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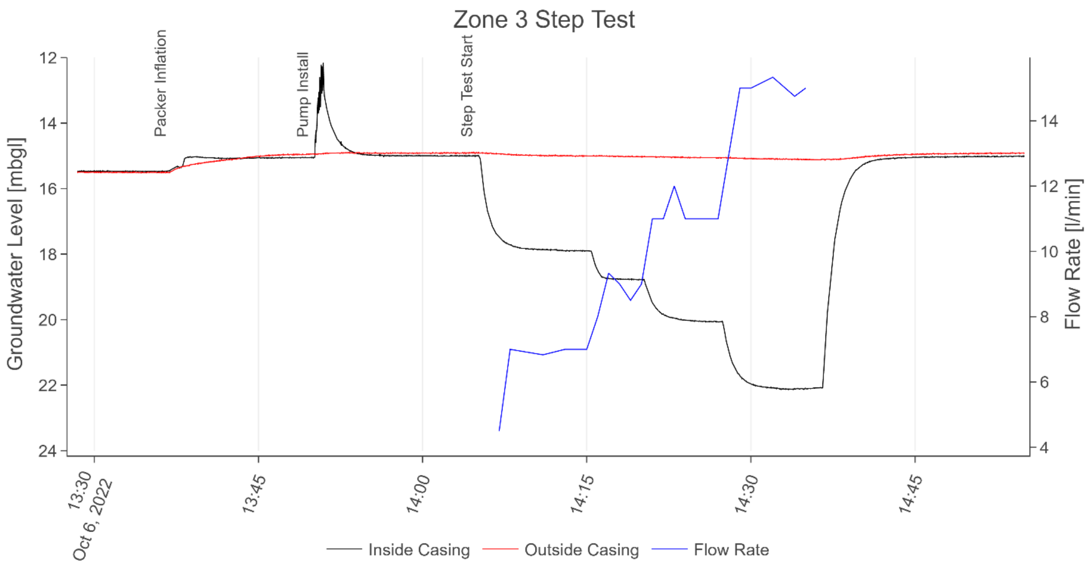
UK Geoenergy Observatories Cheshire: Hydraulic Testing of TH0424 Technical Summary

UK Geoenergy Observatories

Open Report OR/23/037



BRITISH GEOLOGICAL SURVEY

UK GEOENERGY OBSERVATORIES

OPEN REPORT OR/23/037

UK Geoenergy Observatories Cheshire: Hydraulic Testing of TH0424 Technical Summary

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Thanks extend to Andrew McKenzie for conducting a thorough independent science review of the report.

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1 Introduction & Scope

This report details the schedule and results of hydraulic testing of the TH0424 ground investigation borehole at the UK Geoenergy Observatory (UKGeos) Cheshire borehole array, Thornton Science Park during October 2022.

UKGeos aims to establish new centres for world-leading research into the subsurface environment, generating data and knowledge to inform responsible development of new subsurface technologies (https://www.ukgeos.ac.uk/). Observatories are currently being developed at Thornton Science Park (TSP) in Cheshire (near the villages of Thornton and Elton), and near the Cuningar Loop of the River Clyde, Glasgow.

Hydraulic testing was conducted using a straddle packer system to allow for isolated testing through the entire length of the water column, and to isolate specific features of interest (e.g. fractures, low permeability zones etc.), employing step and constant rate pumping test methodologies to provide response data that can be applied to hydraulic property models. The isolation of specific zones also allowed for the opportunity to collect groundwater samples and hydrochemical parameters, providing a profile of hydrochemical composition.

The straddle packer system allows characterisation of dominant flow paths within the borehole and thus will aid in informing the design of multilevel monitoring boreholes within the array. This report does not serve as an interpretation of the collected data (although some basic analysis is undertaken), but rather aims to provide context to the collected dataset that can be utilised by the wider scientific research community.

Development of the site at the time of testing (drilling of boreholes in close proximity) resulted in sub-optimal conditions for hydraulic testing and thus some data have been impacted by these activities. Perturbations or deviations in data thought to arise from these activities have been highlighted where possible. Abstractions from the Thornton Science Park abstraction borehole c.350m from the UKGeos array is also known to be detected at TH0424 with the site sitting within the radius of influence. Abstraction events taking place during individual tests have been highlighted and the full record of abstractions for the testing period is available. Borehole information packs available from UKGeos also provide daily drillers borehole records to relate any potential impacts from drilling activities. Considering the above caveats, care should be taken when using the data obtained during hydraulic testing and it should only be used in context of local activities, events or works.

This report accompanies the full data pack of hydraulic testing data and supplementary information available at https://doi.org/10.5285/f1ad3bf6-f32a-4895-9f5f-8fa95c158832.

2 Geology & Hydrogeological Setting

The UKGeos Cheshire observatory lies south of the Mersey Estuary and Manchester Ship Canal in an area of historic and current industrial development including the Stanlow oil refinery directly west of Thornton Science Park (TSP). Historic industrial activity in the area has resulted in organic and metal contamination of soils and groundwater including BTEX, MTBE, PAH, chlorinated hydrocarbons, arsenic, cadmium, chloride, nickel and zinc (Elsome and Parker, In Preparation). Historic contamination is predominantly confined to the west of TSP with concentrations significantly decreased around the UKGeos array in the north-east corner.

The bedrock in the wider Cheshire region is predominantly of the Triassic Sherwood Sandstone group with the Chester Formation (formerly Chester Pebble Beds) underlying the UKGeos observatory (Figure 2.1) and sits within a north-trending horst block. The Sherwood Sandstone forms an important principal aquifer across the UK. The Chester Formation consists of well cemented medium- to coarse-grained pebbly sandstone with interbedded mudstone (Allen et al., 1997). Locally, the upper part of the bedrock has been weathered to uncemented sand and gravels to a depth of 10 – 20 m (Fellgett et al., 2017; Hannis and Gent, 2017; Kingdon et al., 2019). The Chester Formation has a moderate matrix permeability with faulting/fracturing playing a secondary permeability role with some filled with loose debris or clay infill inhibiting flows and some open fractures often acting as preferential flow paths. Horizontal hydraulic permeability dominates due to mudstone bands throughout the formation. The Chester Formation yields 1000 – 2000 m^3/d at almost all locations (Allen et al., 1997).

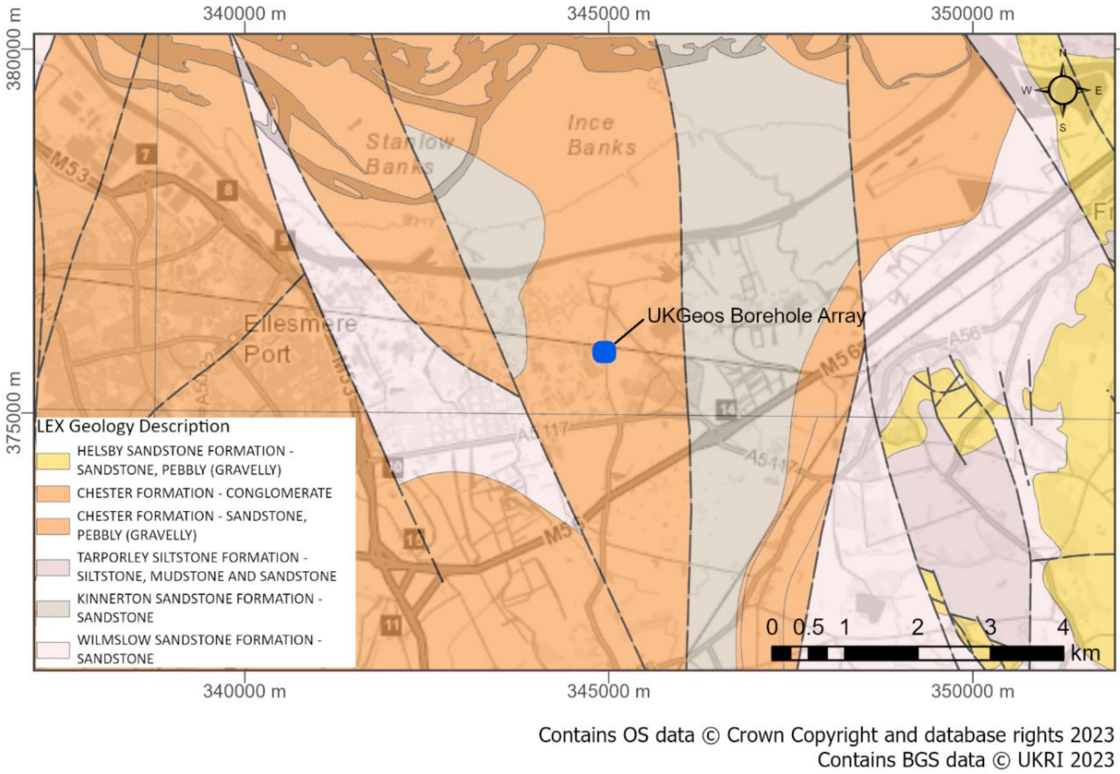

Figure 2.1 – 1:50k geology and major faults around the UKGeos Cheshire observatory. Ordnance Survey Licence No. OS AC0000824781.

Devensian Till is prevalent in the area but is, however, absent over the north-east corner of TSP (Figure 2.2). A thin layer of artificial/made ground (0.5 – 2 m) forms the overburden consisting of bituminous hardstanding, concrete, gravels and sandy clay before grading into weathered sandstone. Recharge from across TSP will be minimal due to widespread impermeable hardstanding with surface run-off feeding into foul sewers/run-off drains. Leakage from underground services is still possible.

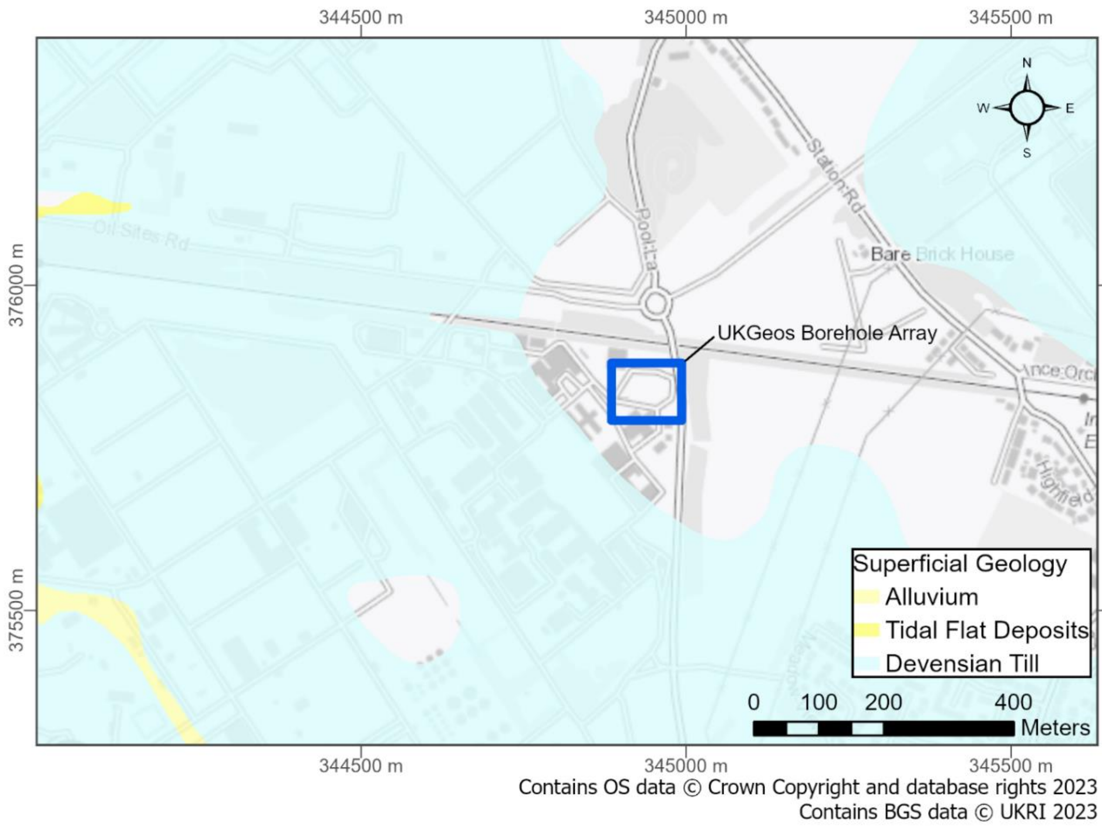

Figure 2.2 – 1:10k superficial geology around the UKGeos Cheshire observatory. Ordnance Survey Licence No. OS AC0000824781.

Groundwater flow is from the main recharge area in the east (Mid Cheshire Ridge; Figure 2.3) towards the UKGeos Cheshire array to the west/north-west (Crane et al., 2018). The Sherwood sandstone outcrops along the western side of the ridge with no superficial deposit cover acting as the recharge zone, whilst along the east the Mercia Mudstone confines the Sherwood sandstone restricting recharge. Some local recharge through higher permeability superficial deposits such as glacial sands and gravels may occur, or through fractures in glacial till.

Precipitation from the Folly Gates rainfall observation station (c.2 km west of TSP) shows an average annual precipitation of 710 mm/yr (1998 – 2022); less than the England and Wales average of 951 mm/yr (1991 – 2020). Precipitation in the higher ground of the Mid Cheshire Ridge is likely >15% greater than the low-lying Folly Gates weather station. Figure 2.3 shows annual precipitation contours interpolated from the 2km HadUK-Grid observation data for the 1991 – 2020 period (Met Office et al., 2022), showing increased precipitation over the Mid Cheshire Ridge and Helsby Hills (>850 mm/yr) versus the lower lying plain where TSP sits (<750 mm/yr).

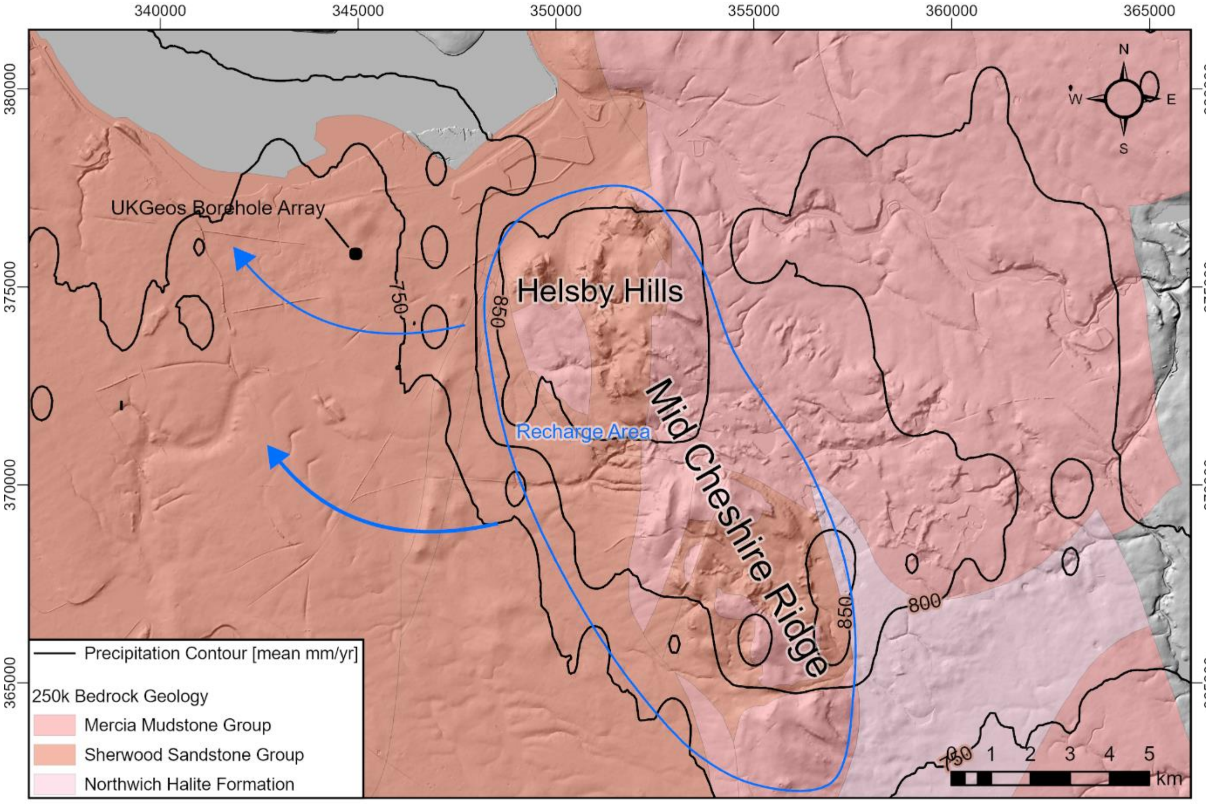

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Figure 2.3 - 1:250k bedrock geology map overlaying a 10m hillshade DTM showing the main recharge area and groundwater flow. Mean annual precipitation contours shown based on 2km HadUK-Grid observation data 1991 – 2020 (Met Office et al., 2022). Blue lines denote recharge area and general groundwater flow direction. Contains public sector information licensed under Open Government License v3.0. Ordnance Survey Licence No. OS AC0000824781.

3 Test Borehole Description – TH0424

A condensed description of TH0424 is given, with a detailed version available in the borehole information pack (UKGEOS Cheshire Project Team, 2023)

Borehole TH0424 was the first ground investigation borehole drilled to 100m at the UKGeos Cheshire site to inform the design of the array and is located in the north-east corner of the array (Figure 3.1; NGR 344965, 375857) at a surface elevation of 20.73 masl. Drilling took place between 08/11/2021 and 30/11/2021, primarily using a Comacchio GEO405 rotary rig and Geobor S wireline coring system to a total depth of 101.14 mbgl. 24” surface casing was installed to 2 mbgl and 11” intermediate casing installed 2 – 20 mbgl. A 146 mm diameter open hole section was left between 20 and 101.14 mbgl. The basic construction is shown in Figure 3.2. Drilling circulation losses were observed below 45 mbgl probably due to highly transmissive fracture zones. Borehole geology is primarily the Chester Formation of the Sherwood Sandstone Group with multiple mudstone bands, open fractures and infilled fractures giving a variable flow, porosity and permeability profile. A detailed sedimentary log obtained from logging of core material along with additional geophysical wireline logs is available in the borehole information pack.

