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Field measurements for characterisation of vertical hydraulic conductivity structure of a carbonate aquifer

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Abstract

The paper aims to characterise vertical variations in horizontal hydraulic properties in a fractured carbonate aquifer, the Cretaceous Chalk in E. Yorkshire, UK. Two approaches are used: an inverse model of well flow applied to flow logs of pumped open wells; and open well dilution testing. In this case study, transmissivity in the unconfined part of the aquifer is dominated by the highly permeable zone of water table fluctuation, where carbonate dissolution has occurred enhancing fracture aperture; a similar enhanced permeability zone is present at the top of the aquifer where it is confined beneath glacial deposits although periglacial physical weathering during Quaternary cold periods, rather than carbonate dissolution, is responsible. The aquifer is also shown to contain deeper permeable horizons of stratigraphic origin which are better developed in the unconfined section.

Understanding the hydraulic conductivity structure of aquifers is essential for accurate prediction of contaminant transport, for example for the purpose of defining protected areas around well-heads (often called Source Protection Zones) or designing remediation schemes. However, the vertical structure of horizontal hydraulic conductivity structure is often poorly characterised. The focus of this paper is a carbonate aquifer (the Cretaceous Chalk) in the UK.

Introduction

The Cretaceous Chalk in Yorkshire is a pervasively fractured carbonate aquifer that also has high matrix porosity, typically between 15 and 40% (Smedley et al. 2004) and hydraulic conductivities of

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of 0.7 to 6.8 x10^{-5} m/day (Hartmann et al. 2004). Fracture systems in the Chalk increase its hydraulic conductivity by many orders of magnitude compared to that of the matrix pore network (Price et al. 1977, Price 1987, Patsoules 1989). Fractures increase Chalk hydraulic conductivity most where they have been enlarged by dissolution (Price 1987) . Surface water attains its carbon dioxide content through atmospheric exchange, but when water infiltrates the soil this is strongly enhanced by carbon dioxide produced by biological activity, which typically has concentrations ten to fifty times that attained from atmospheric exchange (Price et al. 1993). Hence the concentration of dissolved carbon dioxide in the saturated zone is at a maximum at the water table, where most carbonate dissolution occurs (Ineson 1962, Foster and Milton 1974, 1976, Reeves 1979, Price 1987, Rushton et al. 1989, Price et al. 1993, Cross et al. 1996, Salmon et al. 1996, Schürch and Buckley 2002). As a result, the occurrence of solutionally enlarged fractures in the unconfined section of the aquifer reduces drastically between 30 and 100m below the water table resulting in little fracture enlargement below the upper enhanced permeability zone (Headworth et al 1980, Price 1987, Banks et al. 1995, Buckley et al. 2001).

Previous studies have shown that the geological structure and history of the Chalk contributes to heterogeneous permeability development. Bedding–parallel marl (clay) bands act as barriers to vertical flow (Reynolds 1947, Green 1950, Headworth et al. 1980, Barker et al. 1984, Zaidman et al. 1999, Gale and Rutter 2006). In the saturated zone, solution enhanced fractures often occur just above marls, so enhancing horizontal hydraulic conductivity (Gale and Rutter 2006). The distribution of marls and flints within the Chalk is not uniform and in fact these characteristics are used to define the different formations within the chalk. The two most extensive formations are the Burnham and the Flamborough and are described by Sumbler (1996). The Burnham Chalk has thin beds with tabular and discontinuous flint bands up to 0.3m thick. Flint nodules are rare, but there are some marls up to 0.11m thick. This formation forms the crest and plateau of the Yorkshire Wolds. The younger Flamborough Chalk is mostly flint-free and less hard than the underlying chalks. There are numerous marl seams typically 1 to 3cm in thickness occurring almost one per metre, far more frequently than in the underlying chalks.

Periglacial processes have also contributed significantly to the hydraulic conductivity structure of the upper layers of the Chalk during the Quaternary (Gray 1952, Higginbottom and Fookes 1971, Younger and McHugh 1995, Salmon et al. 1996). This dominantly involved freeze-thaw processes that can produce a zone of highly fractured and hence highly permeable chalk, sometimes down to several tens of metres below the palaeosurface, but can also result in completely degraded 'putty chalk' which has low permeability.

The literature allows the development of three hypotheses. The first hypothesis of this study was that it would be possible to observe solutional enhancement of hydraulic conductivity in the zone of water table fluctuation in the unconfined part of the Chalk aquifer. The second hypothesis of this study was that it would be possible to observe stratigraphically controlled solutionally enhanced fractures within the Chalk aquifer. The third hypothesis of this study was that it would be possible to observe the impact of periglacial processes on the permeability structure of the Chalk aquifer.

The aim of the study was to test these three hypotheses and elucidate geological and hydrological factors controlling hydraulic conductivity structure in this aquifer. Preliminary findings have already been incorporated into Farrant et al. (2016) which builds a detailed conceptual model for the area around Kilham. This work will also inform the development of a groundwater flow model (if one were commissioned by the UK Environment Agency). This model could then be used to defining Source Protection Zones in fractured aquifers, which requires detailed fieldwork and modelling (for example Robinson and Barker 2000, Carneiro 2005).

Field area

The Cretaceous Chalk of East Yorkshire (see Figure 1), was uplifted and folded in the Tertiary. As a result, the unconfined part of the aquifer, comprising the Yorkshire Wolds, lie on the western limb of a gentle south-east plunging syncline, the eastern limb being 50 km offshore in the North Sea (Kent 1980, Foster and Milton 1976). During the Quaternary, East Yorkshire experienced several cold periods. A drill core extracted from the Holderness Plain area (Wilfholme Landing Field Site, see Hartman et al 2007) shows alluvial deposits and glacial till down to -10 mASL[3], underlain by ~4m of fully degraded 'putty' chalk (impermeable), then ~10m thickness of periglacially weathered, highly fractured chalk, with fresh unweathered chalk below. The principal surface drainage feature of the region is the River Hull and its tributaries, which flow southwards into the Humber estuary at the city of Kingston-upon-Hull. Surface drainage on the confined chalk (Holderness Plain) has been heavily managed for centuries to make agriculture possible (Gale and Rutter 2006) and water from a

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[3] Above Sea Level or Ordinance Datum, the UK standard for Mean Sea Level

dense network of field drains is pumped into the R. Hull, the elevation of which is several metres above natural ground level along much of its course.

