 day pumping test (2003) which show good agreement with the modelled values. Data beyond 7 days are not shown as these are influenced by recharge events.

Table 2 Drawdown Modelled/Observed After 7 Days of Pumping (2.5 Ml/d)

Distance (m)	Location	Modelled Drawdown (m)			Observed Drawdown (m)		
		Deep Crag	Middle Crag	Shallow Crag	Deep Crag	Middle Crag	Shallow Crag
75	P5 (deep) (Ludham PS)	**2.48**			**2.14**		
450	P3 (shallow) (Sharp Street)			**0.07**			**0.07**
460	P1 (middle) (Sharp Street)		**0.95**			**0.94**	
465	P2 (deep) (Sharp Street)	**1.36**			**1.61**		
1000	Catfield Fen	**0.90**	**0.77**	**0.06**			
2000	Catfield Fen	**0.57**	**0.53**	**0.05**			

The model parameters derived from the radial flow model and from PTEST have been used to inform and refine the calibration the NEAC model. The NEAC model has then been used to assess the influence of pumping from the Alston Ludham Road and Alston Plumsgate Road sources on groundwater levels in the Ludham-Catfield area.

3.3 Conclusions

A certain amount of the pumping test information collected for sources in the Ludham-Catfield area is of limited quality. Where possible, pumping test information for the Alston Plumsgate Road and Alston Ludham Road sources has been re-analysed. The aquifer parameters generated tend to be consistent with those produced from the original analysis.

The pumping tests for the AWS Ludham source have been analysed using analytical (AquiferWin 32) and numerical radial flow modelling (RADMOD) techniques. A good calibration between the model and observed data was obtained using RADMOD (Figure 2) and this indicates that the aquifer system is layered, with water drawn vertically downwards from the water table within the vicinity of the source, which is consistent with the current conceptual understanding.

The aquifer parameters derived from the radial flow model were used to inform the NEAC regional groundwater flow model which is used for predicting the influence of pumping on groundwater levels below Catfield Fen. The NEAC regional groundwater model is the most appropriate tool for assessing the long term impacts of pumping at the correct fully licensed quantities for all the sources within the Ludham-Catfield area.

4. References

AMEC, 2012. Catfield Fen Investigation. Final Report for the Environmental Agency, April 2012.

Atkins/HSI, 2003. AMP Impact of Abstractions, Catfield Fen Impact Assessment, Report for Anglian Water Services, December 2003.

Kruseman G P and de Ridder N A, (1990). Analysis and Evaluation of Pumping Test Data, Second Edition, ILRI publication 47, International Institute for Land Reclamation and Improvement, The Netherlands, 377 p.

Hantush M S, (1964). Hydraulics of Wells, In Advances in hydroscience (V.T. Chow, editor), Vol. 1, 281-432, Academic Press, New York.

Cooper H H and Jacob C E, (1946). A generalised graphical method for evaluating formation constants and summarising well field history. Am. Geophysics. Union Trans. 27, 526-534.