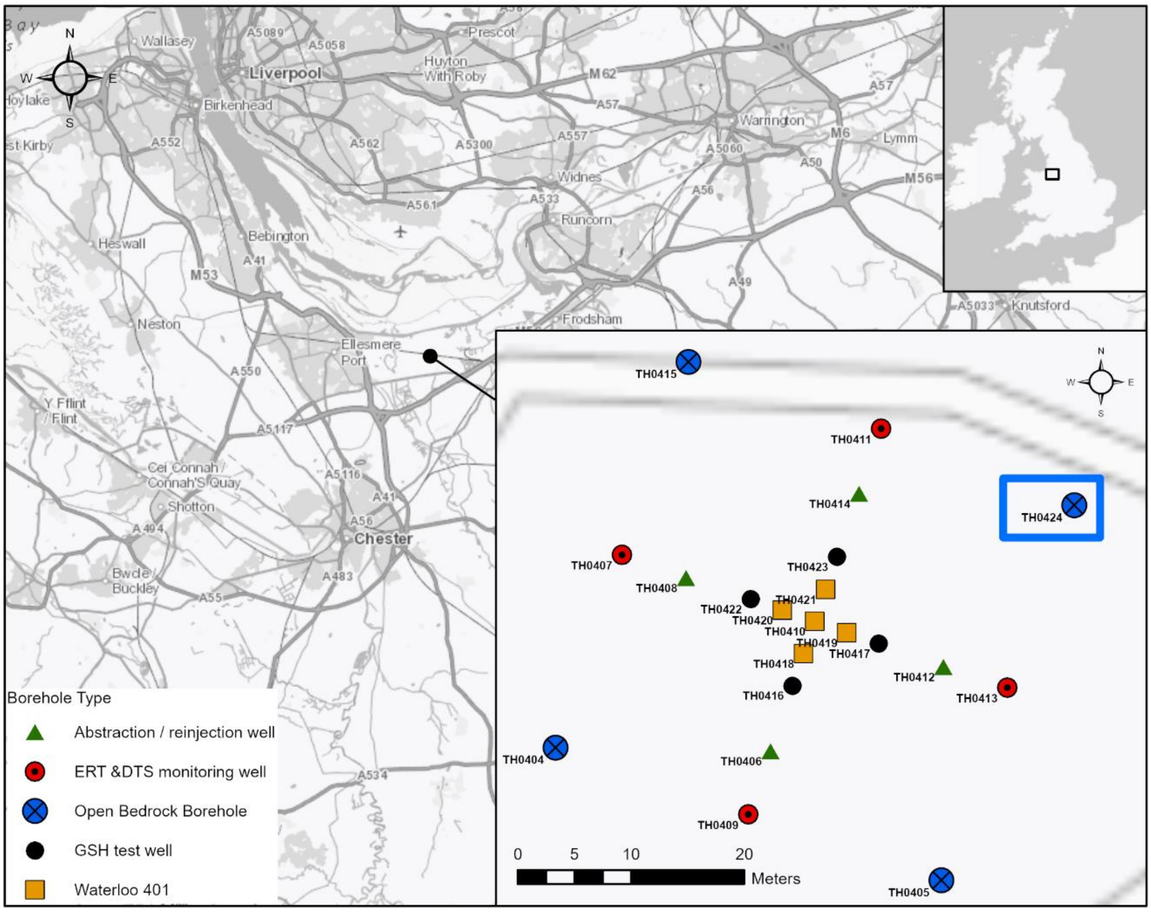


Figure 3.1 - UKGeos Cheshire site location and layout. Ordnance Survey Licence No. OS AC0000824781.

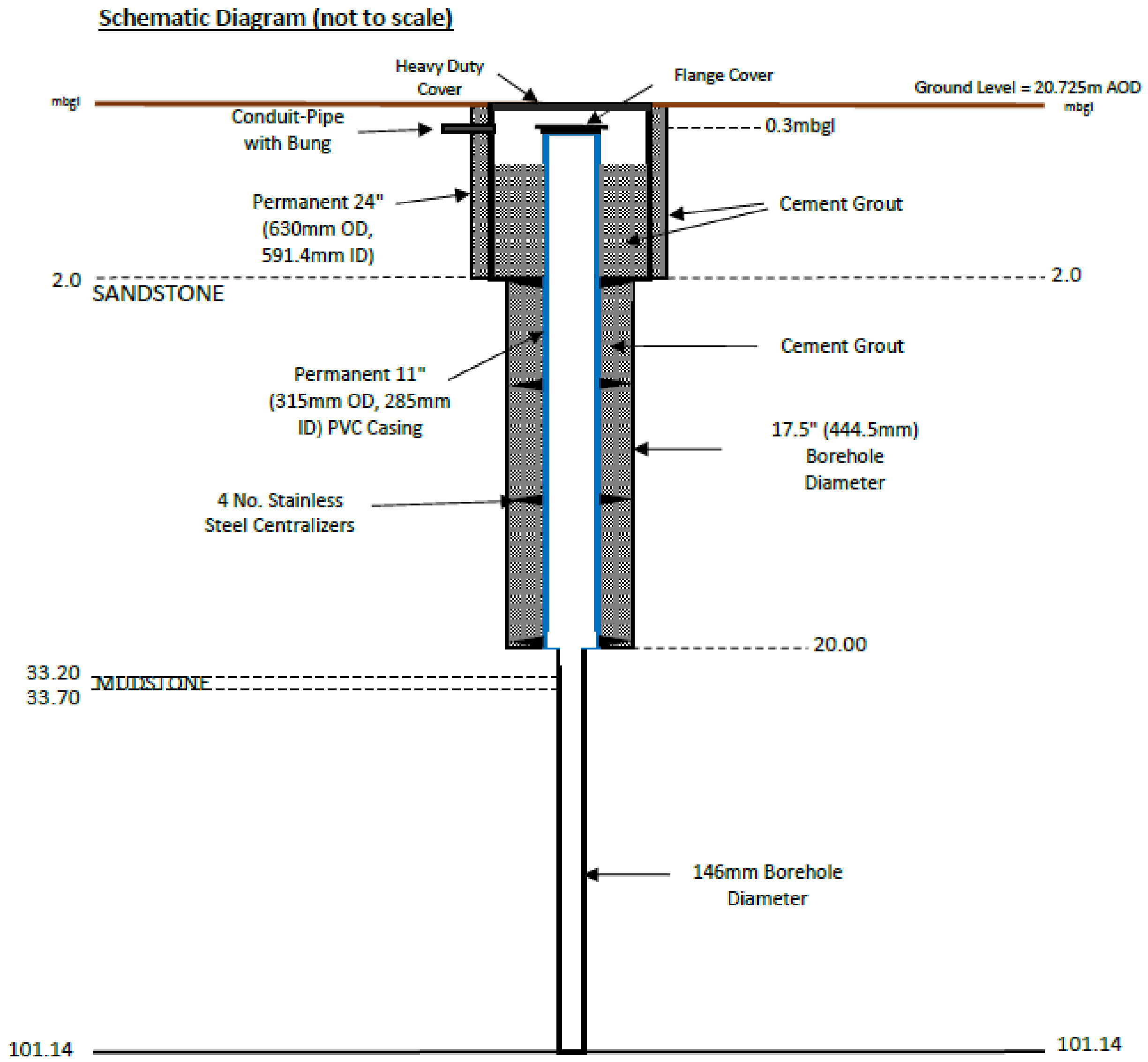


Figure 3.2 – TH0424 drillers construction log (UKGEOS Cheshire Project Team, 2023)

4 Test Interval Identification

The packer test programme included continuous profiling of aquifer properties (phase 1) and targeted testing of large fractures (phase 2). The tests were completed over 2 weeks, with 21 tests planned, assuming a maximum 3 tests per day and 7 working days (3 days were needed for plant mobilisation/demobilisation). The phase 1 tests were given priority due to the importance of understanding the variation in aquifer properties over the full depth of the borehole. A number of candidate fractures were identified for phase 2 testing; however it was only possible to complete two tests in the time available. Fractures at 45.8 and 78.9 mbgl were selected on the basis that significant loss of flush return was observed at these depths during drilling.

The test intervals for continuous profiling of aquifer hydraulic properties were set in accordance with the following practical considerations:

- Average test interval of around 10 m to provide feasible number of tests (approximately half of total possible)
- The need for approximately contiguous test intervals (i.e. minimal gaps between test intervals)

- Both packers to seat on competent smooth formation to provide good sealing (away from breakout zones due to fracturing, as identified from TH0424 borehole caliper log)
- Test interval not to include more than one major fracture zone where possible to avoid ambiguity regarding influence of each zone on formation properties
- The need to safely clamp the packer string (minimum casing stickup requirement)

The setting of test intervals also took into account an initial assessment of the formation properties based on geophysical wireline logging data. This identified high and low permeability horizons based on inferred clay content (from natural gamma emissions), saturated porosity estimates (based on borehole magnetic resonance data) and the presence of potentially connected large- aperture horizontal fractures (identified from the caliper and acoustic logs). Figures 4.1 and 4.2 show the wireline logging parameters for TH0424 plotted alongside the inferred flow zones (A-E) and the packer test intervals (1-9 for continuous profile and 12 &14 targeting fractures, other numbered intervals were identified for Phase 2 but not tested in this field campaign). It should be noted that the intervals for the continuous profile are not exactly contiguous due to the practical considerations listed above.

The rationale for the setting of the test intervals for the continuous profile is as follows:

- Test intervals 1 and 2 are within flowzone A. Two intervals were used so that the major fractures at 23.1 (F1) and 27.3 mbgl (F2) are in separate test intervals.
- Test interval 3 spans an apparent low permeability horizon between flowzones A and B. This is characterised by high natural gamma values, lower BMR saturated porosity and high reflectance in the acoustic log (typically associated with harder, well cemented sandstone).
- Test interval 4 is within flowzone B, which is bracketed by horizons with elevated gamma, lower saturated porosity and higher acoustic reflectance.
- Test interval 5 is mostly within flowzone C but includes the overlying apparent lower permeability horizon. This is to avoid a gap in the vertical profile. This interval includes a major fracture at 58.7 mbgl (F4)
- Test intervals 6 and 7 are mostly within flowzone D. Two 10 m intervals were used to avoid a single excessively long test interval. Flowzone D was identified on the basis of it having only 2 small natural gamma peaks and generally high BMR saturated porosity.
- Test intervals 8 and 9 are mostly within flowzone E. Two 10 m intervals were used to avoid a single excessively long test interval. Flowzone E was identified on the basis of it having generally high BMR saturated porosity, it is separated from flowzone D by a high natural gamma sandstone from 79 to 80 mbgl. Elevated natural gamma from 82.5 to 83.5 mbgl may indicate an additional barrier to flow, however this feature was not considered large enough to merit an additional test section.

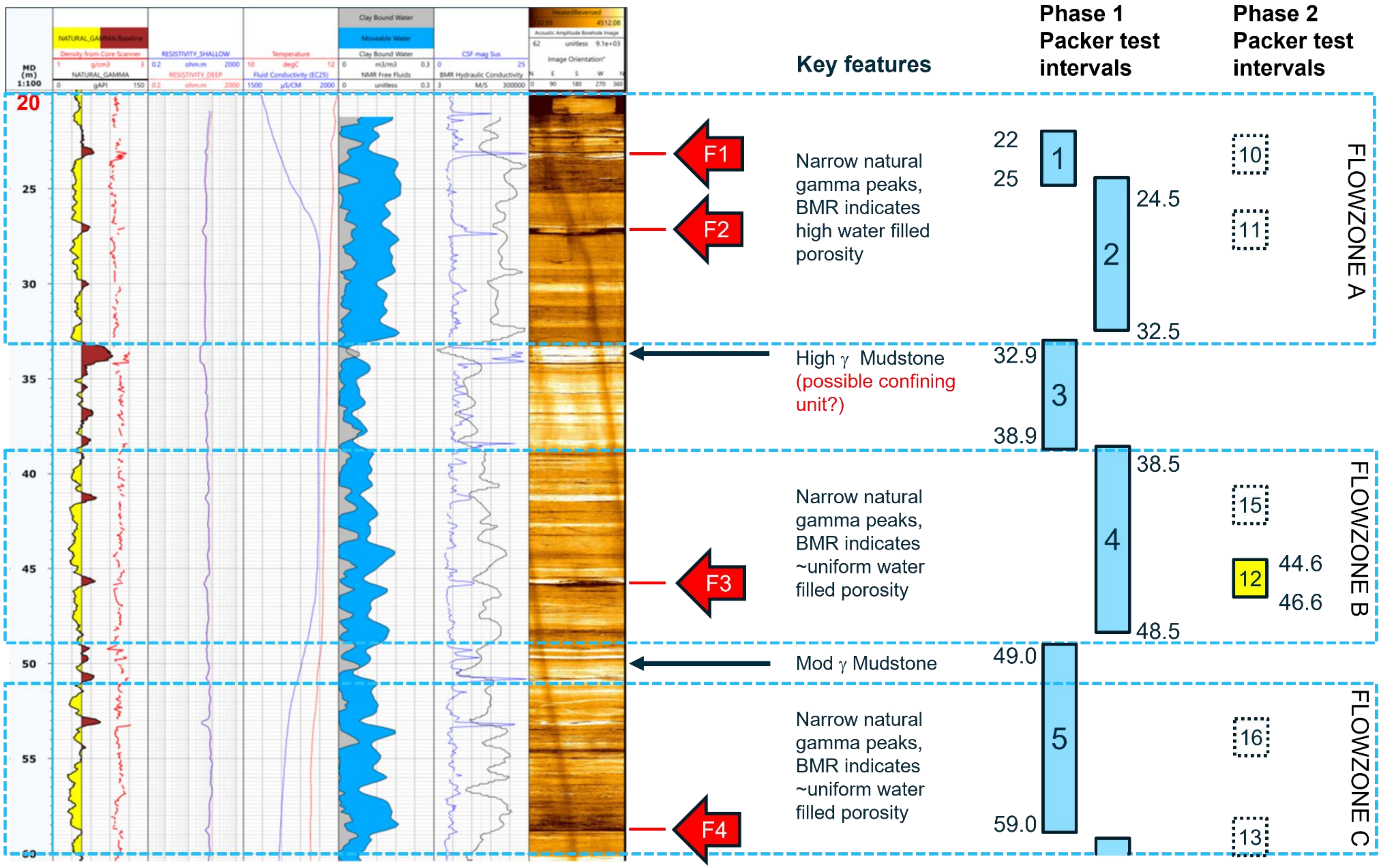


Figure 4.1 - Packer test intervals from 20 to 60m bgl plotted alongside wireline log data and hypothesised flowzones. Packer test intervals are labelled with actual test interval depths (interval from base of top packer to top of base packer). Note that some intervals were not tested (dotted outline). Red arrows indicate major fracture zones. Wireline log plots from UKGEOS Cheshire Project Team (2023) generated in Techlog version 2021.2.

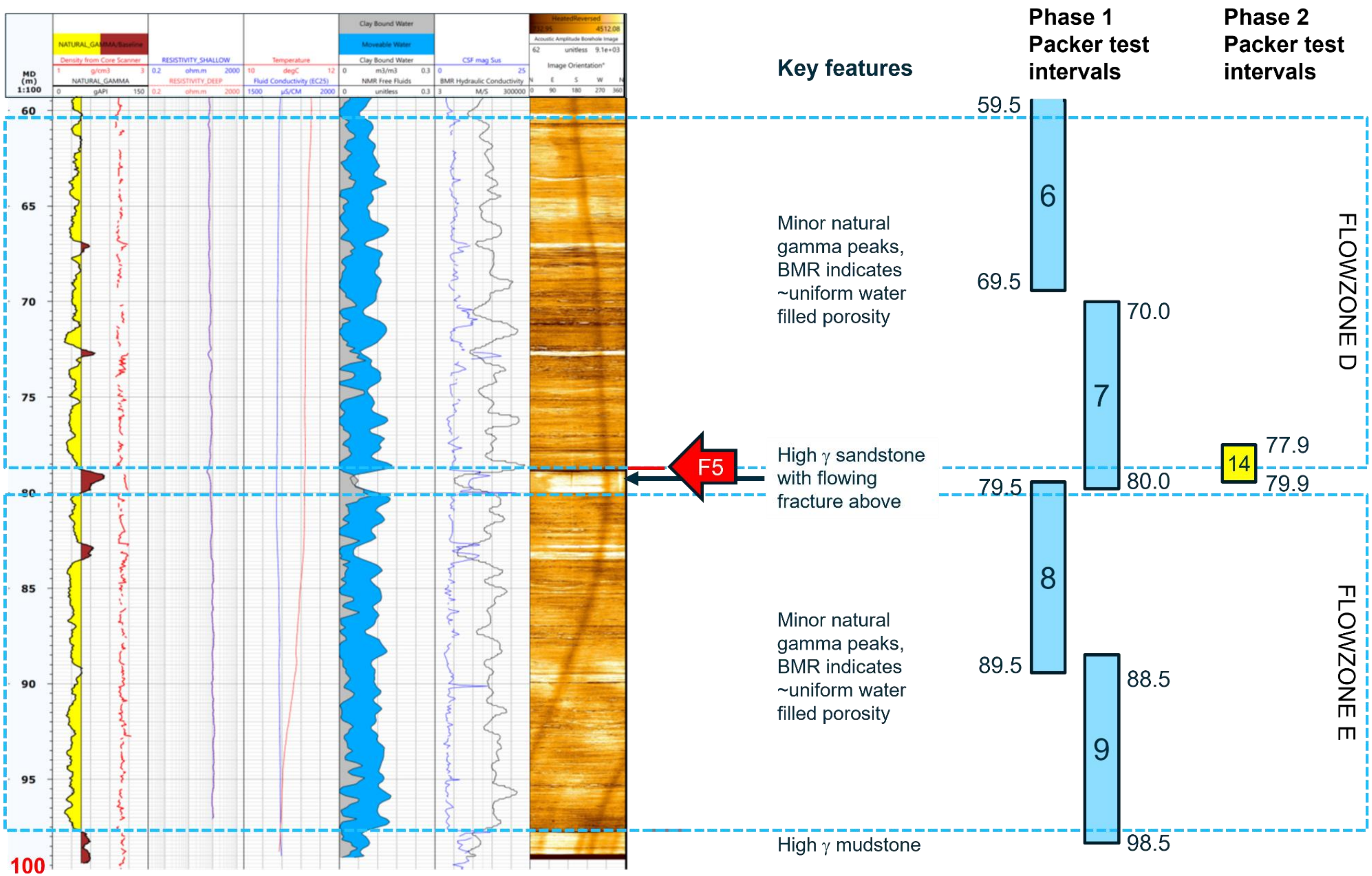


Figure 4.2 - Packer test intervals from 60 to 100 mbgl plotted alongside wireline log data and hypothesised flowzones. Packer test intervals are labelled with actual test interval depths (interval from base of top packer to top of base packer). Red arrows indicate major fracture zones. Wireline log plots from UKGEOS Cheshire Project Team (2023) generated in Techlog version 2021.2.

Table 4.1 - Proposed testing schedule following identification of test intervals. Shaded phase 2 intervals could not be completed in time available.