The natural regional groundwater flow is east-south-eastwards towards the North Sea and the Humber estuary, reflecting the fact that most recharge occurs in the Yorkshire Wolds. A line of springs exists along the feather edge of the largely impermeable Quaternary sequence; some springs emerge further east in small areas where the cover sequence is permeable. Averaged over the period 1961 to 1992, rainfall was 750 mm/year and in the summer evapotranspiration exceeds rainfall so that most infiltration occurs from October to March (Downing 1993, Gale and Rutter 2006). Groundwater abstractions are mostly distributed around the edge of the glacial deposits and around the north edge of the town of Kingston-upon-Hull, see Figure 1. East of the River Hull and within Kingston-upon-Hull, the groundwater is saline, due to both ancient and modern marine intrusions. The UK Environment Agency maintain a network of monitoring wells across both confined and unconfined sections of the aquifer, which are generally uncased and self-supporting in the chalk, and typically 30 – 100m deep. It is this network of monitoring wells which have been used to characterise the vertical structure of horizontal hydraulic conductivity of the Chalk in this study.

Methods

Impeller flow logging

Logging vertical fluid velocity within pumped wells allows the location of and magnitude of inflows into the well to be determined. This method is described in full in Parker et al. (2010). In this study, pumped flow logging of selected UK Environment Agency observation wells on the confined Chalk aquifer (Figure 1) was undertaken. Pumping rates were typically 0.1 to 0.3 m^3/min, which resulted in upflow velocities in 0.15 m and 0.2 m diameter wells of typically 3 to 17 m/min, and well drawdowns of 1-5m. In order to maximise signal-to-noise ratio, logging was conducted with the sonde trolling down the well i.e. against the induced flow, typically at rates of 6 to 8 m/min. The logging was carried out after quasi-steady state had been reached to ensure that flows were proportional to transmissivities. Flow logging under ambient (unpumped) conditions was also undertaken, but ambient flow velocities were usually below the detection limit of the flowmeter of ~0.7 m/min (well dilution testing reported below shows that flows under ambient conditions are generally more than an order of magnitude smaller than under pumped conditions).

Flow logging data were analyzed using a technique described by Parker et al. (2010). In this approach, the flow log data are used to identify the number of hydraulic layers or flowing fractures and the depths of the boundaries of these layers. It involves automated fitting of model flow logs generated for specific numbers of hydraulic layers to the raw (unsmoothed) flow log data, using an algorithm written in the computer code R. Best model fits are identified by regression analysis using varying layer thickness and hydraulic conductivity.

Wells where flow-log measurements were made are shown in Figure 1. Overall well transmissivity data were measured using either a standard aquifer pumping test, interpreted using the Cooper-Jacob 'straight-line' method, or steady state analysis using the observed drawdowns that occurred during pumped flow-logging. Transmissivity data for wells at the Wilfholme Landing Test Site are from Hartmann (2004).

Well dilution testing

Well dilution testing under ambient flow conditions was applied as a second approach to establish the vertical structure of horizontal hydraulic conductivity structure and also to provide an indication of the ambient rate of groundwater flow (see Tsang et al. 1990, West and Odling 2007; Maurice et al. 2011). This was the only approach applied to wells in the unconfined chalk where the water table was deep (up to100m below ground level), as pumping such wells (i.e. for the purpose of flow logging) is impractical owing to the large lift required. Initially, background electrical conductivity profiles were taken using a handheld conductivity probe. Salt solution (containing approximately 230 g/L NaCl) was then introduced throughout the open section of the well using a 1.9 cm internal diameter hosepipe. Where the resting water level was within the well casing, tap water was then added so that the freshwater-saltwater interface within the hosepipe was at the level of the base of the casing. The hosepipe was then slowly removed in order to leave a column of saline water in the open section of the well. Depending on the diameter of the well, lateral mixing with the well water gave initial salt concentrations of 0.2 to 4 g/L. Subsequent electrical conductivity profiles were measured using the handheld conductivity probe. This approach allows identification of fractures or permeable layers where water is entering and leaving the well with vertical flows within the water column between, and of zones where flow is essentially horizontal across the well water column (see Maurice et al. 2011). Mathias et al (2007) successfully used the technique in the Chalk in Berkshire to identify flow horizons linked to a hard layer known as the "Chalk Rock". For both cases, the time required for the salt tracer to be replaced by fresh groundwater provides an indication of groundwater flow rates. Where sections of wells are identified where only vertical flows occur between discrete in and outflows horizons, the vertical well fluid velocity was determined by fitting the Advection-Dispersion Equation (ADE) to the salt concentration profiles. The theoretical basis of this approach is described in full by West and Odling (2007) and so is not reproduced here. Key assumptions are that the rate of vertical flow is constant within the section of the well analysed, and that vertical dispersion of salt at the saline/freshwater interface within the water column is Fickian, and can therefore be described by the ADE approach using a well dispersivity co-efficient. Optimum vertical flow velocity and well dispersivity co-efficient were identified by regression analysis (Parker, 2009). Maurice et al (2011) question the assumption that the dispersivity coefficient is linearly related to the flow velocity, and instead propose a power law relationship. However, for this analysis the regression derived dispersivity is deemed to be adequate. Wells where measurements were made are shown in Figure 1. All wells are on the Flamborough Chalk except Millington, Etton D, Dalton Middle, Sherburn Wold, Kilham Road, Thwing and Bartondale which are on the Burnham Chalk (Farrant et al. 2016).