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Figure

Appendix A
Details of Pumping Tests

1 Page

Period	Time	Site	BHs pumped	Pumping rate (constant rate)	Depth (screen)	Observation borehole	Depth (screen)	Distance from BH (m)	Drawdown (m)	Comments	RESULTS (previous analysis): Method	T (m2/d)	S	Leakance (m)	REASSESSMENT 2013: Method (AquiferWin32)	T (m2/d)	S
23rd to 30th September 2003	7d	AWS Ludham	(new) BH3 BH1	2.5 Mld (29 l/s) 1.55 Ml/d (18 l/s)	43-55m 51-57m	BH 3		-		Pumping well	Cooper-Jacob semi log	670	-	-	Theis Recovery	786	
						P5	37-50m	75	2.14	Deep Crag	Walton log-log Cooper-Jacob semi log	667 672	1.10E-04 1.20E-04	3750 -	Hantush 1964* Cooper-Jacob	684 677	1.00E-04 1.00E-04
						P2	42-54m	465		Deep Crag	Walton log-log Cooper-Jacob semi log	932 942	5.40E-04 5.00E-04	3000 -	Hantush 1964* Cooper-Jacob semi log	899 980	5.50E-04 4.50E-04
						P6	13-18m	80	0.12	Upper Crag, unusual response, sensitive to rainfall					* for leaky aquifer, confined, partially penetrating well		
						P1	23-26m	460	0.94	Middle Crag					Cooper-Jacob P1 Hantush 1964* P1	893 784	5.00E-04 6.00E-04
						P3	6-9m	450	0.07	Shallow Crag							
						P5 NTG 3280	0.45-0.7m	900		**No clear response, data obscured, sensitive to rainfall**							
						P4 NTG 3270	8-9.9m	900		**No clear response, sensitive to rainfall**							
15th August - 14th November 2002	91d	AWS Ludham	BH1 BH2	1.52 Ml/d (17.6 l/s) 0.84 Ml/d (9.7 l/s)	51-57m 49-56m	BH 2		-		Pumping well	Cooper-Jacob semi log Cooper-Jacob Recovery	848	- -	- -			
						P5	37-50m	150	0.54	Deep Crag	Walton log-log Cooper-Jacob semi log Cooper-Jacob Recovery	625 558 628	7.20E-04 7.60E-04 -	3000 - -	Hantush 1964* Cooper-Jacob Theis Recovery	617 596 recovery data obscured by recharge	8.00E-04 6.90E-04
						P2	42-54m	450	0.45	Deep Crag	Walton log-log Cooper-Jacob semi log Cooper-Jacob Recovery	874 849 630	5.00E-05 4.50E-05 -	9000 - -	Hantush 1964* Cooper-Jacob Theiss Recovery	837 833 recovery data obscured by recharge	5.80E-05 5.90E-05
						P1	23-26m	450	0.28	Middle Crag					* for leaky aquifer, confined, partially penetrating well		
						P3	6-9m	450	-	Shallow Crag, **no clear response to PT**							
						P5 NTG 3280	0.45-0.7m	900	-	Shallow, upper Crag, **no clear response**							
						P4 NTG 3270	8-9.9m	900	-	Very shallow alluvial sands, **no clear response**							
						NTG 3261 P1, P2 and P3				**Not monitored**/data faulty(P1)							
						Dykes				Water levels affected by rainfall **not by abstraction**							
12th May to 26th May 1992	14d	Overton TG 39800 20600	Test Bore	1.21 Ml/d (14 l/s)	30m	Test Bore		-		**For drawdown only the test borehole data** could be used. Drawdown decreased after 1 day - leakage?					Cooper-Jacob Theis Recovery Test Bore	230 281	
						P2 (OT2 House)	<10	80	1.22	Only observation borehole with coherent data.	Walton recovery	292*	1.50E-03	400	Theis Recovery Obs P2	330*, 850**	
						P1 (OT1 Barn)	<10	115	1.01	**Drawdown obscured / no recovery data**	*N.B. previous analysis suggested that this T value seems low for Crag				* late recovery data, more closely resembles previous results **early recovery data		
						Sunnyside	?	220	0.07								
						Obs Bore	?	1200	0.06								
28th Sept. to 5th Oct. 1987	7d	Alston Holly Farm TG 38590 20600 (Ludham Rd.)	Test Bore	0.855 Ml/d (9.9l/s)	4.5-33.5m	Wyndhurst	5.2	550	**no clear response**	**Drawdown obscured** by fluctuations in pumping rate, therefore not possible to calculate any values from drawdown data, **T from recovery data.** S from Alston PT 1985 (0.25) used for license purposes.		406			Theis Recovery	447	
15th to 26th July 1985	11d	Alston Holly Farm TG 38180 22300 (Plumsgate Rd.)	Test Bore	1.327 Ml/d (15.6 l/s)	20.7m	Test Bore		-	14.3	**Difficulties** due to unusual water level behaviour of test bore and abandoned bore during drawdown test (breakaway after 3days, might suggest no flow boundary!? but Sutton Broad at 1 km distance would suggest recharge source) **Wide range of results from previous analysis**.	Values were selected from range of results of analysis.	800-3000	0.25		Theis Recovery Test Bore	374	
						Abandoned Bore	9.1	35	0.33						Cooper-Jacob Hantush 1964*	762 671	
						Main bore, Well4, Well2, Bore1, Longmoor Farm				**No response** in these monitoring boreholes.							
12th to 14th August 1985	48h			1.133 Ml/d (13.1 l/s)		Test Bore		-	11.08	Was carried out **to obtain early drawdown data.** Initial test (11d) drawdown data obscured.					Cooper-Jacob Test Bore	250	
						Abandoned Bore	9.1	35	0.11						Theis Recovery Test Bore	330	