Phase	Interval number	Test interval top	Test interval base	Test interval length	Max drawdown for whole test	Features targeted
		mbgl	mbgl	m	m	
Phase 1	Zone 1	22	25	3	4	Depth interval
	Zone 2	25	33	8	7	Depth interval
	Zone 3	33	39	6	10	Depth interval
	Zone 4	39	49	10	10	Depth interval
	Zone 5	49	59	10	10	Depth interval
	Zone 6	59	69	10	10	Depth interval
	Zone 7	69	79	10	10	Depth interval
	Zone 8	79	89	10	10	Depth interval
	Zone 9	89	98	9	10	Depth interval
Phase 2	Zone 10	22.1	24.1	2	4	Fracture at 23.1m
	Zone 11	26.3	28.3	2	8	Fracture at 27.3m
	Zone 12	44.8	46.8	2	10	Fracture at 45.8m
	Zone 13	57.7	59.7	2	10	Fracture at 58.7m
	Zone 14	77.9	79.9	2	10	Fracture at 78.9m
	Zone 15	41.0	43.0	2	10	Sandstone matrix
	Zone 16	53.0	55.0	2	10	Sandstone matrix

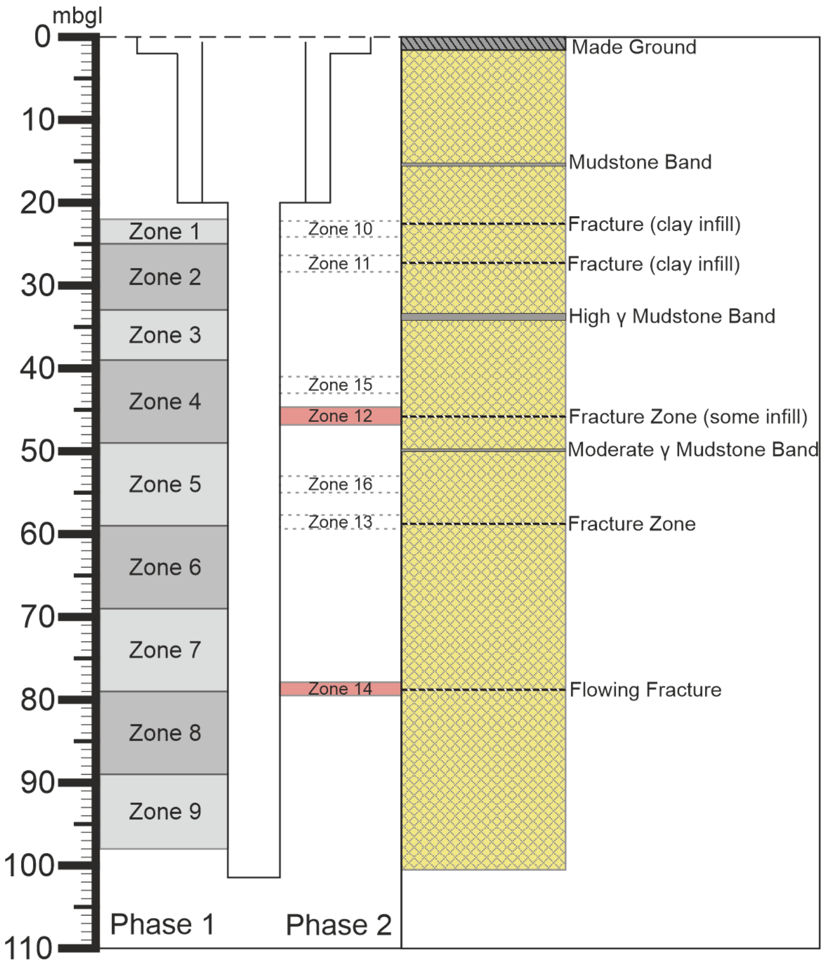


Figure 4.3 - Visual depiction of target testing zones and key features

5 Methodology

Hydraulic testing was carried out by means of a pneumatic straddle packer system consisting of two 88-185 mm rubber sleeved packers (each 1 m in length) separated by 1m lengths of perforated 2” steel casing. The lower packer in the assembly was fitted with a 0.5 m sump and cap. The topmost packer was fitted to an NQ drill rod string (69.9 mm OD, 60.3 mm ID, 3.048 m/10 ft effective length) for raising and lowering the packer string and to house the purging pump and isolated zone level monitoring sensor. Packers were inflated with compressed nitrogen gas from surface via a 6 mm polyamide airline connected to a valve assembly and regulator. Packer pressure could be monitored constantly at surface via a digital pressure gauge. Determination of the packer pressure was made by the equation:

$$P_p = (D_p/10) – (D_w/10) +10$$

Where:
P_p = Packer Pressure (Bar)
D_p = Depth of lowermost packer (mbgl)
D_w = Depth to water outside of the inner casing above the topmost packer (mbgl)

The packer assembly was raised and lowered through the borehole using a Cable Percussion rig and fixed in place using a slip plate and clamp at surface.

A 2” Grundfos MP1 submersible pump was installed inside the “inner casing” (inside the NQ rods attached to the packers taking in water from the isolated zone) to an appropriate depth for each zone (allowing for adequate drawdown) and a 1” flexible rising main connected to a flow monitoring assembly at surface consisting of a 2 m length of rigid pipe, ball valve, turbine flowmeter and “T” take-off allowing groundwater samples to be collected. 2” layflat hose then took the groundwater to waste. A check valve was also placed at the pump outlet. A variable frequency drive at surface was used to alter the pump flow rate.

Two pressure transducers were used to monitor water levels: one in the inner casing (monitoring the packer interval) and one outside the NQ casing rod but installed within the borehole (monitoring above the packer interval). The main purpose of the outside casing transducer was to confirm an adequate seal of the topmost packers with the borehole wall. As there was no logger below the isolated interval, it could not be known if the lowermost packer created an adequate seal. Inside casing level was monitored using an LevelTroll 700 transducer and outside casing level monitoring using a LevelTroll 400 transducer. Both transducers were set to log at 1 second intervals during testing and were connected to monitoring screens at surface so that groundwater levels could be monitored in real time. Manual dip measurements were also taken at regular intervals during tests to ensure the accuracy of the transducer measurements.

The configuration of the downhole and surface monitoring assemblies can be seen in Figure 5.1.

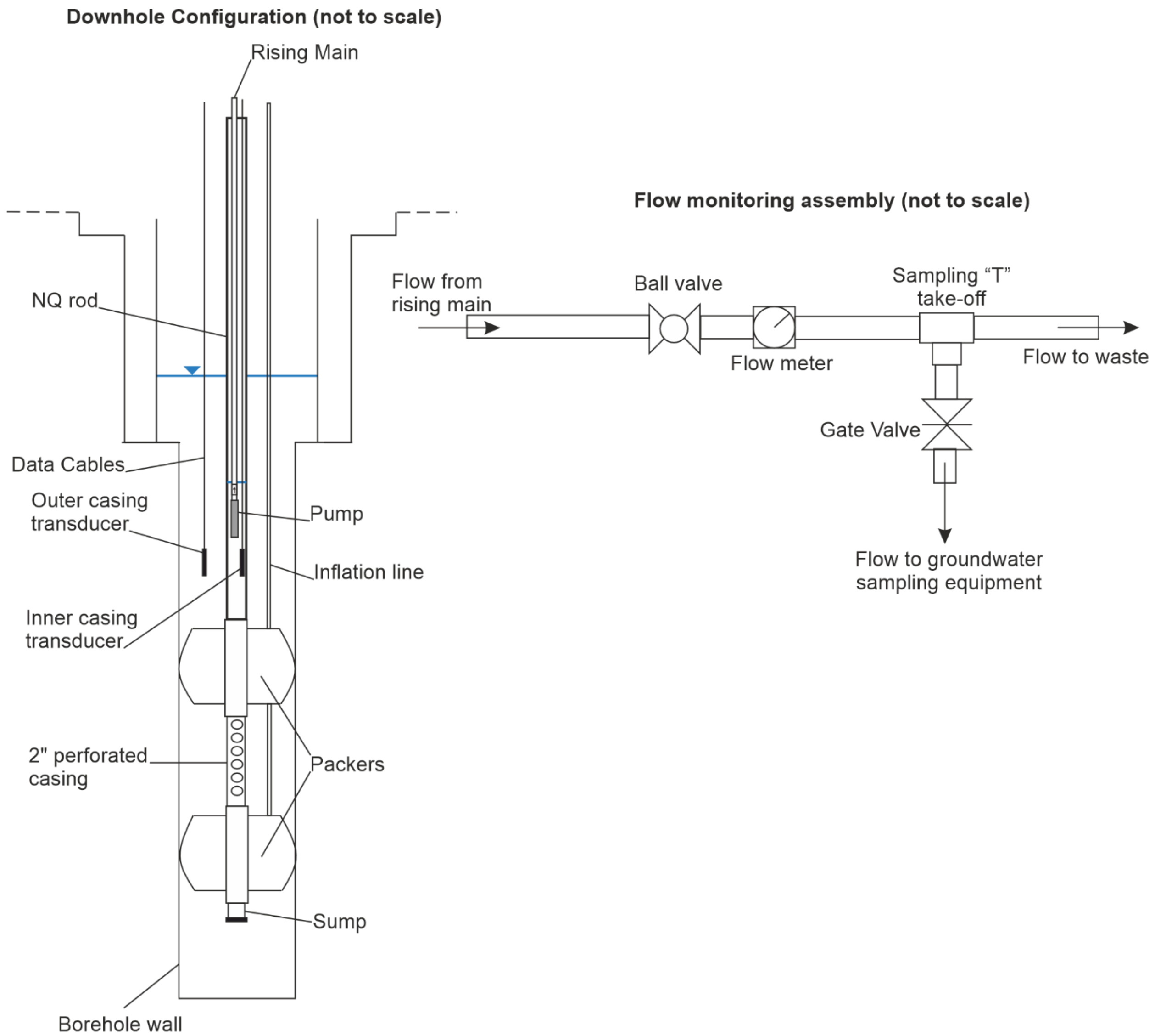


Figure 5.1 - Downhole equipment and flow monitoring assembly configuration

A BaroTroll barometric pressure logger was installed at surface on site for the duration of the testing schedule to allow for barometric compensation of groundwater levels.

During test 10, communications with the inside logger were lost and was not regained. The test was re-run with the LevelTroll 400 logger installed in the inside casing and the long term Seametrics CT2X logger suspended in the outer casing on Kevlar, logging at 10 second intervals (the same set up was employed for subsequent tests). There was no capacity to monitor the CT2X logger in real time so manual dip measurements were used during test 10 and all subsequent tests to ensure a good packer seal. Additionally, data from the inside logger during test 16 (zone 9 step test) was corrupted and thus the manual dip record was used for analysis.

Two types of tests were scheduled for each interval, a step drawdown test and a constant rate test. The step drawdown test would be used to plan the target flow rate for the constant rate test, taking into consideration the depth of logger and pump installation, drawdown rate and strain on the pump. Each step was conducted for 5 – 20 minutes until generally stable level readings were observed before moving onto the next one. Flow rates were recorded manually from the flowmeter during tests at high frequency during the initial drawdown stages and then at a lower frequency during more stable level measurements. Following completion of the final step, the ball valve on the flow monitoring assembly was closed and the pump switched off. Recovery was monitored. Once stable level readings were observed, a constant rate test was conducted using the chosen flow rate from the step test. The constant rate test was conducted for a minimum of 100 minutes and until groundwater level was stable with no significant increase or decrease. Flow rates and manual dips were recorded throughout the test. After 100 minutes and stable readings were observed, the ball valve was closed and pump switched off with recovery monitored. Groundwater level was allowed to recover until stable readings were observed.

During the constant rate test, a multiparameter probe was connected to the take-off point via a flow cell allowing a constant flow of water through the flow cell without exposure to the atmosphere. pH, specific electrical conductance (SEC at 25°C), temperature, dissolved oxygen and oxidation reduction potential (later corrected to Eh) were recorded from the multiparameter probe at 5-minute intervals. Once stable readings for all parameters were established, groundwater was sampled for analytes included in Table 5.1. Alkalinity as HCO_3 was determined by on-site manual colorimetric titration using 1.6N H_2SO_4 and bromocresol green indicator. Filtered samples for cations, anions, NH_4, As speciation, δ^{13}DIC and dissolved fluorescein were collected using a 0.2 µm in-line (direct from flow) filter to limit oxidation or formation of precipitates prior to filtering. NPOC samples were filtered using a 0.45µm silver impregnated filter.

All samples were analysed at the BGS Centre for Environmental Geochemistry in Keyworth and Wallingford. Major and minor cations and anions were determined by IC & ICP-MS to UKAS accreditation (aside Ag and I) at the BGS Keyworth inorganic geochemistry facility along with NPOC via TOC analyser and pH and alkalinity via potentiometric titration to UKAS accreditation. Isotopes were analysed at the BGS Keyworth stable isotope facility via IRMS and dissolved radon measured via an alpha decay counter (RAD7) after purging of the sample. CFC and SF_6 samples were analysed via GC-ECD at BGS Wallingford along with NH_4 via colourimetry.

Table 5.1 - On site and laboratory determinands sampled for

On Site Determination	Laboratory Analysis
pH SEC (@ 25°C) Temperature Dissolved oxygen Oxidation Reduction Potential (& Eh) Alkalinity as HCO_3 via on-site titration	Major & minor dissolved cations (preserved with 1% v/v HNO_3 in field) Major & minor dissolved anions Dissolved ammonium (NH_4) Dissolved speciated arsenic (As) Non-Purgeable Organic Carbon (NPOC) Oxygen isotopes ($\delta^{18}O$) Hydrogen isotopes (δ^2H) Dissolved inorganic carbon isotopes (δ^{13}DIC) Radon Chlorofluorocarbons (CFC) Sulphur hexafluoride (SF_6) Fluorescein (dissolved and total)

6 Results

6.1 HYDRAULIC TESTING

Due to time limitations and equipment failures, the full schedule of testing could not be carried out as planned. Table 6.1 shows the completed schedule of testing. During periods of equipment failure, zones 1 and 2 were isolated and the water level monitored over time to obtain information about connectivity to local abstractions or drilling activities. Zone 5 step rate test was re-run due to a failure of the inner casing transducer during the test. 20 tests were carried out in total including 2 isolated zone water level monitoring tests, 6 completed step tests, 11 completed constant rate tests and 1 failed constant rate test. Time series for all tests can be found in Sections 6.1.1 - 6.1.20 along with descriptions of the results of each test. Drawdown levels quoted are calculated from the resting groundwater level before the start of pumping and the maximum stable pumped groundwater level during each test or step. Flow rates quoted are the median for each constant rate test or for each step with step tests. These data are also summarised in section 6.2. Reference is made to detection of local abstraction events and drilling induced perturbations; these are discussed in greater detail in sections 7.1 and 7.2.

The barometric pressure measured at site over the testing period is displayed in Figure 6.1. All subsequent groundwater levels quoted and in graphs have been barometrically compensated.

Table 6.1 - Actual testing schedule completed

Test Number	Interval number	Test interval top	Test interval base	Test interval length	Date of Test	Test Type
		mbgl	mbgl	m		
1	Zone 1	22	25	3	04/10/2022	Water Level Monitoring
2	Zone 2	24.5	32.5	8	05/10/2022	Water Level Monitoring
3	Zone 2	24.5	32.5	8	05/10/2022	Step Test
4	Zone 2	24.5	32.5	8	06/10/2022	Constant Rate Test
5	Zone 3	32.9	38.9	6	06/10/2022	Step Test
6	Zone 3	32.9	38.9	6	06/10/2022	Constant Rate Test
7	Zone 4	38.5	48.5	10	07/10/2022	Step Test
8	Zone 4	38.5	48.5	10	07/10/2022	Constant Rate Test
9	Zone 5	49	59	10	07/10/2022	Step Test
10	Zone 5	49	59	10	10/10/2022	Constant Rate Test**
11	Zone 5	49	59	10	10/10/2022	Constant Rate Test
12	Zone 6	59.5	69.5	10	10/10/2022	Constant Rate Test
13	Zone 7	70	80	10	11/10/2022	Step Test
14	Zone 7	70	80	10	11/10/2022	Constant Rate Test
15	Zone 8	79.5	89.5	10	11/10/2022	Constant Rate Test
16	Zone 9	88.5	98.5	10	11/10/2022	Step Test
17	Zone 9	88.5	98.5	10	12/10/2022	Constant Rate Test
18	Zone 1	22	25	3	12/10/2022	Constant Rate Test
19	Zone 14	77.9	79.9	2	13/10/2022	Constant Rate Test
20	Zone 12	44.62	46.62	2	13/10/2022	Constant Rate Test

** Internal logger failed; test had to be re-run

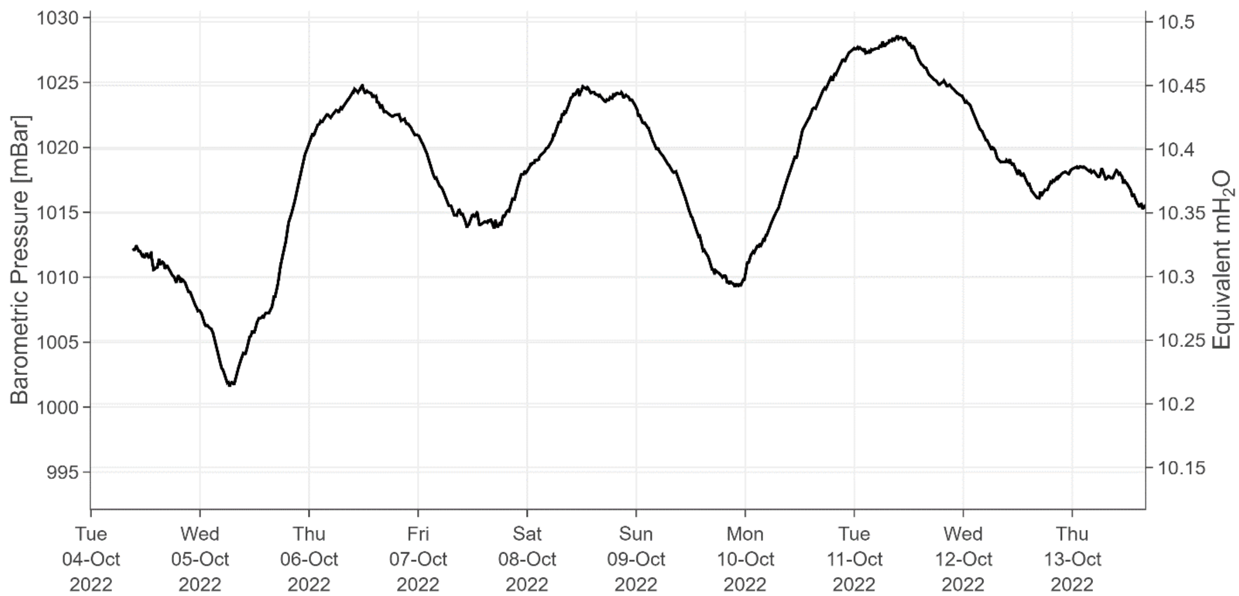


Figure 6.1 - Barometric pressure across testing period

6.1.1 Test 1 – Zone 1 Water level Monitoring

Test 1 conducted static water level monitoring in zone 1. Some peaks and troughs are seen during installation and removal of faulty pumps. An increase in both the outer and inner transducers is observed. Levels above the isolated zone are approximately 0.29 m shallower than in the isolated zone. No local abstraction events were recorded during this period and there are no obvious perturbations from local drilling.