Results and interpretation

Transmissivity distribution

Measurements of hydraulic conductivity structure need to be viewed in the context of the horizontal pattern of aquifer transmissivity. Therefore a transmissivity map (Figure 2) was created from fifty well transmissivity measurements including those determined in this study, and collated from other sources (Hartmann 2004; Allen et al. 1997; R. Farrell,UK Environment Agency, personal communication, 2008). Six apparently anomalous measurements (i.e. those that were at least an order of magnitude lower than nearby measurements, thus suggesting problems with well construction) were excluded. Figure 2 shows that transmissivity typically varies between 100 and 1000m^2/day on the Holderness Plain where the Chalk is confined by the glacial sequence. Higher transmissivities of up to 2000m^2/day occur in the confined aquifer near the feather edge of the glacial sequence (especially near the Etton abstraction, northwest of Beverley, and near the major public water supply abstractions north of Driffield, see Figure 2); lower values of <100m^2/day occur in the easternmost part of the aquifer, east of the R.Hull. Transmissivity values of between 500 and 10,000m^2/day are typical of the unconfined Chalk, with the higher values tending to occur near the base of the dip slope (eastern side of the unconfined chalk outcrop area), north of Driffield and west of Beverley. These are the sites of a series of major public abstraction wells (see Figure 1). The relatively high transmissivity values for the unconfined aquifer, compared to the confined aquifer, indicate fracture enlargement by carbonate dissolution.

Flow logging results

An example of impeller flow log data and the resulting hydraulic conductivity model from a well on the confined Flamborough Chalk (Wilfholme well M3) is shown in Figure 3, with n being the number of layers.. The raw flow log data (Figure 3a), with the superimposed modelled flow velocities for the cases of 5, 6 and 7 discrete hydraulic conductivity layers, shows that most of the water entering the well comes from above -35 mASL, i.e. the upper 20m of the aquifer, with more than half coming from the upper 10m. A small proportion of the water enters the well at a deeper level (-43 to -48 mASL). The model output hydraulic conductivities (Figure 3b) are given for the seven layer case; the model output quantifies the trends seen in the raw data, and provides an estimate of uncertainty in hydraulic conductivity and layer boundary positions. However, note that the hydraulic conductivity value for the uppermost permeable layer (37 m/d, layer thickness 3.4 m) is overestimated because the solid well casing protrudes into the upper section of the aquifer; a corrected value (14 m/d, layer thickness 8.9 m), shown by the dashed line in Figure 3, has been found by assuming that no flow comes from the aquifer above the base of the casing(i.e. the K value of the uppermost permeable layer is found using the true layer thickness, rather than only that intersected by the well below the casing). In this example the correction shows that the uppermost permeable layer identified by the model is a distortion caused by the well casing; in fact the hydraulic conductivity is the same as that of the layer below. Model outputs from the other eight wells where pumped flow logging was conducted are summarised in Tables 1a (Wilholme Landing test site wells) and 1b (other wells); similar corrections to the uppermost layer hydraulic conductivity for the presence of well casing have been applied.

The cumulative vertical transmissivity distribution for the flow-logged wells (Figure 4), found from the hydraulic conductivity values reported in Table 1, indicates that transmissivity is focussed in the upper 10 to 30m of the aquifer. In the case of North End Stream, which is the only flow-logged well on the unconfined aquifer, there is very high hydraulic conductivity (~140 m/d) in the upper 10m, which corresponds to the zone of seasonal water table fluctuation . The upper permeable zone in the confined aquifer is typically thicker, and usually includes a layer of chalk gravel (locally known as ‘bearings’) up to 10m thick underlain by up to 20m thickness of periglacially weathered chalk. [In the case of the Wilfholme Landing Test Site, the permeable layer can be seen to correspond with the depth of periglacial weathering in the core extracted from the site (Hartmann, 2004)]. Hydraulic conductivities for these zones range from a few to ~50 m/d, see Table 1; these estimates are entirely consistent with those derived from a forced gradient tracer test conducted at the Wilfholme site (see Hartmann et al. 2007). Some deeper permeable layers are identified (e.g. seen at the well at Carnaby, see Table 1b and Figure 4), but the transmissivity contribution of such layers is relatively small. These may relate to flow along marl layers as all these boreholes are in the marl-rich Flamborough Chalk.

Well Dilution Testing

Well dilution tests under ambient flow conditions were carried out at the Wilfholme Landing Test Site (TA062472) in order to provide direct comparison with the pumped-well flow logging approach. Generally, these wells showed slow responses compared with those on the unconfined aquifer, with flushing of the salt water taking several days (Figure 5a); this reflects the slower groundwater circulation in the confined part of the aquifer due to the smaller hydraulic gradients present (Gale and Rutter 2006). The pattern of response seen is dominated by flow across the well within the upper permeable zone as identified from the flow logs (compare Figure 5a with Figure 3b); below this zone dilution is slower, for example the feature at -55m develops a lot more slowly than the higher features. Thus, while dilution does not provide quantitative permeability data, it provides an excellent and quick method for the identification of its distribution with depth.

An example of the patterns seen in the dilution profiles from across the unconfined aquifer is seen in Weaverthorpe well (Figure 5b) on the Flamborough Chalk, which shows downwards vertical flow from near the water table (50 mASL), exiting the well at mid-depth (34 mASL); upwards flow occurs below this depth (from an inflow at 31 mASL). Flow is relatively rapid with flushing taking only 2 hours indicating much more rapid groundwater circulation than in the confined aquifer; fitting with the ADE (dashed curves) gave flow velocities of 0.3 and -0.1 m/min (negative sign indicates upflow) for above and below the outflow respectively. The results of other ambient well dilution tests are summarised in Table 2. Like Weaverthorpe, most wells in the unconfined aquifer show water enters the well near the water table and flows downwards to outflows 5 to 30m below. This upper zone of active circulation is likely to represent the zone of enhanced permeability associated with fracture enlargement by calcite dissolution, such as that identified in North End Stream well by flow logging.