BH = Borehole T = Transmissivity S = Storage coefficient Obs = Observation

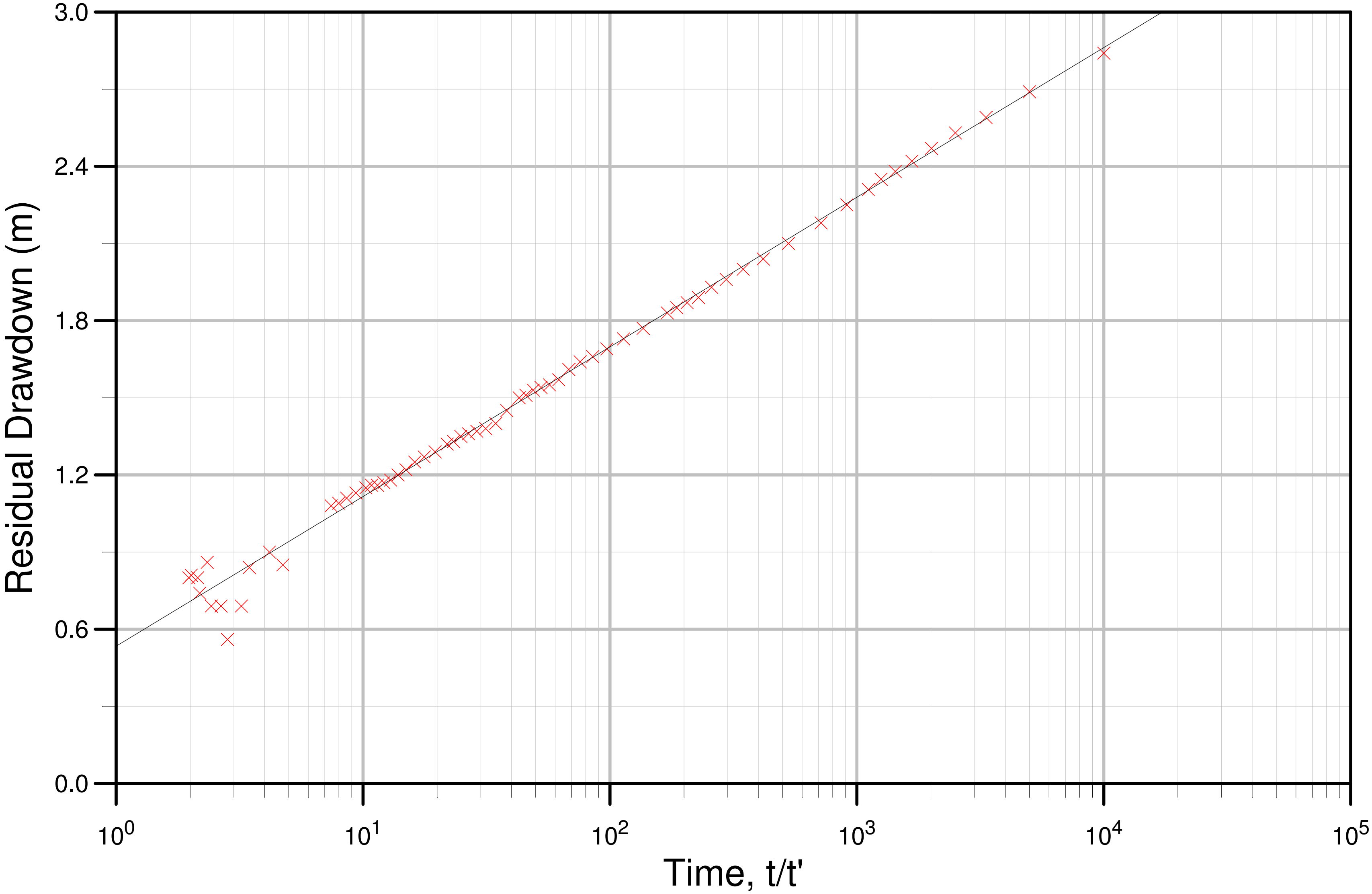
Appendix B
Example of Pumping Test Analysis (PT 2003 Ludham PS BH3 – Theis Recovery)

1 Page

PT 2003 Ludham PS - BH3

Transmissivity **785.632 sq m/d**

Theis Recovery



Appendix C
Example of Pumping Test Analysis (PT 2003 Ludham PS Observation BH P5 – Cooper and Jacob)