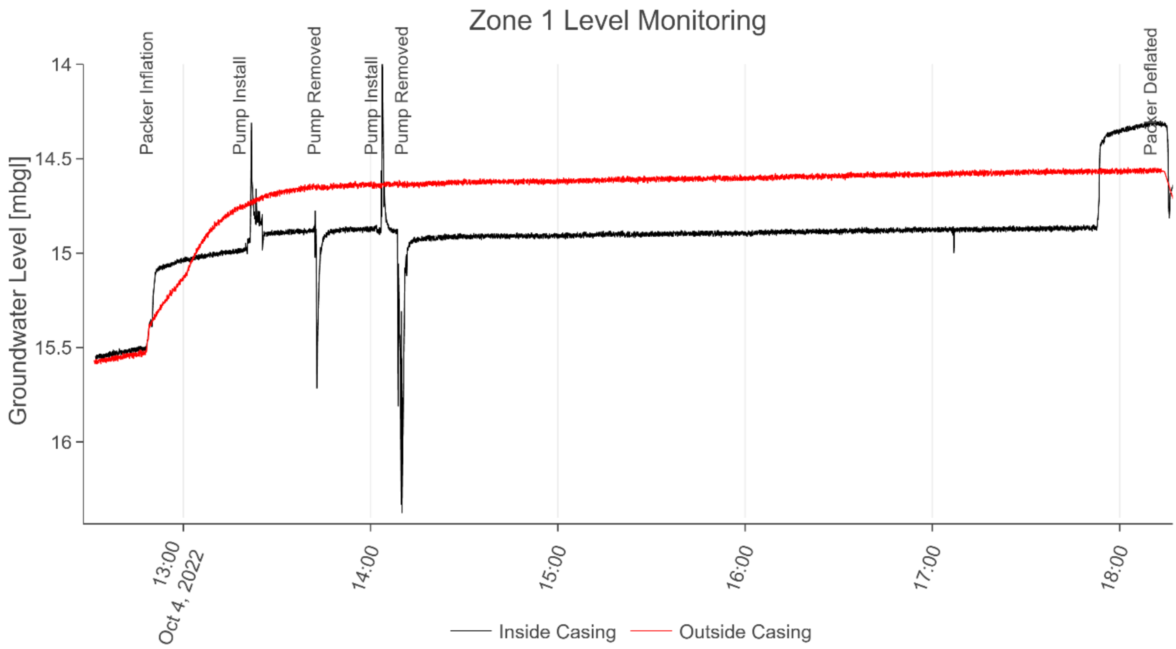


Figure 6.2 – Test 1: Zone 1 water level monitoring time series

6.1.2 Test 2 – Zone 2 Water Level Monitoring

Test 2 conducted static water level monitoring in zone 2. Following packer inflation, groundwater level in zone 2 rose rapidly whilst levels above the isolated zone rose more gradually. Static levels above the isolated zone were approximately 0.26 m shallower than zone 2. An abstraction event was recorded during test 2. There are no obvious drilling perturbations.

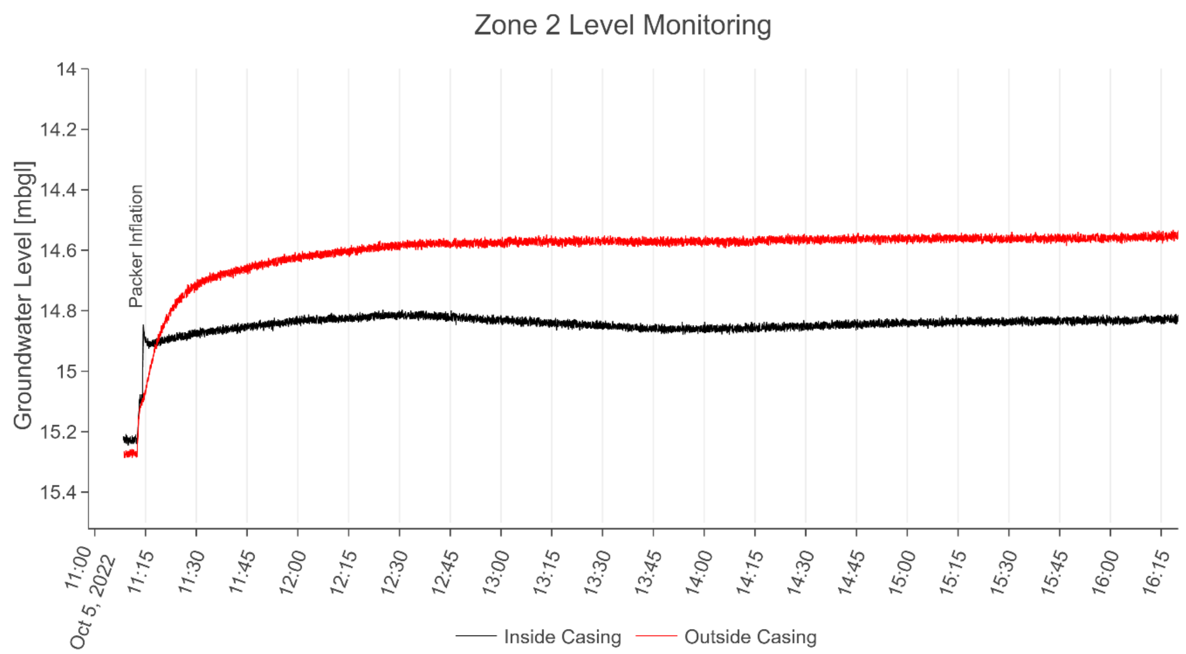


Figure 6.3 – Test 2: Zone 2 water level monitoring time series

6.1.3 Test 3 – Zone 2 Step Test

Level data from test 3 suggests slight vertical connectivity between zone 2 and above the isolated zone. The three steps carried out during the test resulted in drawdown of 2.22 m (16 l/min), 2.68 m (18 l/min) and 3.18 m (22 l/min) from the static inside casing level. The recovery curve following pump shutdown shows a good recovery with no failure of the check valve. An abstraction event was recorded during the step test between 16:23 and 17:13. Drilling related perturbations were not obviously detected. Flow rates were not taken at regular or frequent intervals during this test due to a lack of personnel available accounting for sparse flow rate data.

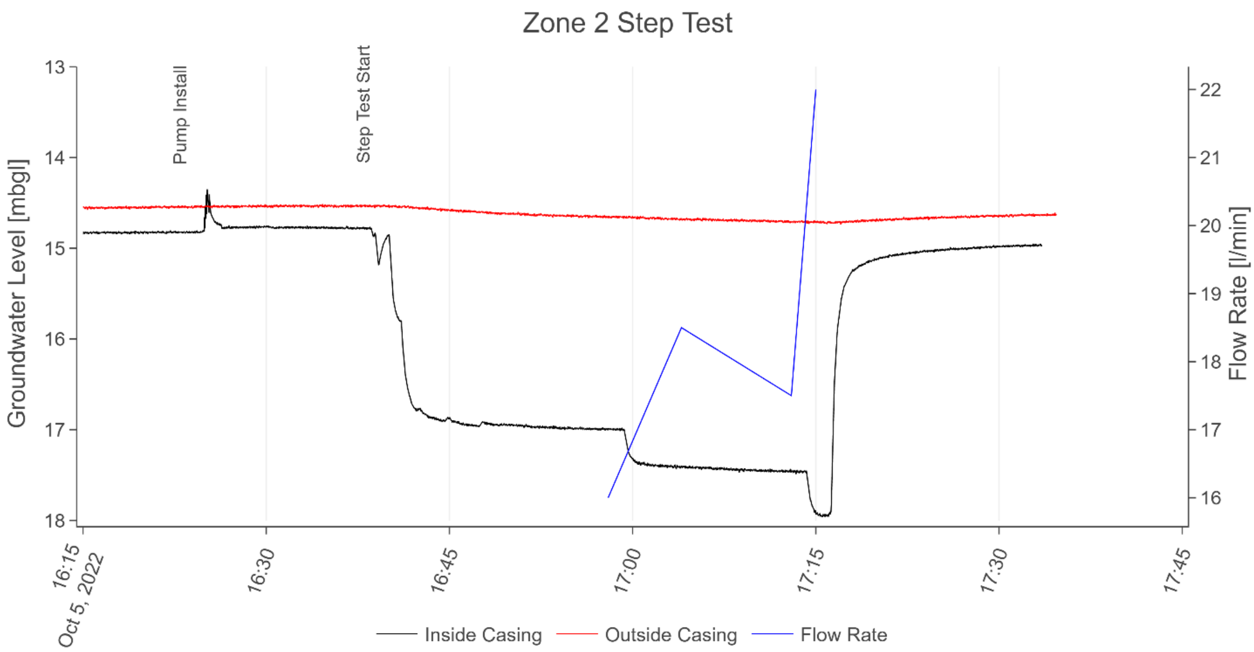


Figure 6.4 - Test 3: Zone 2 step test time series

6.1.4 Test 4 – Zone 2 Constant Rate Test

Test 4 was conducted at a median flow rate of 16.6 l/min with a drawdown of 2.51 m. The outside casing level fluctuated rapidly to a minor extent (~5 cm in amplitude) and this is attributed to the vibration of the pump against the casing wall. No abstraction events were recorded during the test. No drilling perturbations were obviously noted during the test, aside from two small peaks towards the end of the test resulting in two pulse increases of around 10cm. It is not obvious if this was induced by local works or from pumping rate fluctuation. The recovery curve shows good recovery data.

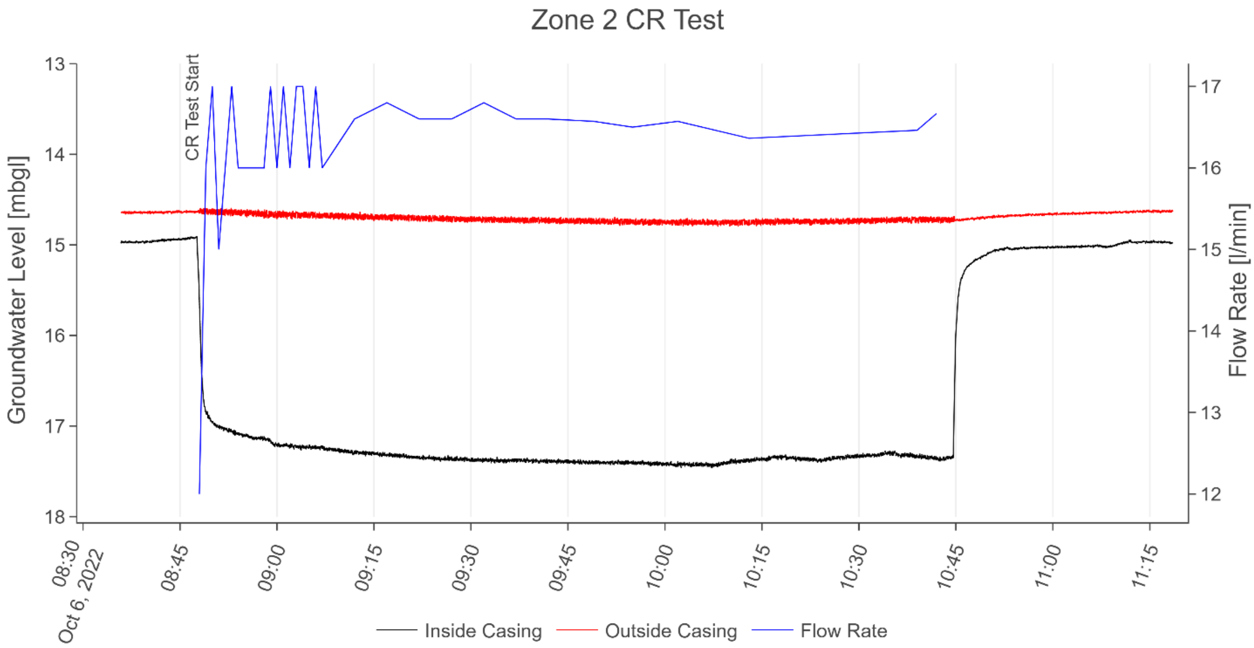


Figure 6.5 - Test 4: Zone 2 constant rate test time series

6.1.5 Test 5 – Zone 3 Step test

Following packer inflation in test 5, both inside and outside casing levels rose with the outside casing level rising to ~0.09 m higher than the isolated zone 3. During the test, there was a slight decrease of 0.10 m in the outside casing level. Four steps were completed during the test resulting in drawdown levels of 2.90 m (7 l/min), 3.77 m (9 l/min), 5.05 m (11 l/min) and 7.09 m (15 l/min) from the inside casing static level. The recovery curve shows good recovery data. No abstraction event was recorded during the test; however, an abstraction event was recorded to have ended ~30 minutes prior to the step test meaning levels were still likely in recovery.

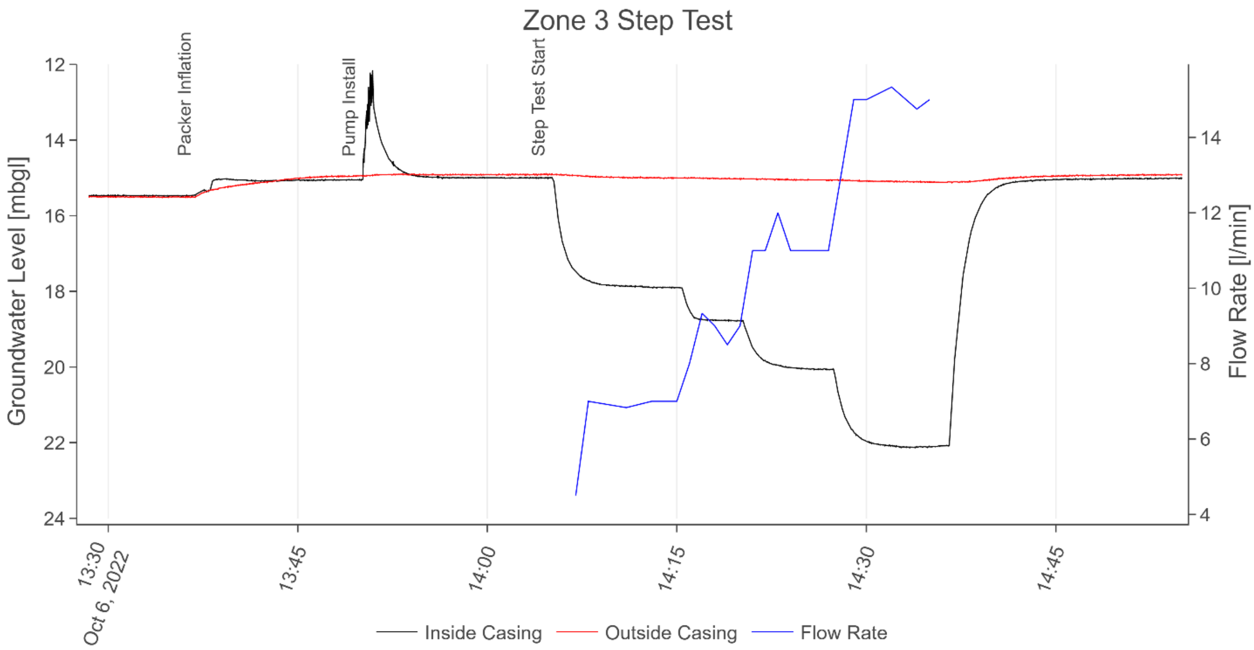


Figure 6.6 - Test 5: Zone 3 step test time series

6.1.6 Test 6 – Zone 3 Constant Rate Test

Test 6 was conducted at a median flowrate of 11 l/min with an overall drawdown from static level of 5.12 m in the inside casing. A small drawdown in the outside casing logger indicates a good seal. Small cyclical events can be seen during the test with inside level varying by ~0.24 m. The cyclical nature suggests this is the result of drilling flush rather than variations in flow rate. The recovery curve shows good data. No abstraction events were recorded during the test; however, an event was recorded during the recovery phase from 16:55 to 18:15.

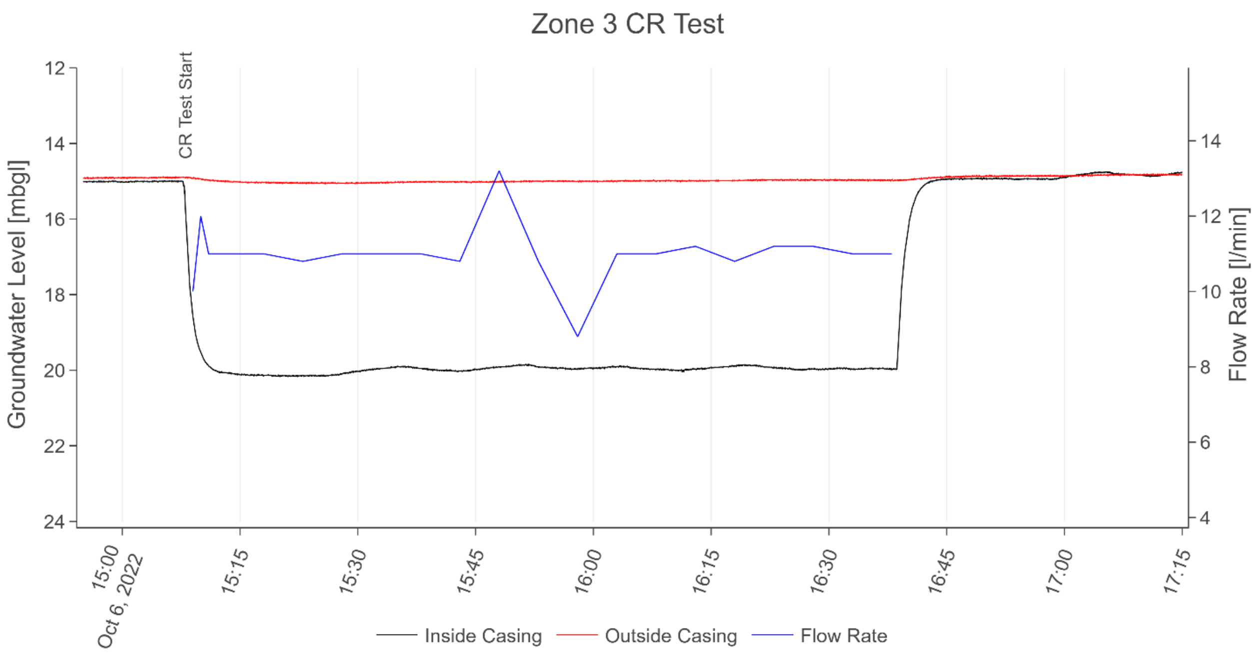


Figure 6.7 - Test 6: Zone 3 constant rate test time series

6.1.7 Test 7 – Zone 4 Step Test

Following packer inflation, groundwater levels rose in both outside and inside casing. The level above the isolated zone rose ~0.17 m higher than the isolated zone. There was obviously significant perturbation during the step test attributed to local drilling activities (flow rate did not vary significantly during each step). As a result, these data are not reasonably representative of the isolated zone under normal static conditions and thus attempts to analyse these data is challenging. Perturbations are also detected in the outside casing logger with small variations in level following variations in the inside casing logger (this could also be due to slight leakage or connectivity between the isolated zone and above water column). An attempt was made to identify drawdown for each step by taking the minimum level achieved, however, these are considered unreliable. Three steps were attempted during the test with internal drawdown from static level of 0.36m (9 l/min), 0.57 m (15 l/min) and 0.73 m (18 l/min). The recovery curve generally shows good data although the pump was shut down before stable groundwater levels were achieved. Perturbations can also be seen in the recovery phase after the initial recovery curve. An abstraction event was recorded during the test between 10:32 and 11:59. The compounding effects of drilling and abstraction events renders data from test 7 unsuitable for analysis and modelling models, however, some data may be used in conjunction with the drilling record to test connectivity.