Most wells show downflow, but exceptions are seen in those wells that penetrate to below sea level, where inflows from deeper permeable horizons create upflows (Bartondale, Henpit Hole); in the case of Henpit Hole very rapid upflow (5m/min) from such a horizon (-15 mASL) is seen which suggest that this well has intersected a permeable horizon with relatively high hydraulic head, connected to topographically higher locations in the nearby Wolds. Such deep permeable horizons cannot be within the zone of water table fluctuation; their origin and nature is discussed further below. Impeller flow logging of ambient (unpumped) flows in the Henpit Hole measured similar ambient upflows of 4 m/min; i.e. good agreement is seen here between the two approaches. These flows show that there are significant head differences between permeable layers in the Chalk. There must be very few vertical conduits connecting these permeable layers as the head differences are maintained.

Note that the ambient vertical flows in the other wells identified from dilution testing (see Table 2) were below the detection limit of the impeller flow logging technique (0.7 m/min); this result illustrates the greater sensitivity of the dilution testing approach, which was able to detect vertical flows as small as 0.001 m/min. No flow logging method that we are aware of can measure such small flow velocities.

Discussion

Vertical structure of horizontal hydraulic conductivity of the Chalk in E Yorks

Results indicate that most of the permeability of the fully confined aquifer is likely to reside in its upper layer comprising chalk gravel and periglacially weathered chalk, typically between 10 and 30m thick, thus confirming the third hypotheses. This is not observed in the Chalk of southern England because the glaciation did not extend that far. The unconfined chalk aquifer also shows an upper high permeability zone, but here it is associated with the zone of seasonal water table fluctuation, thus confirming the first hypothesis. This is common to the Chalk of both southern England and Yorkshire. The unconfined section of the aquifer also shows deeper permeable horizons which are below this zone (& in some cases below sea level); these are also present in the confined section of the aquifer (i.e., some ambient well flows are seen at depth) but may be less well developed. This confirms the second hypothesis.

Where ambient flow measurements were performed in wells within a few hundred metres of each other, it was possible to correlate deep permeable horizons between wells to further test this second hypothesis. This confirmed that deeper permeable zones within the unconfined section of the Chalk (i.e. below the zone of enhanced permeability development related to water table fluctuation) are stratigraphically correlated. This is illustrated in Figure 6 which shows that the inflow and outflow horizons identified in ambient flow measurements in Bartondale, Yorkshire Wolds, are correlated along stratigraphic dip. The most likely explanation is that these permeable horizons represent enhanced permeability caused by calcite dissolution where flow has been focussed along the top of flint or marl (clay) layers known to be present within the Flamborough Formation of the Chalk (Buckley and Talbot, 1994). It has been previously proposed that marl layers in the chalk act as aquitards in both southern England (Reynolds 1947, Headworth et al. 1980, Jones and Robinson, 1999, Buckley et al 2001) and Yorkshire (, Green 1950, , Barker et al. 1984, Buckley and Talbot, 1994, , Zaidman et al. 1999, , Gale and Rutter 2006) which corrobortates this second hypothesis. Such horizons are likely to be less well developed in the confined chalk, where the groundwater is calcite saturated and has little dissolving potential remaining.

Given that there is high permeability (and presumably storativity),within the zone of water table fluctuation in the unconfined aquifer, if droughts or increased rainfall moved the water table the aquifer characteristics could vary, as proposed by Price et al. (1998). However he cites an unpublished study which concluded there would be no significant changes to flows under the likely climate changes up to 2050 in a Chalk catchment in Hampshire.

The methods used in this study are not without limitations. The well dilution testing in particular requires manual interpretation which will not be fully objective. It also proved practically impossible to attain a column of constant conductivity water despite the trial of various methods (for example using a spinner to mix the water column); further experimentation would be useful here. Minor flows can be dwarfed by major ones. The interpretation can also be affected by the necessary assumptions, for example the value of influx conductivity and well dispersivity, and that the rate of vertical flow is constant within the section of the well analysed. Nevertheless it is an extremely cheap and easy method that could be used to identify where more detailed studies are needed. The flow logging requires more expensive, specialist equipment but is more limited in its application, being only possible in boreholes that can be pumped with a surface pump (unless a powerful, narrow submersible pump can be sourced; low pump rates had a tendency to stall the impeller).   The interpretation is more robust and less subjective following the analysis method developed by Parker et al. 2009 which also gives confidence limits.

Conclusions

The purpose of the investigation was to improve understanding of the nature and origin of the permeable layers in confined and unconfined carbonate aquifers.   The unconfined section of the carbonate aquifer investigated was characterised by high permeability within the zone of water table fluctuation where enhancement of fracture apertures by carbonate dissolution is maximal. Deeper, thin permeable horizons were related to fracture permeability developed along stratigraphic features such as marl and flint layers. Where the aquifer is confined beneath a glacial sequence (comprising mostly impermeable till) its uppermost layer was also relatively permeable.   This enhancement is the result of periglacial weathering during Quaternary glaciations, which resulted in highly fractured, brecciated rock, overlain by a layer of permeable chalk gravel (‘bearings’). This high permeability layer needs careful incorporation into the groundwater models.   Deeper, stratigraphically controlled permeable layers are also present within the aquifer beneath the confining layer, but may be less well developed than in the unconfined aquifer. This probably reflects the relatively slow flow in this deeper zone of the aquifer, and its inaccessibility to water containing sufficient dissolved carbon dioxide. The findings support the three hypotheses presented in the introduction.   The information gained from the field measurements reported here, such as permeable layer thicknesses and estimates of hydraulic conductivity, may be used in the refinement of the existing groundwater flow model for the region. Specifically this paper can inform the layers that the model will need.

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Well name	UK Grid Reference	Ground surface Elev. mASL	Elev. of top of aquifer mASL	T m^2/d	Layer thickness m	Layer K m/d	Lower 95% confidence limit on K	Upper 95% confidence limit on K
Wilfholme P	TA062472	2	-15.3	490	8.6	55*		
					28.4	0.54	0.5	0.6
					26.7	0		
Wilfholme M1	TA062472	2	-15.0	495	9.3	13*		
					15.2	11	11	12
					2.1	100	92	110
					29.4	0		
Wilfholme M2	TA062472	2	-12.9	485	11.3	13*		
					4.8	0.6	0.6	2.5
					2.3	100	89	100
					9.9	6.2	5.9	6.7
					8.8	4.4	4.1	5.7
					21	0		
Wilfholme M3	TA062472	2	-15.0	490	17.4	14*		
					1.8	70	∀	70
					2.0	14	∀	22
					5.7	0.45	∀	1.6
					4.7	8.6	7	∀
					1.5	34	∀	33
					21.9	0		

*upper layer value corrected for presence of well casing as explained in the text; no CI given

∀ confidence interval could not be computer by R

Table 1a. Hydraulic conductivities from pumped impellor flow logging on the confined chalk aquifer, Wilfholme Landing Test Site, June and October 2005.