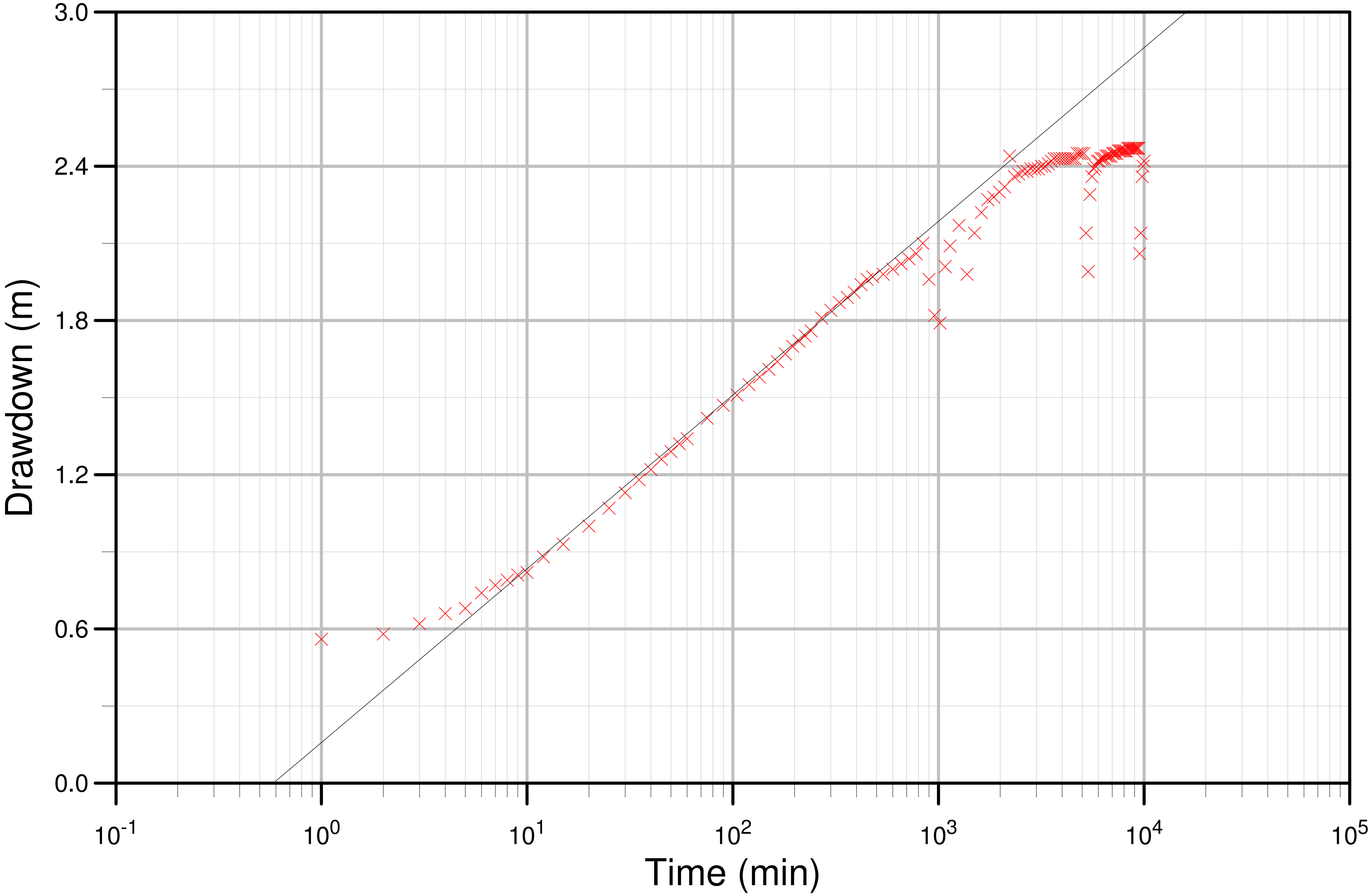
1 Page

Transmissivity **677.538 sq m/d**

Storage Coefficient **0.000109555**

PT 2003 Ludham PS Observation BH P5

Cooper and Jacob



Appendix D
Example of Pumping Test Analysis (PT 2003 Ludham PS Observation BH P5 – Hantush)