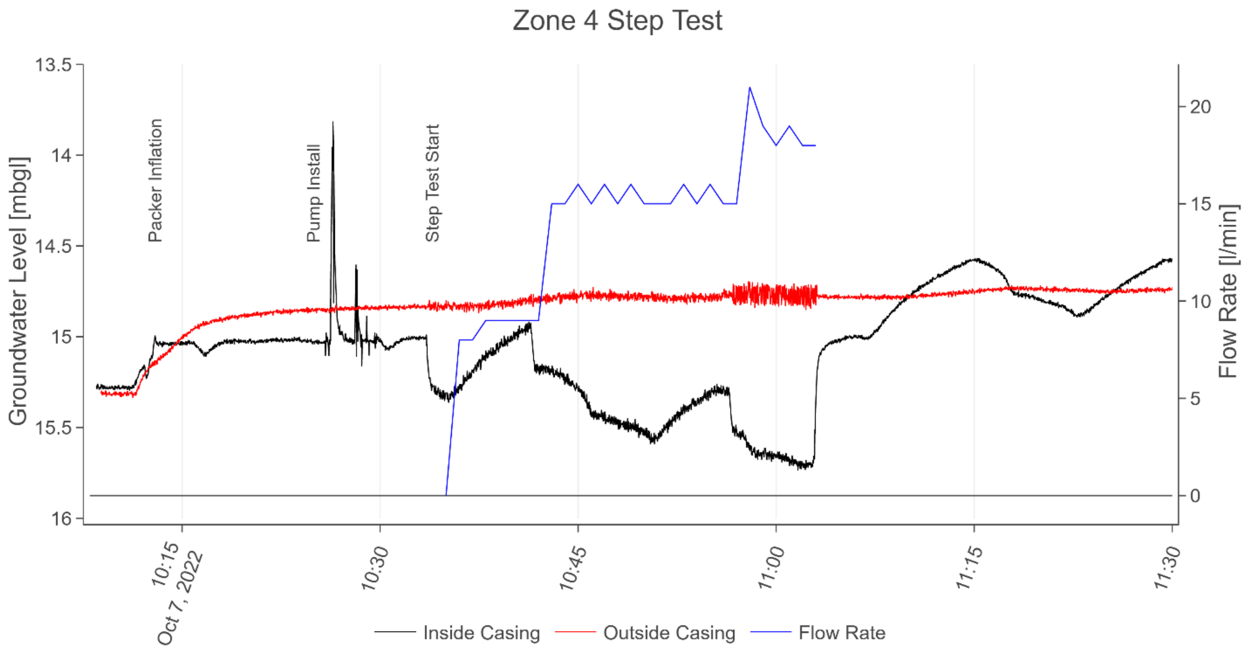


Figure 6.8 - Test 7: Zone 4 step test time series

6.1.8 Test 8 – Zone 4 Constant Rate Test

Test 8 shows significant interference from local drilling events in the isolated zone and to a lesser extent in the outside casing above the isolated zone. Even though the groundwater level was falling prior to the start of the test, the test was started at 15.0 mbgl as this was the starting point for the previous step test where levels were relatively static. The initial drawdown phase was relatively unimpacted by external influences until ~17 mins into the test where a cyclical increase in inside (and to a lesser extent outside casing) groundwater level was observed. Subsequent data are not useable for further hydraulic analysis but may again be used in conjunction with the drilling record to reveal connectivity. Data prior to drilling perturbations may be used for further analysis, although a static pumped groundwater level was not achieved. A drawdown of 0.75 m was recorded at a median flow rate of 13.8 l/min. An abstraction event was in progress at the start of the test ending at 11:59; recovery from this event would have been ongoing through the majority of the test. The end of this abstraction event may have caused the small deviation at 11:59 prior to obvious drilling related perturbations.

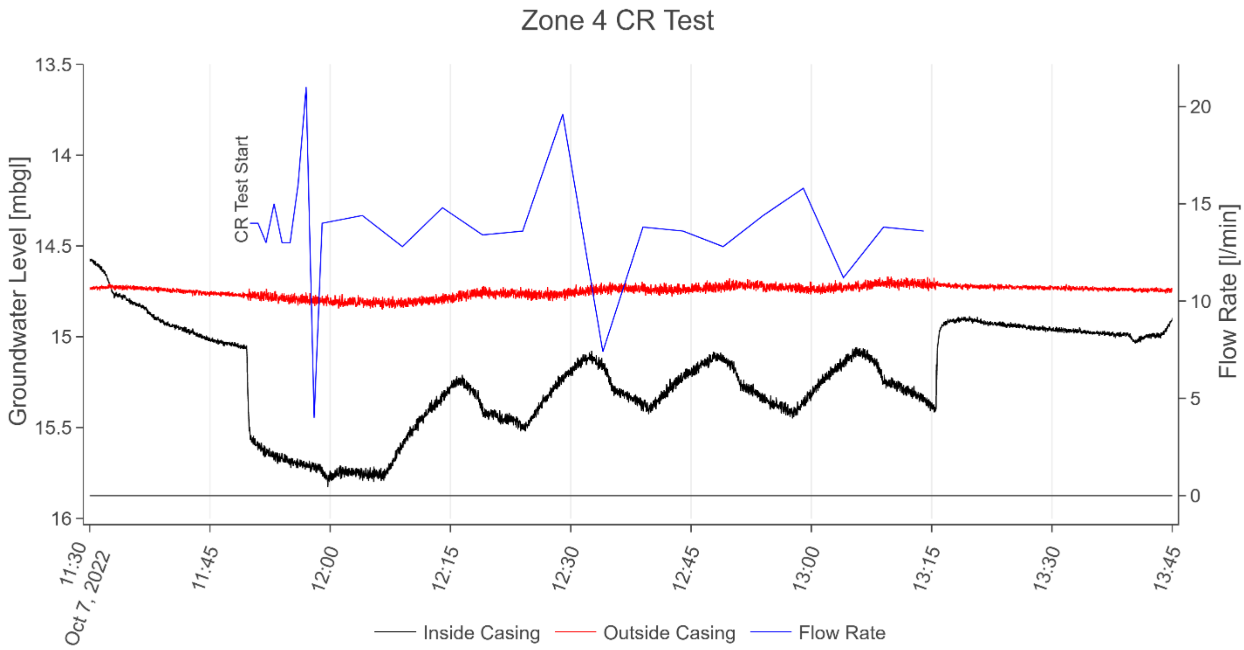


Figure 6.9 - Test 8: Zone 4 constant rate test time series

6.1.9 Test 9 – Zone 5 Step Test

Following packer inflation, groundwater level deepened slightly in both inside and outside casing levels. This change was greater in the inside casing than the outside casing with the isolated zone level ~0.14 m deeper than above the isolated zone. Level data collected is variable and is attributed to a flushing event at TH0410 between 15:10 and 15:30. Three steps were attempted during the test, the results from the first and second steps are of low quality, but the third step presents more consistent data, following termination of the TH0410 flushing event. The three steps resulted in isolated zone drawdown, from the static level, of 1.86 m (12 l/min), 2.09 m (15 l/min) and 2.81 m (19.5 l/min). No abstraction event was recorded during the test.

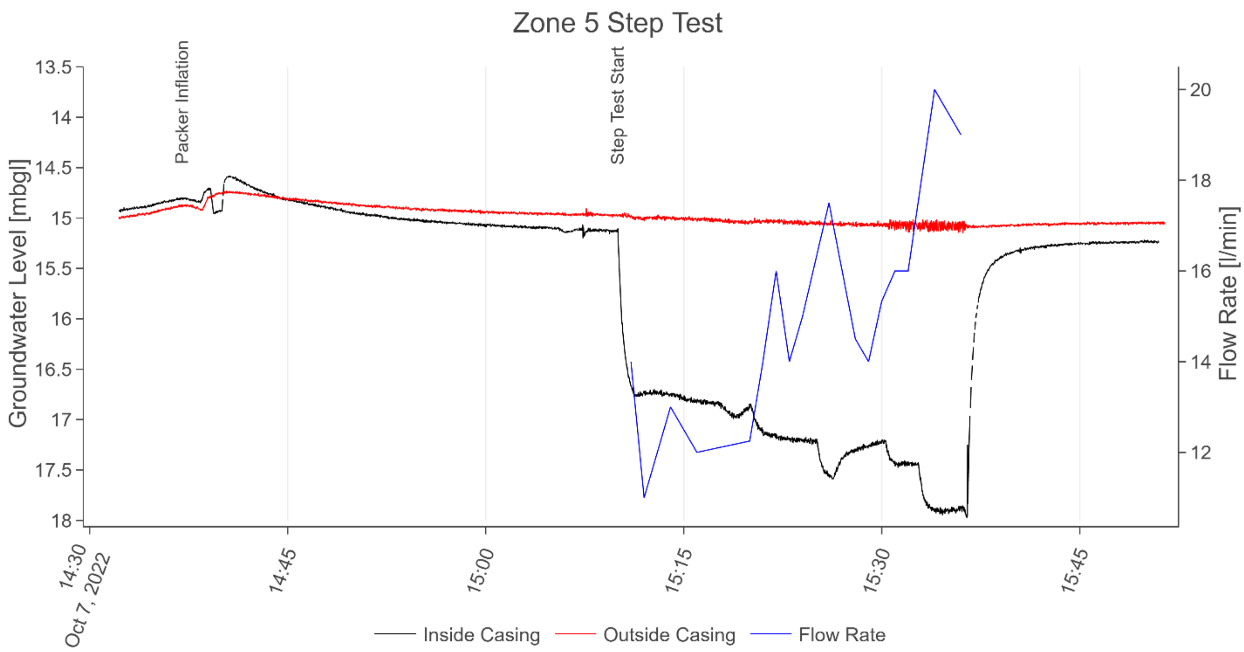


Figure 6.10 - Test 9: Zone 5 step test time series

6.1.10 Test 10 – Zone 5 Constant Rate Test

Test 10 was impacted by a failure of the inside casing level logger and thus data could not be retrieved. The test was abandoned, and levels allowed to recover before repeating using a different logger as test 11.

6.1.11 Test 11 – Zone 5 Constant Rate Test

Test 11 carried out the same constant rate test as test 10 in zone 5 but using different level loggers. Isolated zone groundwater level drawdown was 2.46 m from the static inside level at a median flow rate of 17.2 l/min. Some cyclical influence was detected creating ~0.18 m increases in level in the inside casing and ~0.05 m increases in the outside logger level. The recovery curve shows a potential failure of the check valve with the resemblance of a critically damped response consistent with a slug of water being reinjected back into the well. No abstraction event was recorded during the test, however an event finished at 12:14 with possible continuing recovery of local levels during the pump test.

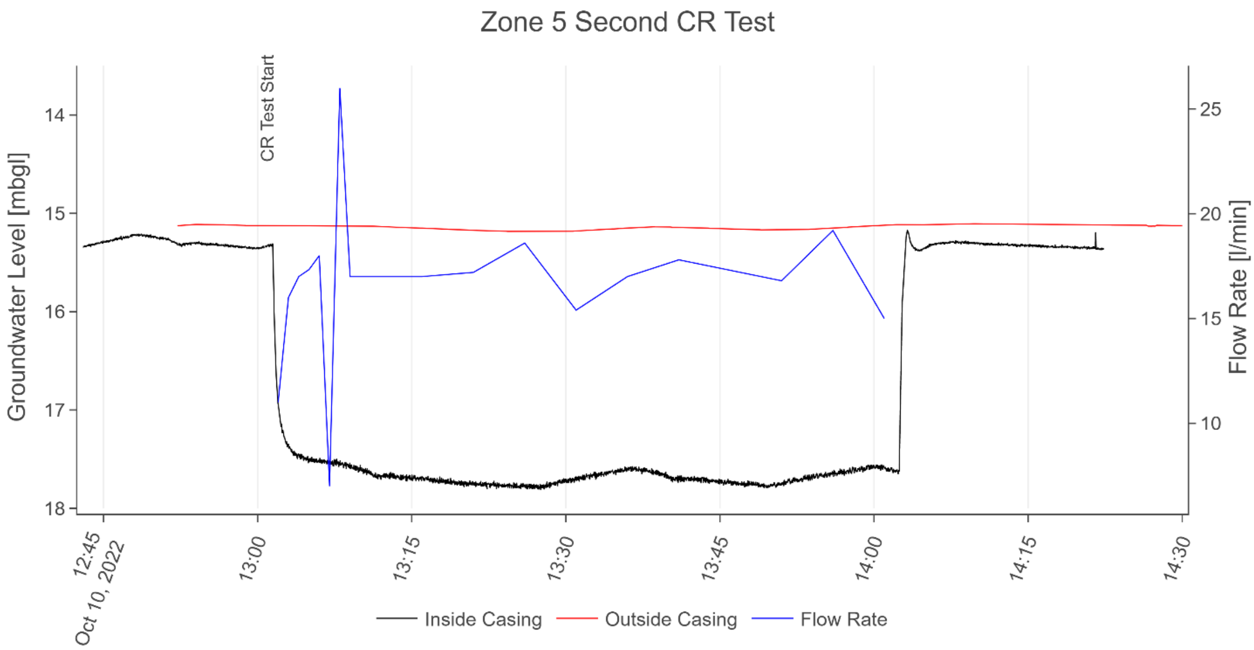


Figure 6.11 - Test 11: Zone 5 constant rate test time series

6.1.12 Test 12 – Zone 6 Constant Rate Test

Packer inflation resulted in a small decrease in groundwater level in the inside casing and level remained the same in the outside. Drawdown was recorded at 9.39 m during the test at a median flowrate of 13.6 l/min. No abstraction event was detected during the test; however, an event was detected during packer inflation between 14:50 and 15:41 and would likely be in recovery during the test. There were no obvious deviations due to drilling activities.

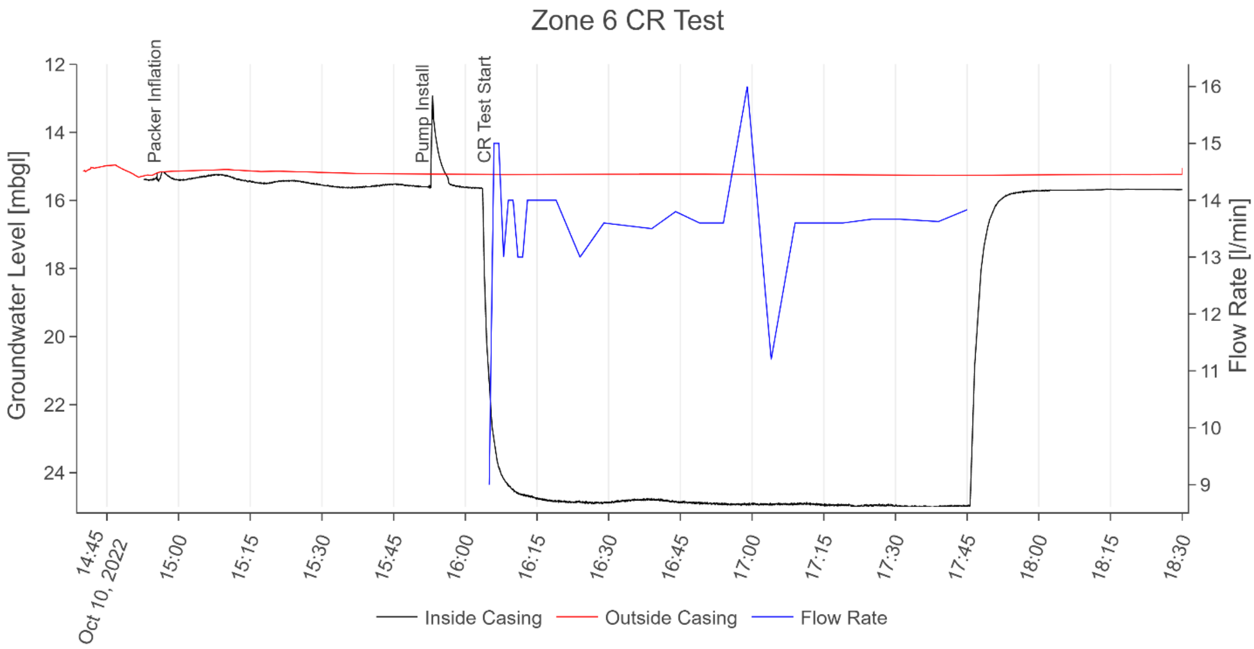


Figure 6.12 - Test 12: Zone 6 constant rate test time series

6.1.13 Test 13 – Zone 7 Step Test

Test 13 displayed significant deviations as a result of local drilling activities. Reaming of TH0410, which included flushing, resulted in cyclical increases in groundwater level. Following packer inflation, levels in the outside casing rose ~0.20 m above the original level and levels in the inside casing fell by ~0.26 m. Three steps were attempted with only steps 1 and 2 discernible. Step 3 proved difficult to analyse due to obvious cyclical influence (the lowest level of the cyclical peaks was taken as the drawdown value). Three steps achieved drawdown from the static isolated zone level of 0.19 m (9 l/min), 0.39 m (17 l/min), and 0.59 m (22.5 l/min). There is little confidence in the data obtained during the third step. An abstraction event was in progress during the test between 09:11 and 10:20 and combined with local drilling influence renders test 13 a very poor dataset.

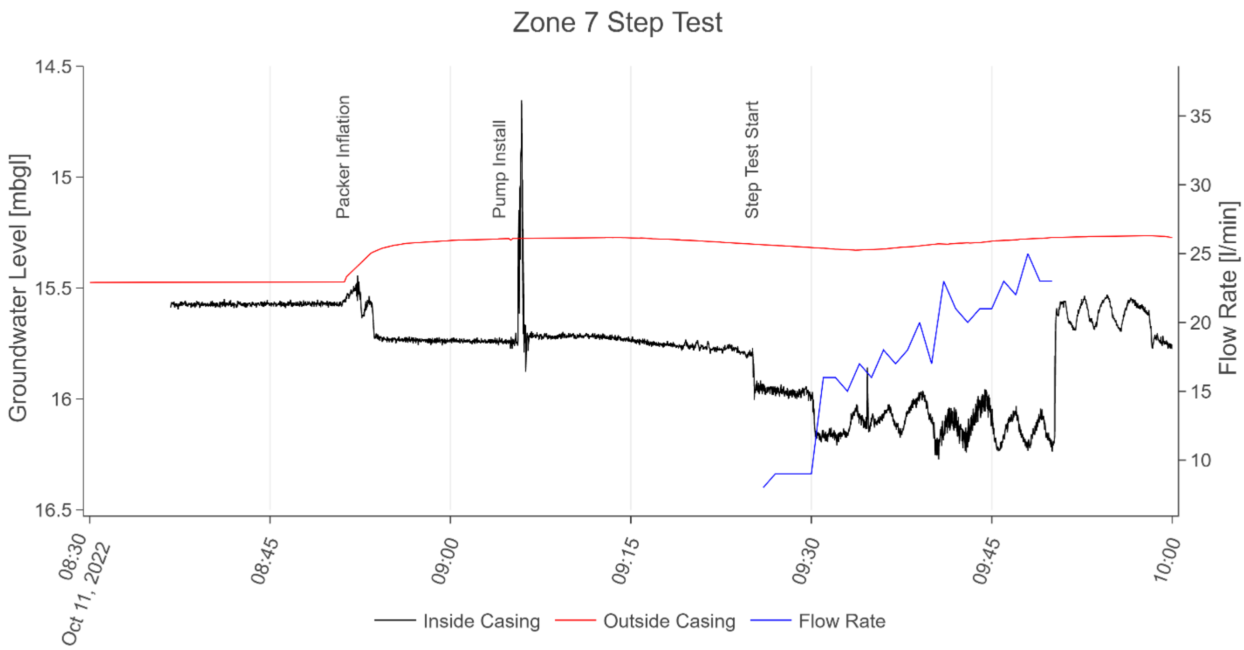


Figure 6.13 - Test 13: Zone 7 step test time series

6.1.14 Test 14 – Zone 7 Constant Rate Test

Test 14 showed sustained cyclical interference for the majority of the test from reaming of TH0410. The last 30 minutes of pumping was carried out during a period of inactivity and thus this section of the curve can be used for analysis. Overall drawdown from static level was 0.6 m at a median flowrate of 18.9 l/min. The recovery curve seems to suggest a failure of the check valve due to the rapid initial increase in level with a bounce; drilling activity continued during the recovery stage making further analysis difficult. No abstraction events were detected during the test; however, an event ended at 10:20 just prior to test start and was likely in the recovery phase.