Well name	UK Grid Reference	Ground surface Elev. mASL	Top of aquifer mASL	T m^2/d	Layer thickness m	Layer K m/d	Lower 95% confidence limit on K	Upper 95% confidence limit on K
Confined aquifer								
Benningholme	TA123389	2.5	-16.4	320	8.1	38*		
					35	0.25	0.23	0.25
					13	0		
Carnaby	TA151648	15	-9.4	130	2.8	19*		
					68	0.84	0.83	0.85
					0.2	96	0	870
					2.6	0		
Hempholme	TA095495	1.6	-13.3	90	13.9	2.5*		
					1.0	55	47	63
					5.3	0		
Thornholme Moor	TA117606	11	-8	130	14.8	7.4*		
					6.2	3.3	2.8	3.3
					6.0	0		
Unconfined aquifer								
North End Stream	TA022584	18	12¤	1070	6.3	143*		
					8.0	27	25	27
					2.5	0		

*upper layer value corrected for presence of well casing as explained in the text; no CI given

¤ water table elevation within Chalk on 11/05/07 – varies between 4.5 and 13 mASL

Table 1b. Hydraulic conductivities from pumped impellor flow logging, other wells (conducted in September 2006 and May 2007, except Carnaby which was logged in December 1996, data provided by D. Buckley of the British Geological Survey).

Well name	UK Grid reference	Ground Surface Elev. mASL	Water table Elev. mASL	Inflow depth mASL	Outflow depth mASL	Well base Elev. mASL	Vertical flow rate m/min[¤]
Unconfined aquifer							
Bartondale	TA054669	50	21	-8	21	-15	-0.01
Dalton Middle	SE903514	110	20	20	10	2	0.002
Etton D	SE966430	34	14	*	*	-37	*
Field House, Kilham	TA071673	69	28	28	6	6	0.001
Garton Wold	SE982622	49	22	22	13	5	0.2
Grindale	TA140718	74	20	20	*	0	<0.001
Henpit Hole	TA025658	49	35	-15	35	-15	-5
Kilham Road,Thwing	TA050690	115	33	33	16	10	0.002
Little Kilham Farm	TA045649	40	24	*	*	-11	*
Millington	SE847539	99	87	87	66	62	0.75
Sherburn Wold	SE969745	122	65	65	35	22	0.002
Weaverthorpe	SE981702	71	50	50, 31	36	23	0.3, -0.1
Confined aquifer							
Wilfholme P	TA062472	2	1	-79	-26	-79	-0.006
Wilfholme M1	TA062472	2	1	-41	-36	-68	*
Wilfhome M2	TA062472	2	1	-33	-42	-68	*

[¤] negative values indicate upflow *not determinable (horizontal flow dominates)

Table 2: Results of ambient well dilution testing (conducted in June and November 2008)