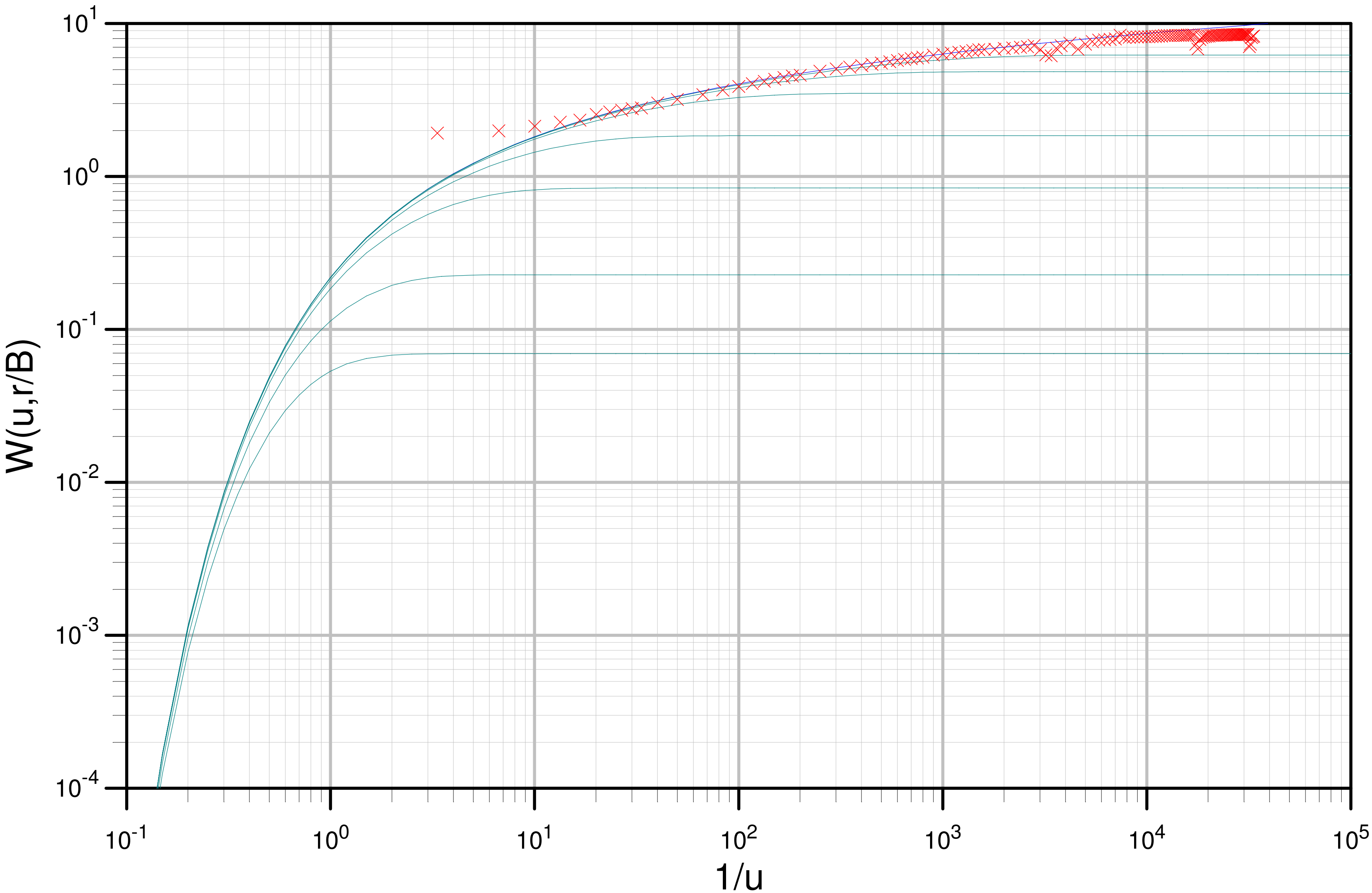
1 Page

Transmissivity 683.658 sq m/d

Storage Coefficient 0.000101174

PT 2003 Ludham PS Observation BH P5

Hantush



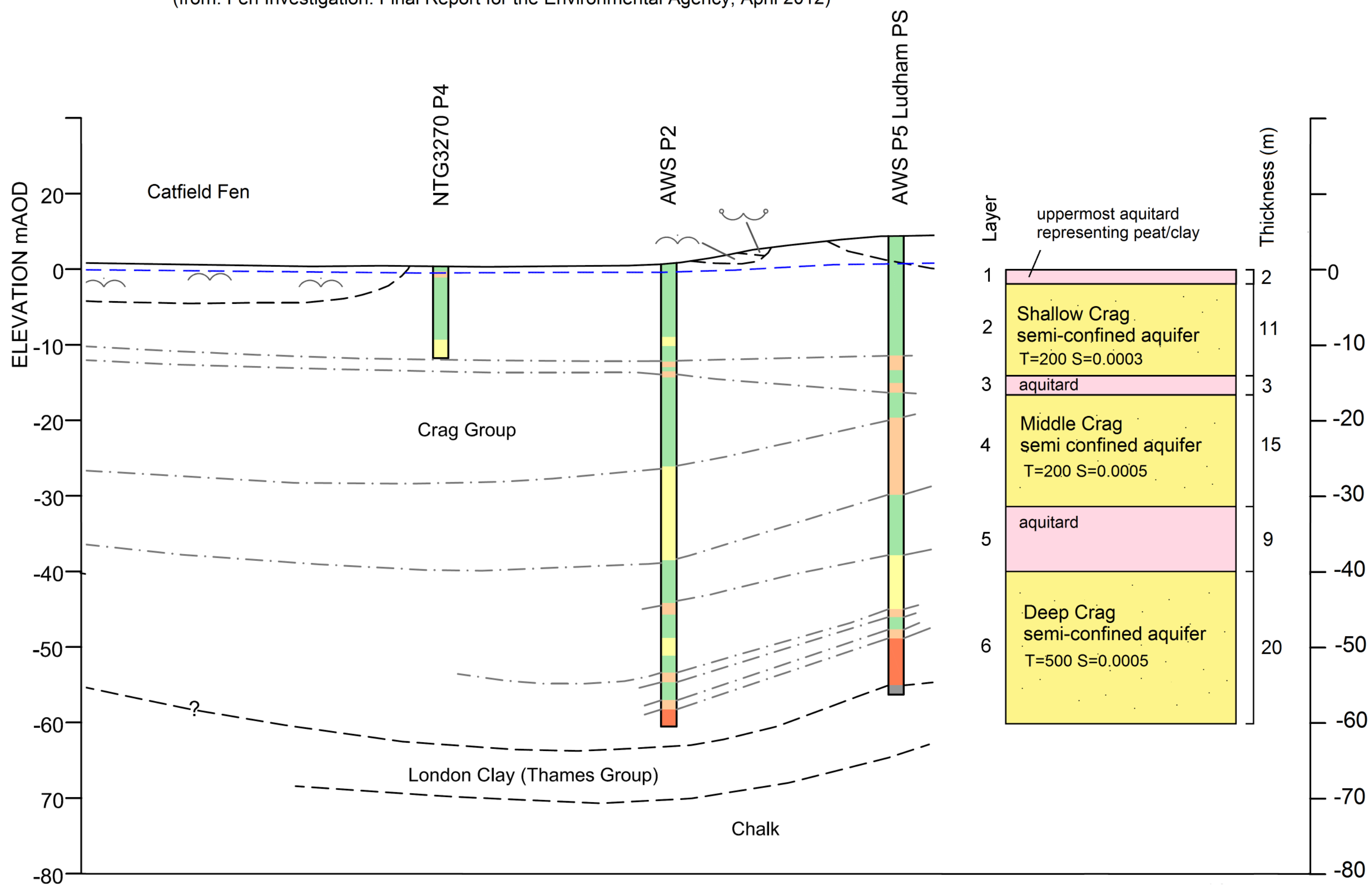
Appendix E
Cross Section

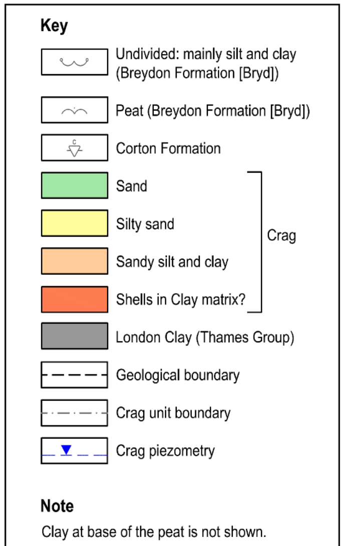
1 Page

Hydrogeological section through Catfield Fen

(from: Fen Investigation. Final Report for the Environmental Agency, April 2012)

Model structure Radial Flow Model





Appendix E: Hydrogeological section through Catfield Fen compared to Model structure (Radial Flow Model)

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