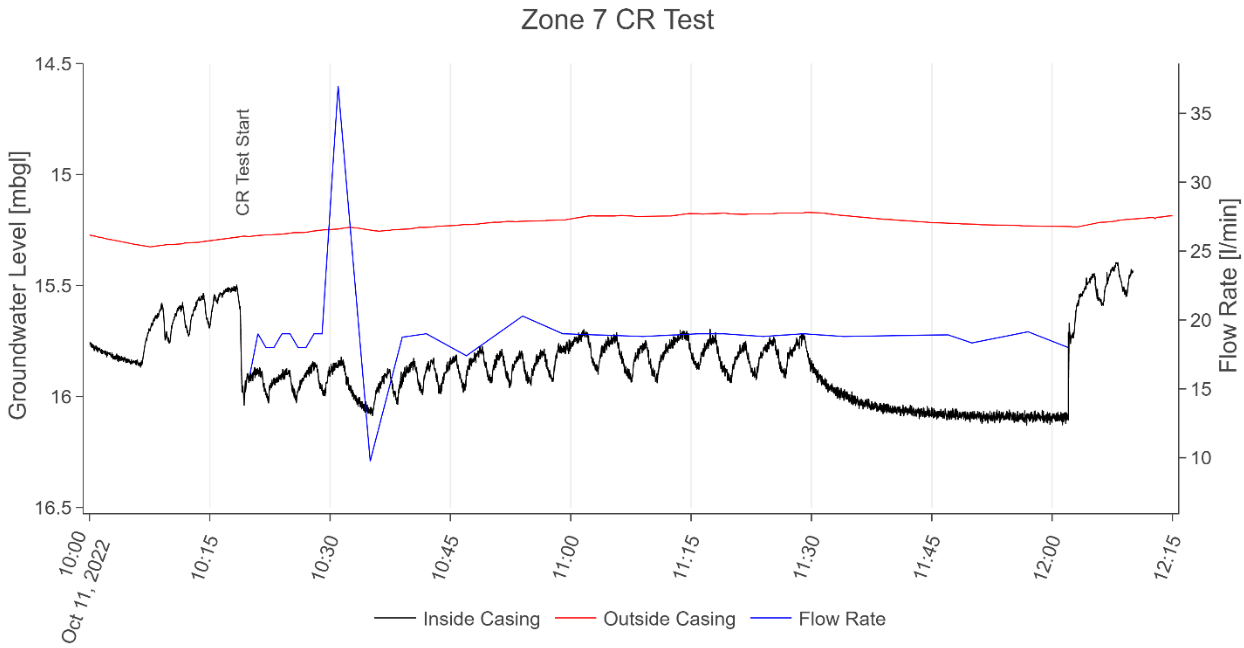


Figure 6.14 - Test 14: Zone 7 constant rate test time series

6.1.15 Test 15 – Zone 8 Constant Rate Test

During packer inflation for zone 8, level changed a negligible amount from the original static level indicating a neutral vertical gradient. Levels appear to have a small downward trend with the start of an abstraction event. Inside casing level drawdown was 5.74 m at a median flowrate of 9.25 l/min. No obvious perturbations can be seen during the test. An abstraction event was in progress during the start of the test between 13:38 and 14:59; a slight upward trend in the outside logger can be seen following the end of the event.

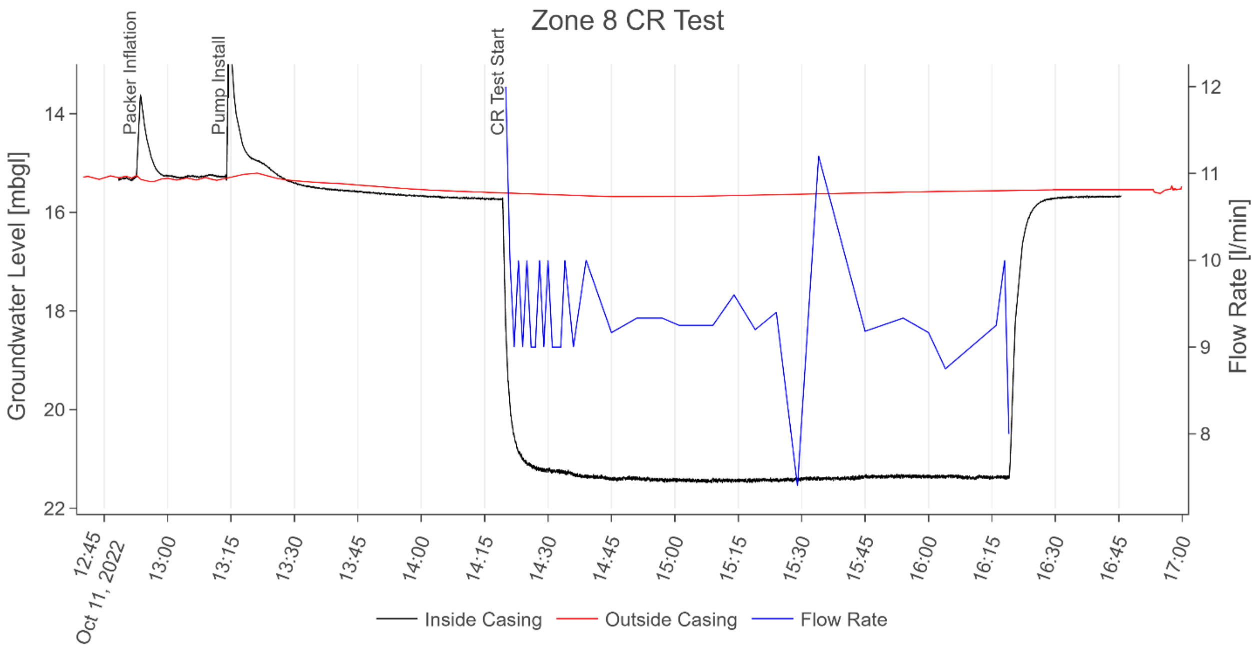


Figure 6.15 - Test 15: Zone 8 constant rate test time series

6.1.16 Test 16 – Zone 9 Step Test

Data from the inside casing transducer for test 16 was found to be corrupt and so the manual dip record was used for time series analysis. Data from the outside logger indicates a good seal created by the packers and little vertical connectivity. Steps 1, 2 & 3 drew down water level by 2.82 m (7.5 l/min), 5.75 m (14.5 l/min) and 7.82 m (20 l/min) respectively from the resting groundwater level. A kick upwards in groundwater level during step 4 resulted in 2.15 m of drawdown (21.4 l/min) from the original groundwater level. It is thought that the increased pumping rate cleared out clay or drilling mud infill from a minor fracture, increasing the flow into the interval. No abstraction events were detected during the test.

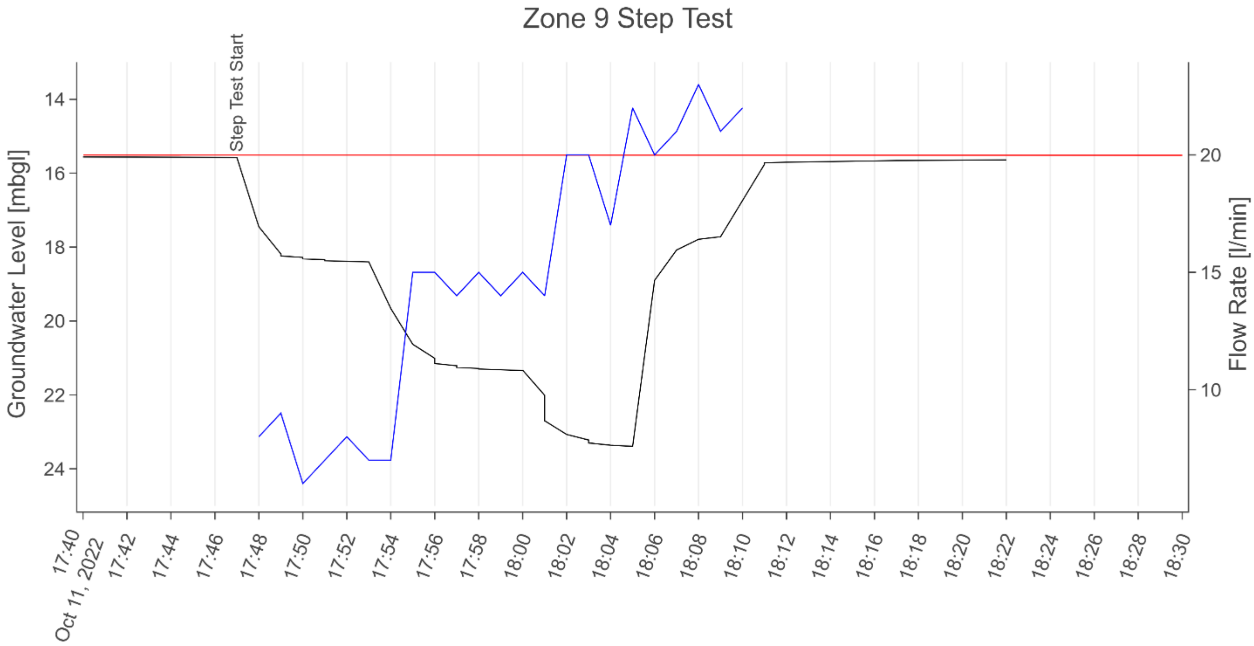


Figure 6.16 - Test 16: Zone 9 step test time series

6.1.17 Test 17 – Zone 9 Constant Rate Test

Packer pressure had dropped overnight due to a slow valve leak at surface; packers were deflated and re-inflated to obtain a new seal. Groundwater level in the outside logger rose by ~0.05 m with the inside casing logger falling by ~0.10 m. Overall drawdown during the pumping stage was 1.37m at 18.6 l/min. Rapid recovery may potentially be the product of a leaky check valve, but this is unconfirmed. No local drilling events were detected. No abstraction events were recorded during the test with a previous event finishing at 08:08.

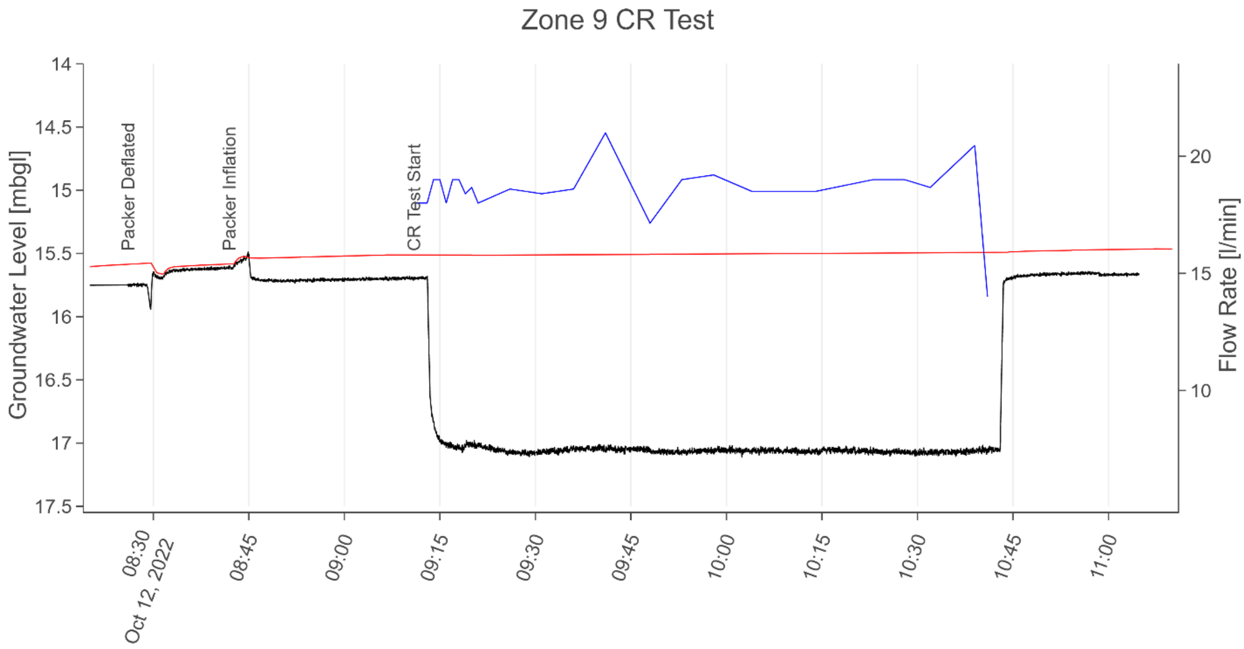


Figure 6.17 - Test 17: Zone 9 constant rate test time series

6.1.18 Test 18 – Zone 1 Constant Rate Test

As the water in the borehole above the isolated zone only has a very small open hole section, as analysis of the vertical gradient in this zone cannot be made and the outside logger is used solely to confirm a good packer seal. Drawdown in the inside casing from the static groundwater level was 2.28 m at a median flowrate of 8 l/min. An abstraction event was recorded during the event between 13:53 and 15:14. It is unclear if the gradual drawdown observed during the test is a result of local abstraction, but the lack of increase in level following the end of the abstraction event would suggest that the abstraction event had a negligible effect. The recovery of this zone proved to take a long time and time constraints on resources resulted in monitoring of the recovery being cut short. Pumping of TH0410 also began during the recovery phase of the test.

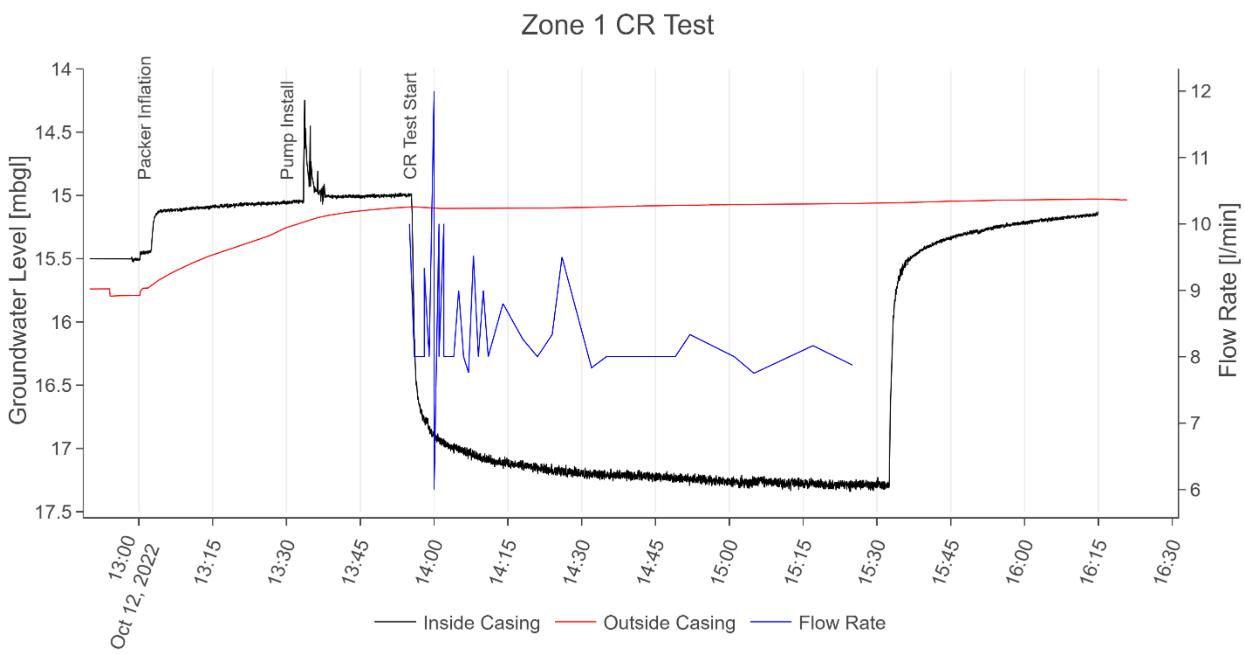


Figure 6.18 - Test 18: Zone 1 constant rate test

6.1.19 Test 19 – Zone 14 Constant Rate Test

Test 19 was a shorter, focused interval on a fracture feature. Overall drawdown from static level within the isolated zone was 0.37m at a median flowrate of 19 l/min. There was potential influence from an external source towards the end of the pumping phase and during recovery with the installation of a FLUTe liner in an adjacent borehole. The initial shape of the recovery curve suggests a failure of the check valve, however, the obvious high transmissivity of this zone could produce a critically damped recovery or potentially dual porosity effects. No abstraction event was recorded during the test.

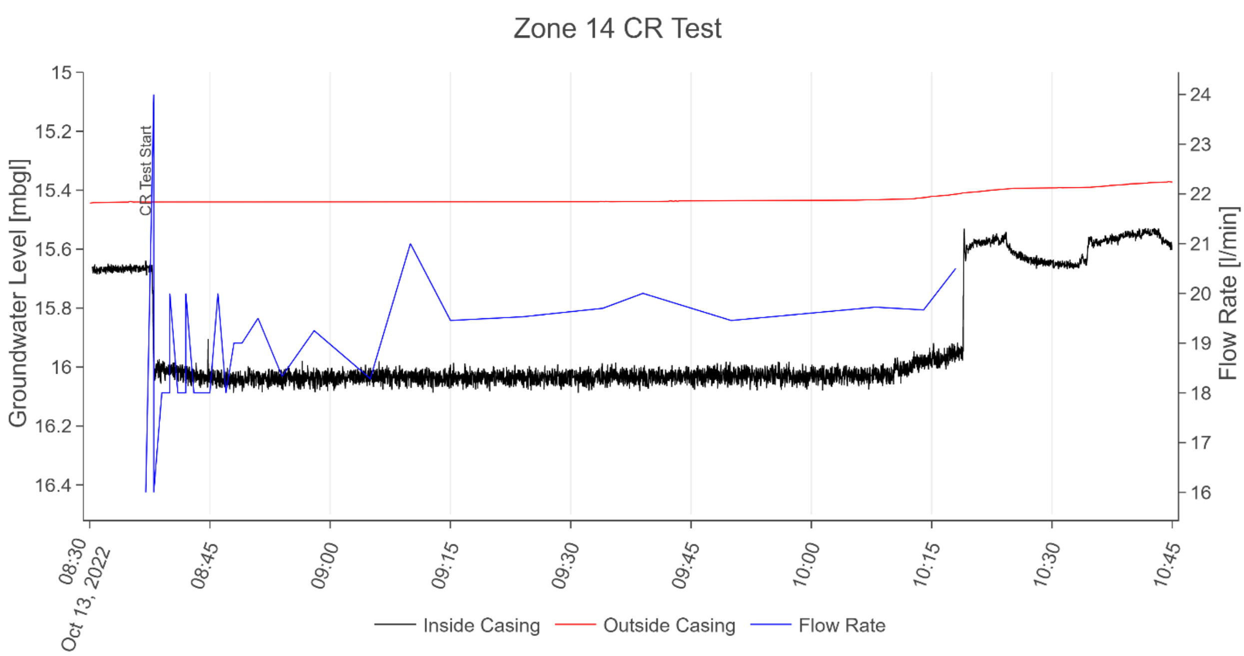


Figure 6.19 - Test 19 Zone 14 constant rate test time series

6.1.20 Test 20 – Zone 12 Constant Rate Test

Test 19 was a shorter, focused interval on a fracture feature. Following packer inflation, both inside and outside levels rose to a comparable level. Drawdown during pumping was 1.21 m at a median flow rate of 19.6 l/min. An abstraction event was in progress during the start of the test between 11:56 and 13:29 levels in both loggers can be seen to increase following the end of this event.