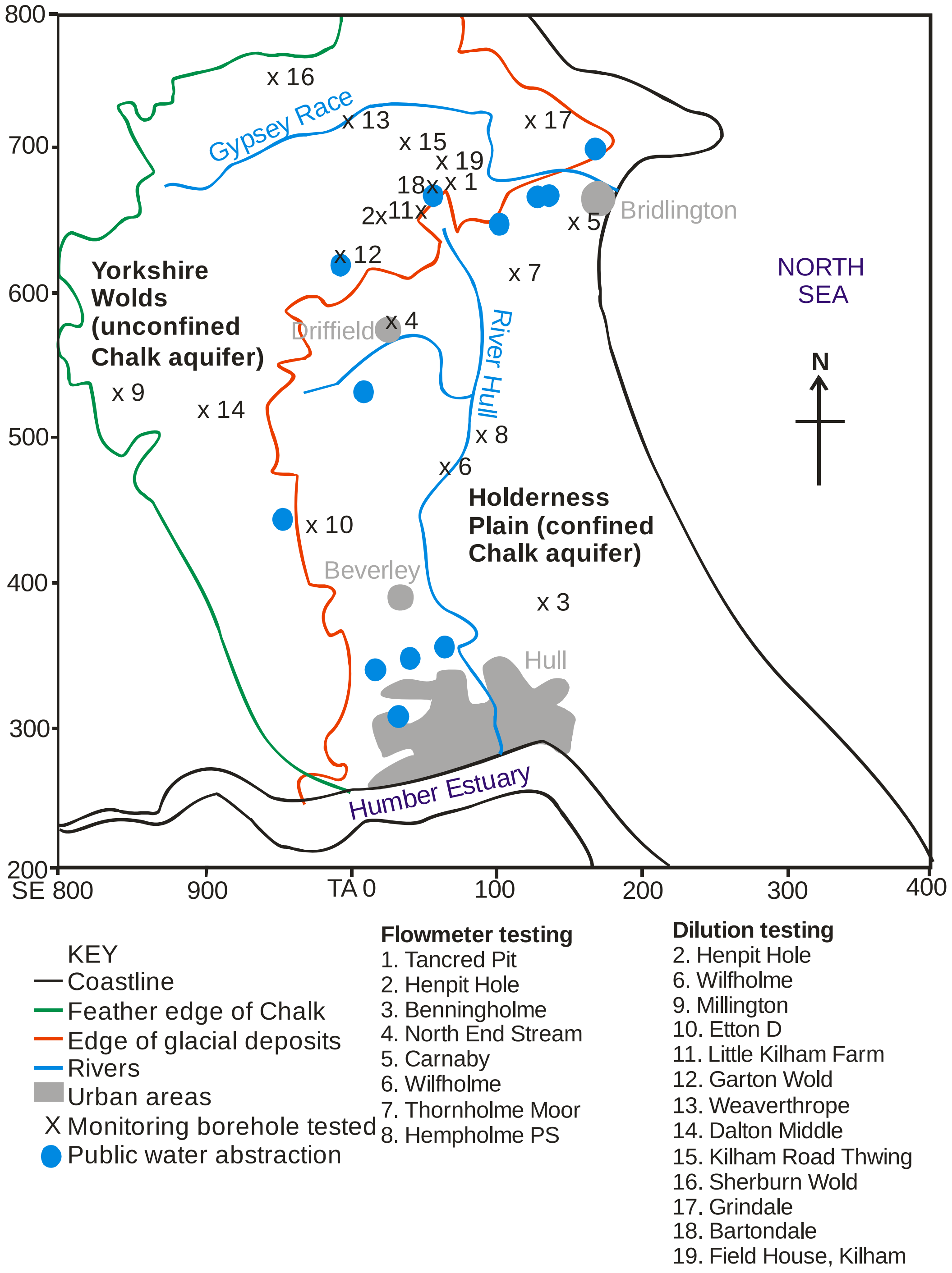


Figure 1: Map showing the location of the field area. Boreholes where flow logging and dilution testing carried out are indicated.

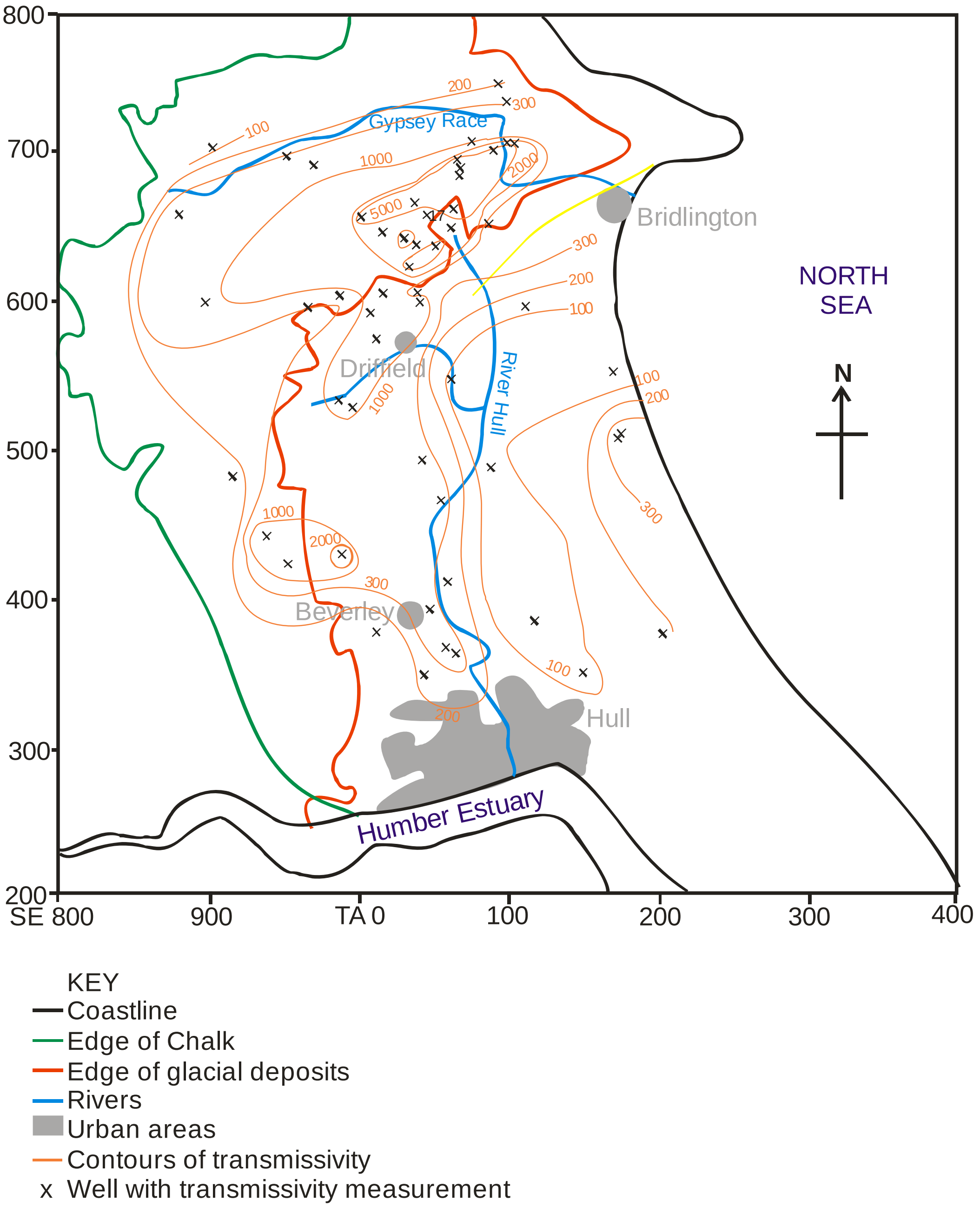


Figure 2: Map showing contours of transmissivity based on pumping tests (data from UK Environment Agency, British Geological Survey, and this study). Contours were drawn by inspection.