Figure 6.20 - Test 20: Zone 12 constant rate test time series

6.2 SPECIFIC CAPACITY ANALYSIS

Whilst interpretation of the collected data is not within the scope of this report, a simple assessment of the hydraulic response of the test zones has been carried out, using specific capacity as a simplistic indicator of zone response to pumping. Specific capacity (described in Bennett and Patten (1960)), is primarily a measure of well performance over time and is normally applied to pumping of the entire borehole rather than to packered intervals. Nonetheless, it is an adequate measure by which to compare the response of the test zones.

Results of specific capacity analysis are shown in Table 6.2 & Figure 6.21. Tests that were obviously impacted by local drilling perturbations have been included in the analysis; however, these results should be treated with extreme caution and further detailed modelling of hydraulic properties should not be carried out using these test zone data. In particular, zone 7 step tests display highly variable specific capacity values where a relatively constant value would be expected (Figure 6.21). There are also significant differences between the specific capacity values obtained from step and constant rate tests for zones 4, 5 and 7 where drilling perturbations were experienced. Specific capacity values between step and constant rate tests for other zones are much more comparable. There is, however, an opportunity to match daily drilling activities (depth of flush etc) to these test zones to make preliminary assessments of local connectivity (see Section 7.1).

Zone 9 step test displayed a significant deviation during step 4. Steps 1 – 3 displayed high drawdown rates resulting in low specific capacity values (~2.5 l min^{-1} m^{-1}), whereas step 4 resulted in a sudden increase in groundwater level with a calculated specific capacity of 10 l min^{-1} m^{-1} (high frequency measurements of the zone 9 step test were not available due to a logger failure; results are based on manual dip readings during the test). The following constant rate test also resulted in a specific capacity of 13.6 l min^{-1} m^{-1}. It is likely that the higher rate of pumping during step 4 was adequate to clear out a small fracture that may have been clogged with drilling mud or clay infill towards the bottom of the interval (~97.8 mbgl).

Table 6.2 - Constant rate and step test specific capacity results (tests highlighted in grey are those obviously impacted by local drilling activity or other perturbation)

Zone	Depth Interval	Start gwl	Finish gwl	Median Flow Rate	CR Specific Capacity	Step Test	Step Test Specific Capacity
	mbgl	mbgl	mbgl	$l\ min^{-1}$	$l\ min^{-1}\ m^{-1}$	No.	$l\ min^{-1}\ m^{-1}$
1	22-25	14.94	17.22	8	3.5	N/A	
2	24.5-32.5	14.75	17.258	16.6	6.6	Step 1	7.2
						Step 2	6.7
						Step 3	6.9
3	32.9-38.9	14.85	19.97	11	2.1	Step 1	2.4
						Step 2	2.4
						Step 3	2.2
						Step 4	2.1
4	38.5-48.5	14.98	15.73	13.8	18.4	Step 1	25.0
						Step 2	26.3
						Step 3	24.7
5	49-59	15.15	17.61	17.2	7.0	Step 1	6.5
						Step 2	7.2
						Step 3	6.9
6	59.5-69.5	15.45	24.84	13.6	1.4	N/A	
7	70-80	15.38	15.98	18.9	31.5	Step 1	47.4
						Step 2	16.6
						Step 3	38.1
8	79.5-89.5	15.63	21.37	9.25	1.6	N/A	
9	88.5-98.5	15.68	17.05	18.6	13.6	Step 1	2.7
						Step 2	2.5
						Step 3	2.6
						Step 4	10.0
12	44.62-46.62	15.27	16.48	19.6	16.2	N/A	
14	77.9-79.9	15.61	15.98	19	51.4	N/A	

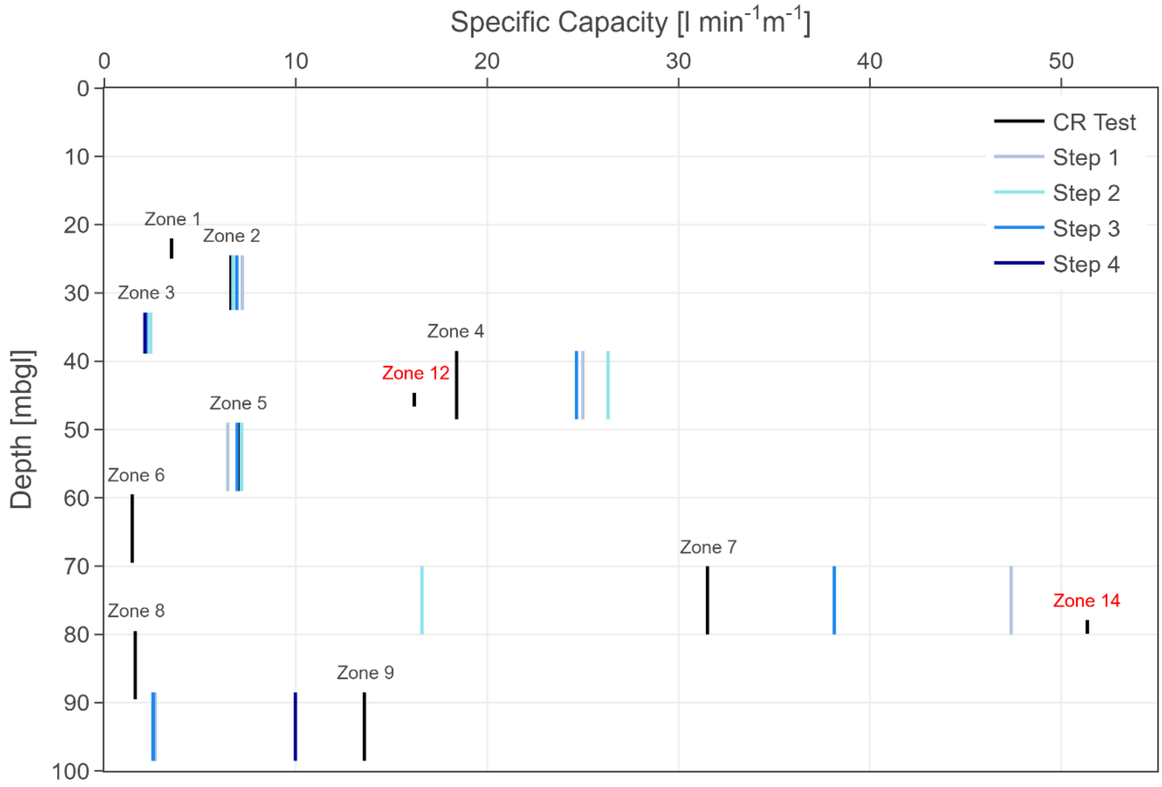


Figure 6.21 – Constant rate test and step test specific capacity results profile graph. Red zones indicate targeted fracture zones.

6.3 HYDROCHEMICAL RESULTS

Sampling for hydrochemical analytes was conducted during the constant rate test for each of the tested zones. All hydrochemistry data are available as part of the testing data pack. There is potential for contamination of the local groundwater by drilling fluid from TH0410. The source of drilling fluid was from a local abstraction borehole and no additives were added that would change the chemical or isotopic signature allowing drilling fluid to be traced to packer test interval samples. During the drilling process of all cored boreholes at the UKGeos array, fluorescein was added to ensure no contamination of drilling fluid into pore waters of core which would later be spun for pore water sampling. Fluorescein was added to drilling fluid of TH0410 (at a target concentration of 1 mg/l in the active tank) until loss of drilling flush at ~44 mbgl. Fluorescein was sampled for in TH0424 during packer testing to aid in identifying any possible contamination of samples. Interval zones 2 & 3 were sampled during fluorescein dosed drilling fluid, with some potential latent fluorescein present in local groundwaters at the time of sampling zones 4, 5 & 6 (see Section 7.1), allowing for local travel times. Fluorescein was not detected at a concentration that would be deemed above an analytical threshold, noting that the initial concentration of fluorescein added to drilling fluid was likely significantly diluted between TH0410 and TH0424, and groundwater is thought to flow in a north-westerly direction thus migration of groundwater from TH0410 and TH0424 would not occur under the normal hydraulic gradient. This combined with a lack of cyclical change in temperature from the transducers during drilling activities suggests that drilling fluid migration into the isolated interval is unlikely. However, caution should be taken when interpreting these hydrochemical results.

Figure 6.22 displays the depth profile of on-site measured parameters and Figure 6.23 & 6.24 show major-ion chemistry with a piper plot for all zones shown in Figure 6.25. Results that are below the analytical limit of detection (LOD) are displayed as LOD/2. Ionic imbalances for all collected samples were calculated as <5%. Some descriptions of the data refer to UK and EU legislation for water supply, drinking water and groundwater; these are purely to provide a frame of reference and do not constitute a comment on the water's suitability for consumption or to the status of the groundwater resource.

Plots for minor analyte chemistry can be found in Appendix 1.

On-site measured parameters show slightly acidic water in the upper part of the water column, with a noticeable step change of decreased temperature, SEC and alkalinity at around 40 mbgl which is also apparent in the Cl, HCO_3, Na, Mg and K values. This is consistent with a mudstone band at ~33 mbgl which may act as a significant confining layer between the main aquifer and a perched aquifer above. Zone 3 straddles the mudstone band so may take in water from both aquifers. Eh values show a decreasing trend with depth with a slight increase in Eh and dissolved oxygen (DO) at 70 – 80 mbgl with decreased alkalinity and SEC, pointing towards fresher water and a potential major inflow depth (zones 7 & 14). Zones show a predominantly Ca-Cl water type. All values for nitrate are above the groundwater threshold value of 37.5 mg/l as defined in The Water Environment (Water Framework Directive) Regulations (2015) and are relatively consistent throughout the water column. All Cl values are also above the threshold value of 188 mg/l. All collected samples are of calcium chloride water type (Figure 6.25). All samples for ammonium (NH_4) were below the limit of detection.

All zones show high Fe content with all zones aside from zone 1 above the 200 µg/l national limit of the The Water Supply (Water Quality) Regulations (2018). Zone 8 in particular shows highly elevated Fe concentrations of >1500 µg/l. Zones 7, 8 and 14 show Mn concentrations >50 µg/l and zone 1 shows an elevated Cd concentration >5 µg/l. Zone 1 is also relatively elevated in concentrations of other minor ions and trace metals such as Sr, Be, B, Al, Ni, Se, Y, La, Nd, Sm, Gd, Dy and Er compared to deeper sections.

Some differences are seen in the hydrochemistry of targeted fracture zones and the larger interval testing zones which includes the fractures, particularly between fracture zone 14 and interval zone 7. Significant differences can be seen with higher concentration in the targeted fracture of Ba, Sr, Mn, B and Cu and lower concentrations of Zn, As, W, Pb and U.

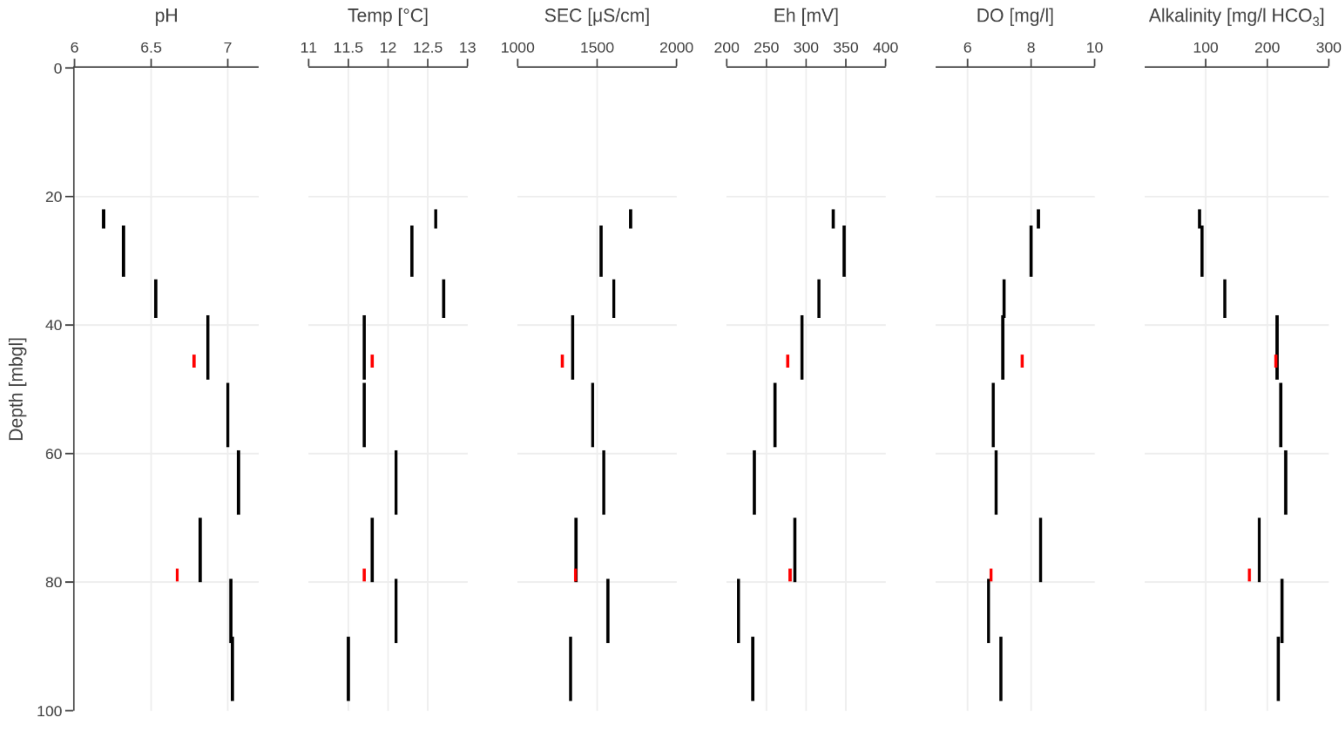


Figure 6.22 - Depth profile of measured field parameters. Red lines indicate targeted fracture zones.

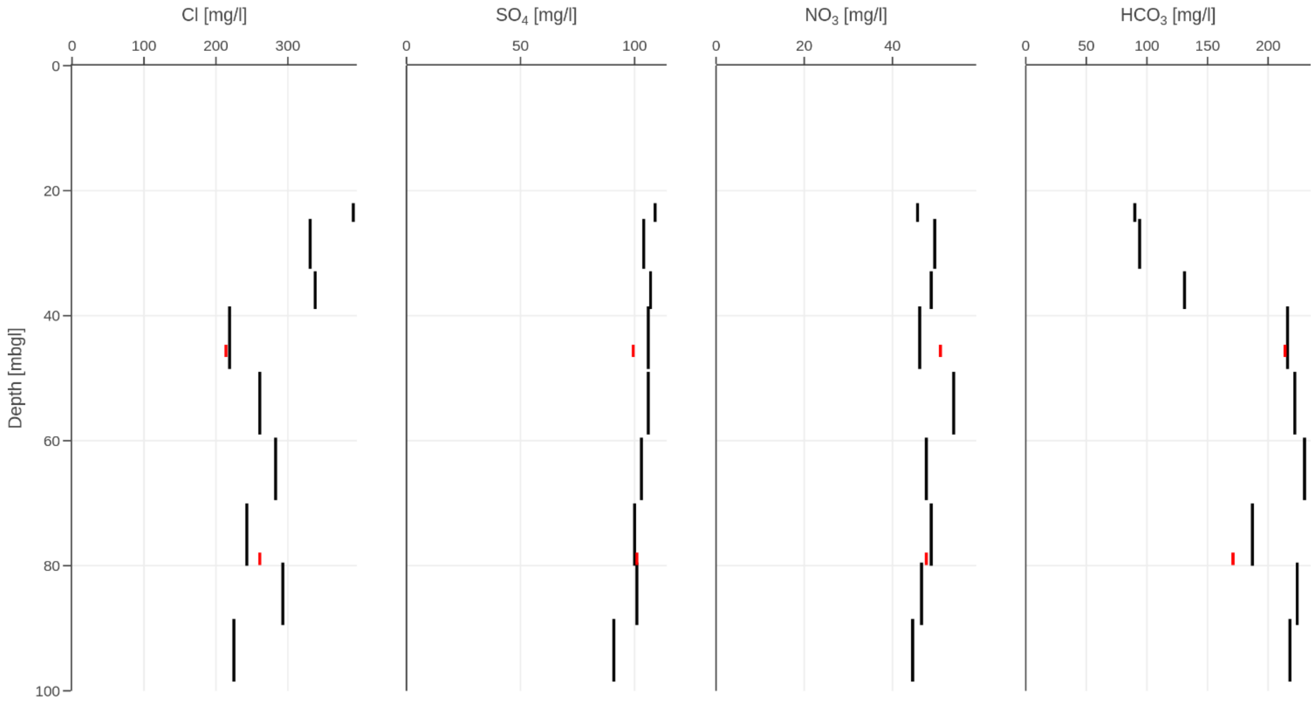


Figure 6.23 - Depth profile of dissolved major anion chemistry. Red lines indicate targeted fracture zones.