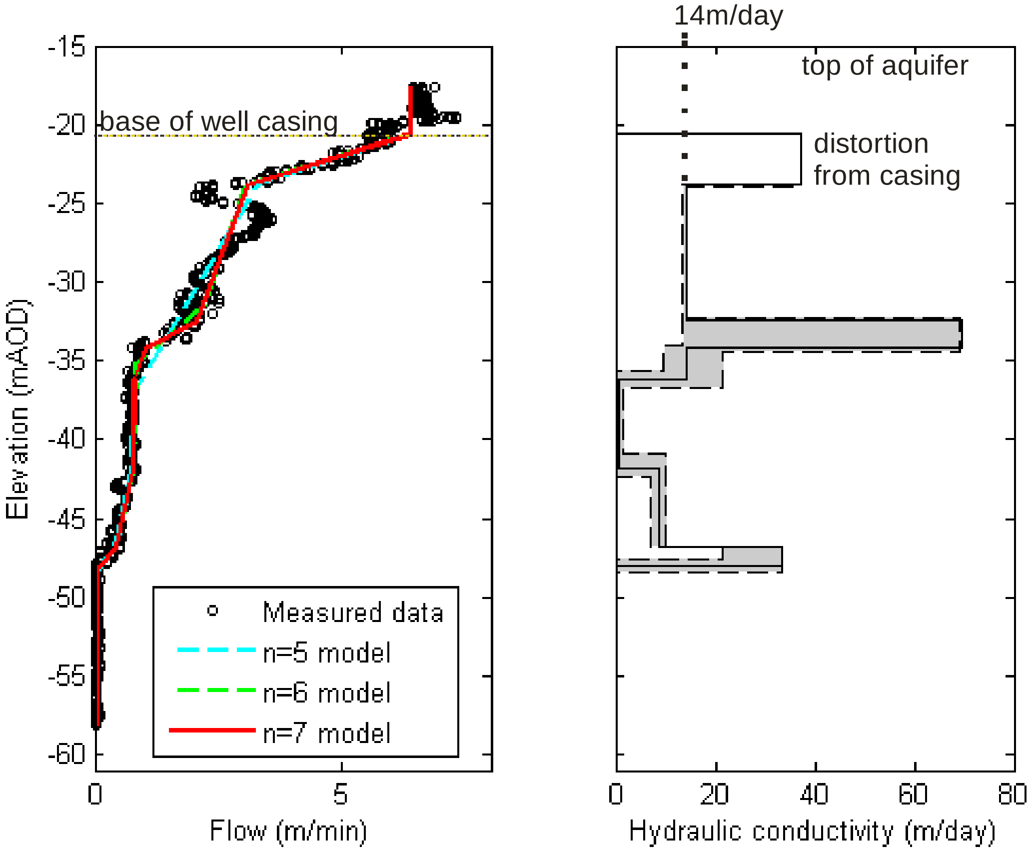


Figure 3: a) Impeller flow log and b) model-derived hydraulic conductivity profile from Wilfholme borehole M3 (TA062472) shown by solid line; dashed lines & shaded area shows 95% confidence limits, dotted line value for upper layer corrected for presence of impermeable well casing.

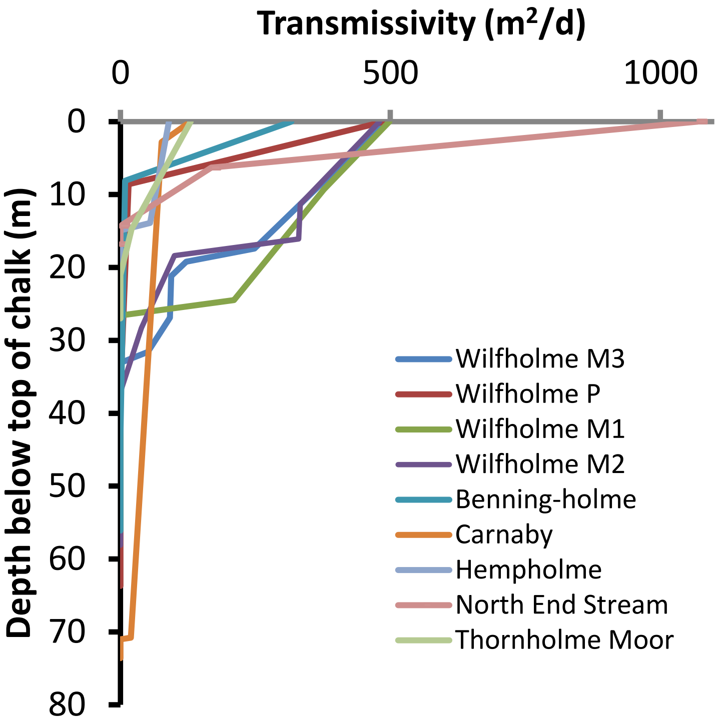
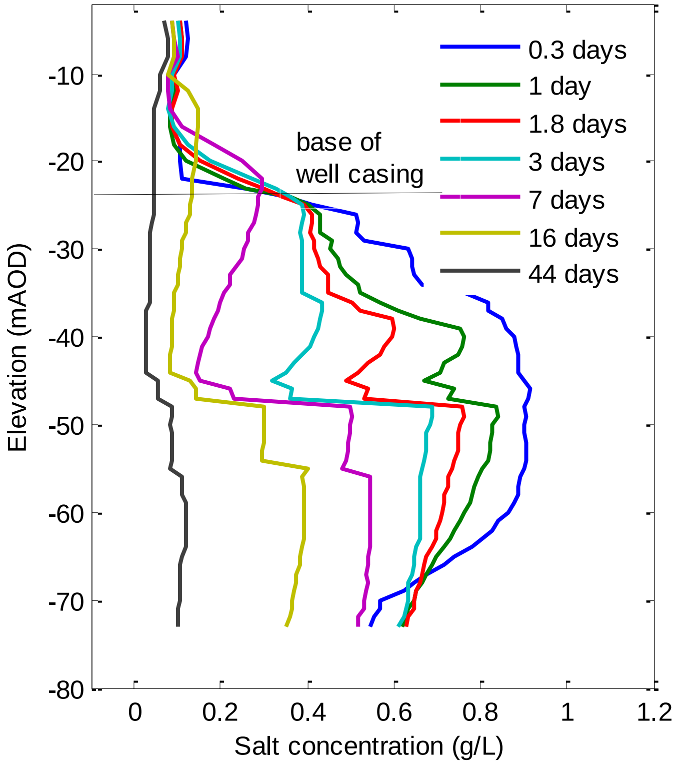
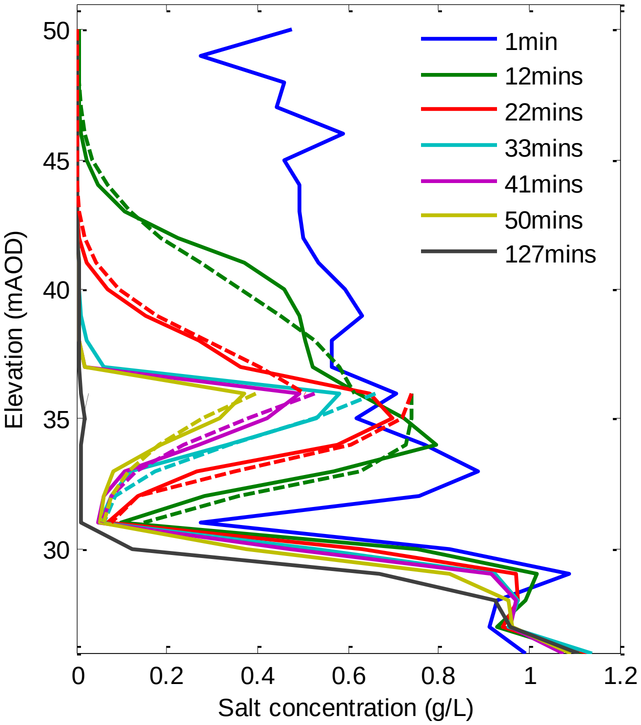


Figure 4: Cumulative transmissivity versus depth below top of the aquifer. Note that the top of the aquifer is defined as the top of the uppermost permeable layer, which is often chalk gravel (bearings), see Tables 1a and b.

494 a)



495 b)



496

c)

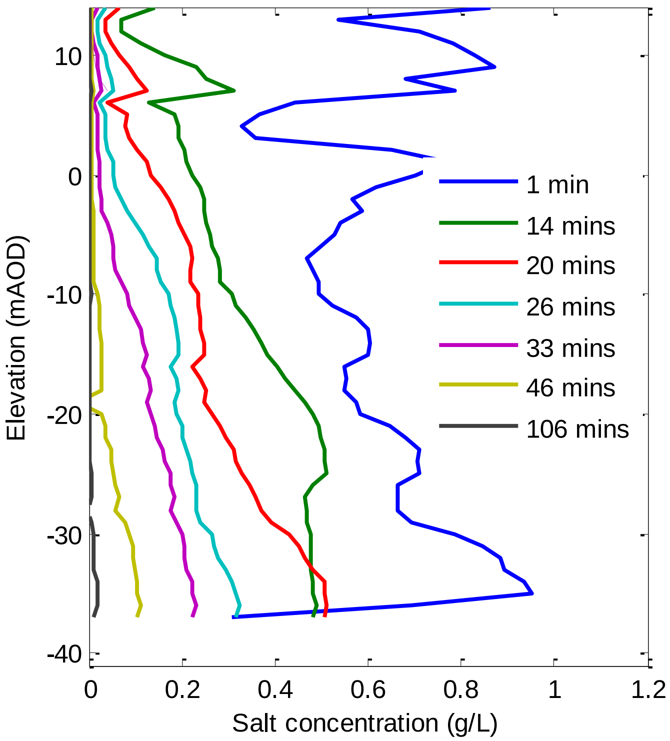


Figure 5. Salt concentration profiles from a) Wilfholme borehole M1 b) Weaverthorpe (solid lines – data; dashed lines – model fits to the ADE assuming vertical flow in well) and c) Etton borehole D

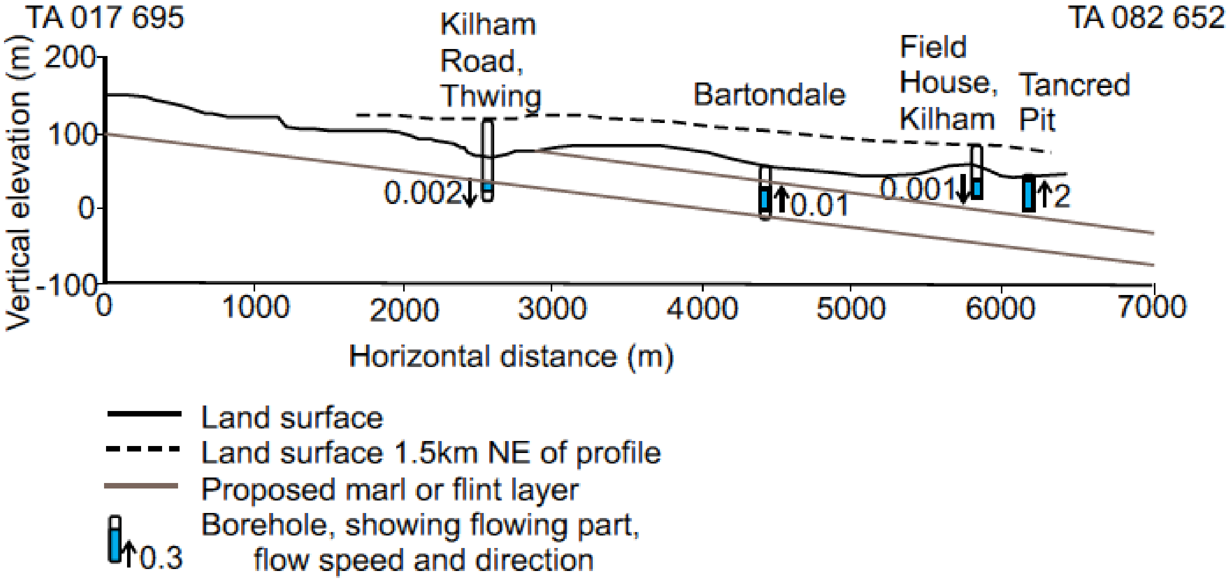


Figure 6: Profile along Bartondale. Borehole flow velocities shown in m/min. Kilham Road Thwing and Bartondale are in the Burnham Formation and Field House Kilham and Tancred Pit are in the Flamborough Formation according to Farrant et al (2016)