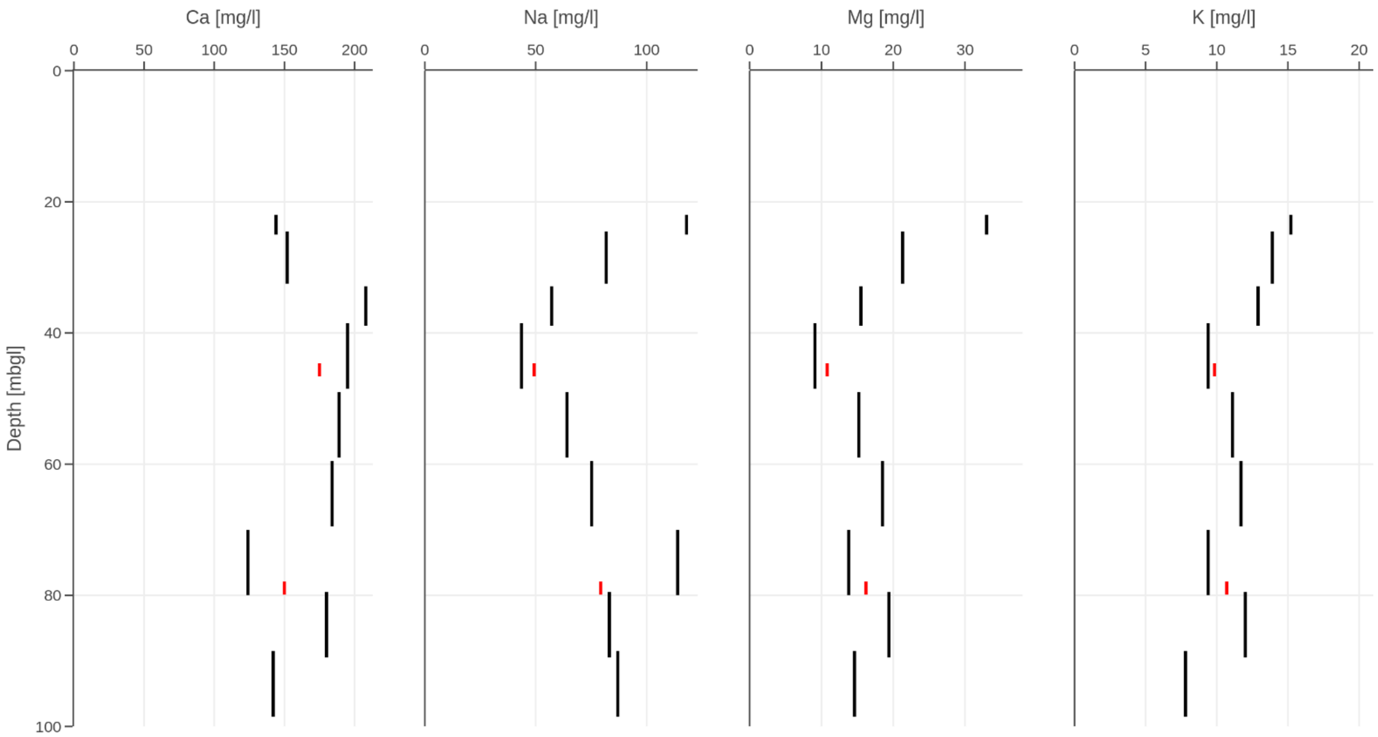


Figure 6.24 - Depth profile of dissolved major cation chemistry. Red lines indicate targeted fracture zones.

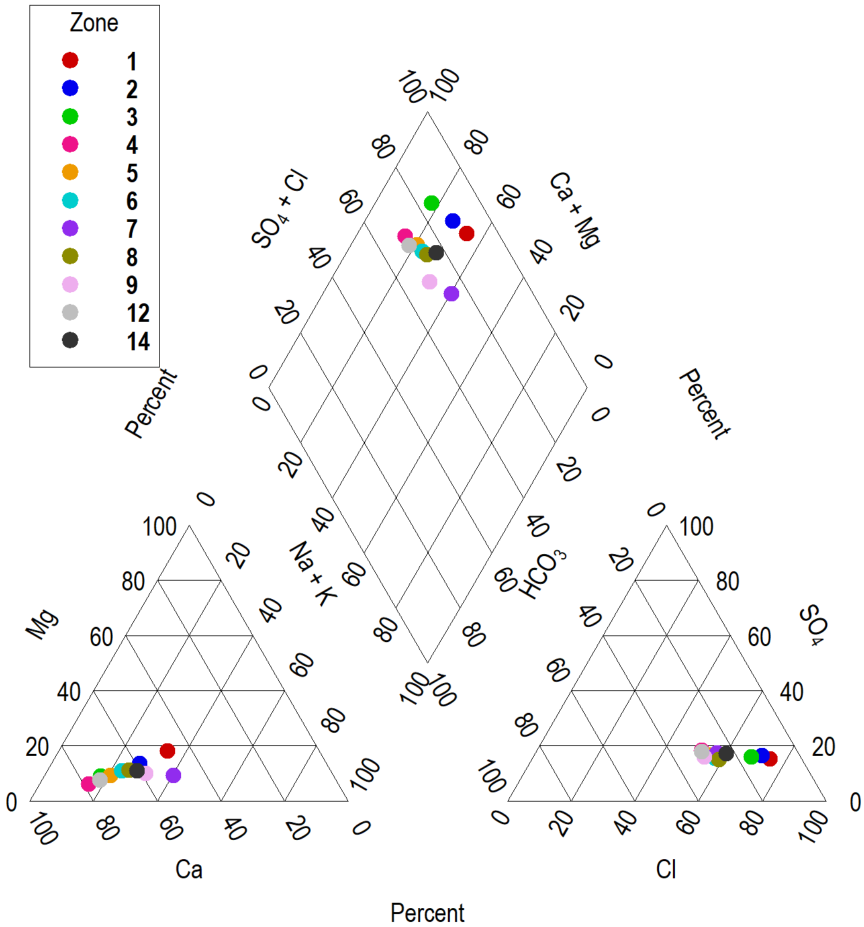


Figure 6.25 - Piper plot for tested intervals

Stable isotope analysis of δ^2H and $\delta^{18}O$ in the sample waters indicates a tight grouping along the global meteoric water line (GMWL; Figure 6.26) of around -7.27 to -7.08 $\delta^{18}O$ and suggests recharge of modern meteoric waters across all zones. This is supported by CFC and SF_6 residence time indicators with all zones showing an "over modern" year of recharge, aside from zone 4 data that suggests a slightly older year of recharge of 2018. Zone 12 fracture focused data shows an "over modern" year of recharge but sits within zone 4 mixed "older" waters and suggests that the matrix waters found within zone 4 are likely much older than 2018.

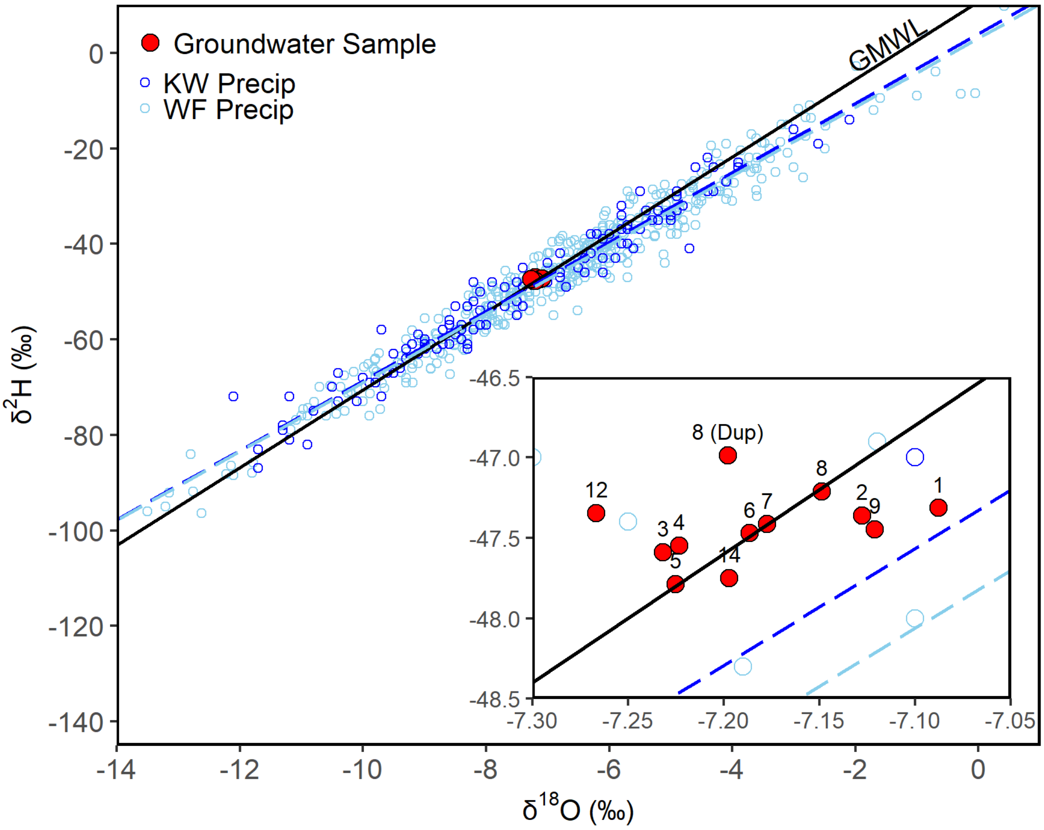


Figure 6.26 - Stable oxygen and deuterium isotopic compositions of TH0424 packer testing groundwater samples and UK precipitation. Monthly precipitation data from IAEA GNIP network (IAEA/WMO, 2023) for Keyworth (KW; 1985 - 1996) and Wallingford (WF; 1979 - 2019) stations. Groundwater data shown with zone labels in inset plot.

Dissolved radon concentrations generally follow the trend of uranium, increasing in concentration with depth aside from an increased concentration in zone 1 for both analytes (Figure 6.27). Differences arise in targeted fractures with increased radon concentration in fractures compared to the equivalent profiled interval, whereas uranium concentrations remain comparable. Radon concentrations remain well below the The Water Supply (Water Quality) Regulations (2018) indicator value of 100 Bq/l and uranium concentrations remain below the EU drinking water directive parametric value of 30 µg/l (EU Directive, 2020).

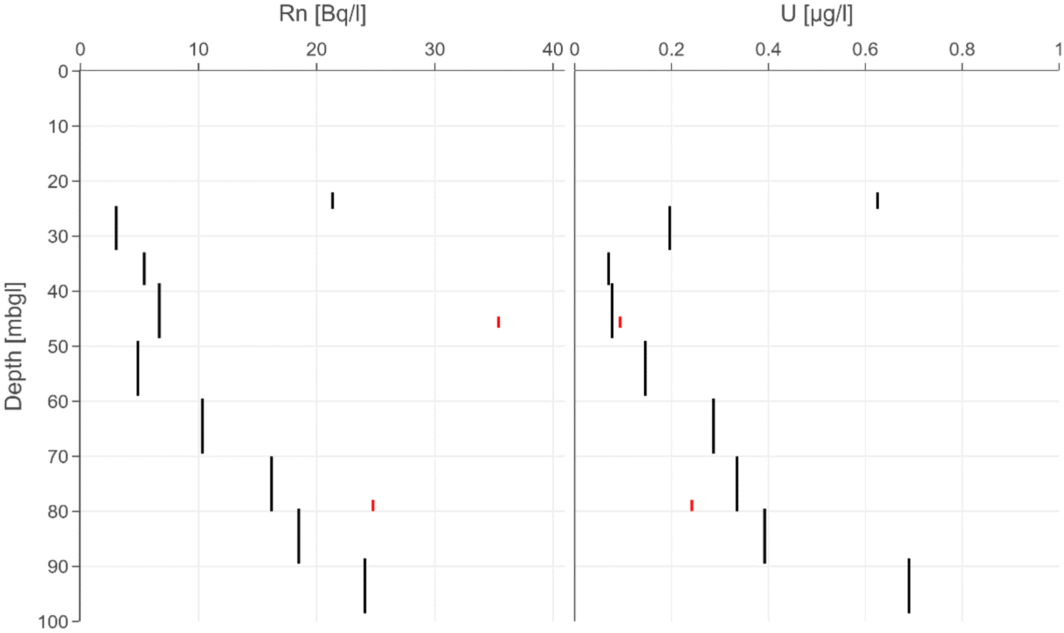


Figure 6.27 - Dissolved Radon activity and dissolved uranium concentration profiles. Red lines indicate targeted fracture zones.

7 Discussion

7.1 LOCAL DRILLING PERTUBATIONS

TH0424 is approximately 25m linear distance from TH0410 (Figure 7.1) which was being drilled during the testing period. Figure 7.2 shows the timeline of coring progress for TH0410 along with the timing and depth of testing intervals and other site activities. It is apparent from the data that cyclical deviations in water level correlate with coring runs from the drilling of TH0410, with the pressure perturbations observed at different magnitudes dependant on the interval being monitored and depth of the coring activity (e.g. Figure 7.3 & Figure 7.4). Zone 3 constant rate test levels deviated ~0.15 m per coring run, whereas zone 4 constant rate test deviated ~0.4 m per coring run. The difference in response is thought to be from the position of mudstone bands and major fracture zones inhibiting and being conducive to pressure transmission respectively. Tests that were obviously impacted by coring of TH0410 are zones 4 and 5 with zone 7 experiencing significant perturbations from reaming of TH0410. Plots of test intervals during drilling activities are available in Appendix 2. The timing of core drilling is available as part of the testing data pack (note: core drilling and site timing information is taken from draft field data only and has been published with the permission of the drilling contractor).

Other activities denoted in Figure 7.2 that may have influence on level data are detailed in Table 7.1.

Table 7.1 - Activities on site during the testing period (taken from draft field data only). Data released with permission of AECOM/Marriot Drilling.

Activity	Depth of activity (mbgl)	Time of activity
TH0410 Flush	0 – 77.2	07/10/2022 15:10 – 15:30
TH0410 Reaming	20.2 – 100	11/10/2022 09:05 – 13:15
TH0410 Purging	0 – 100	12/10/2022 15:50 – 17:05
TH0410 FLUTe Liner Installation	0 – 100	13/10/2022 08:45 – 11:15
TH0420 Reaming	2.0 – 6.3	13/10/2022 17:00 – 18:05

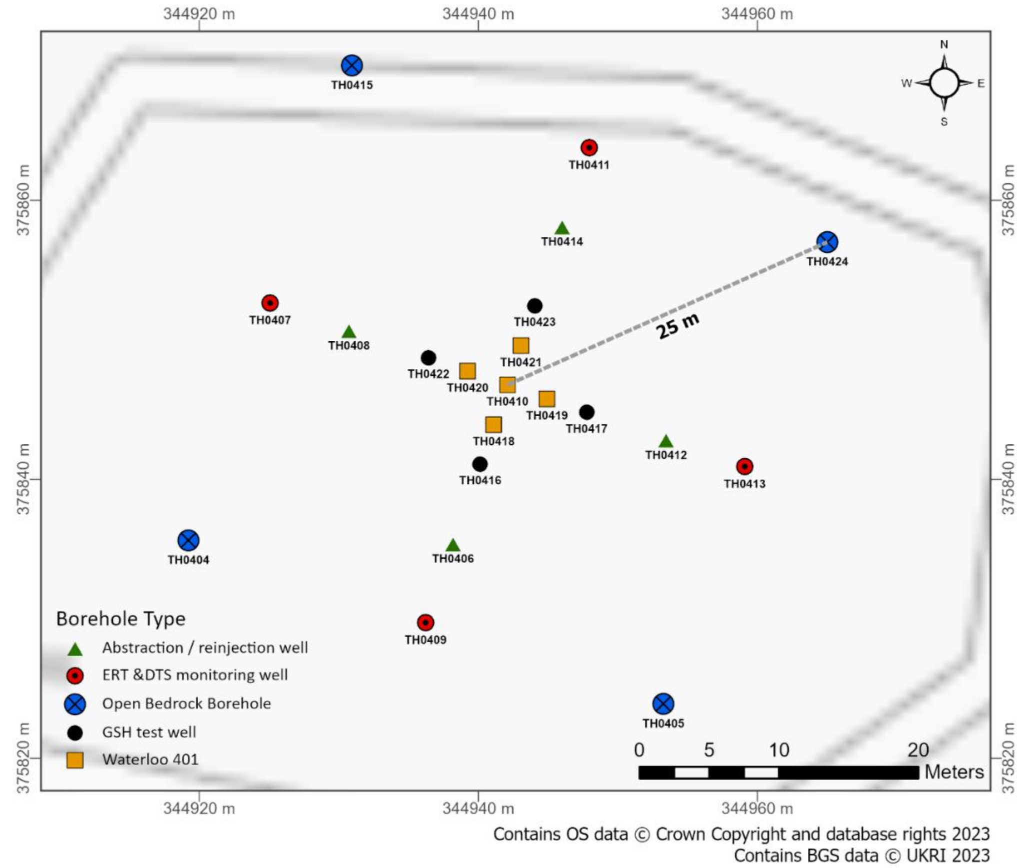


Figure 7.1 - UKGeos Cheshire array layout showing linear distance between TH0424 and TH0410. Ordnance Survey Licence No. OS AC0000824781.

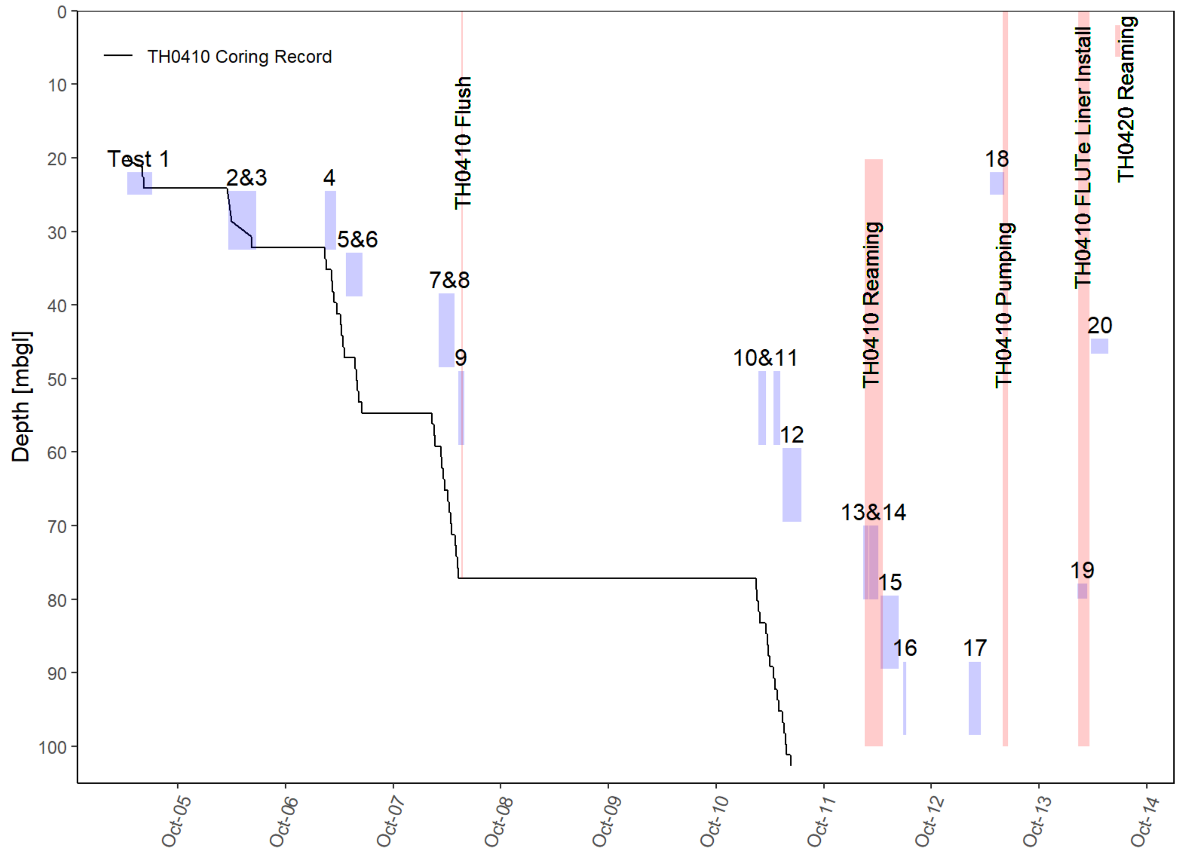


Figure 7.2 - Time series of coring progress of TH0410 (black line) and hydraulic test zones of TH0424 (blue zones). Other activities on site also depicted (red zones). Coring and site activity timing taken from draft field data only. Data released with permission of AECOM/Marriot Drilling.

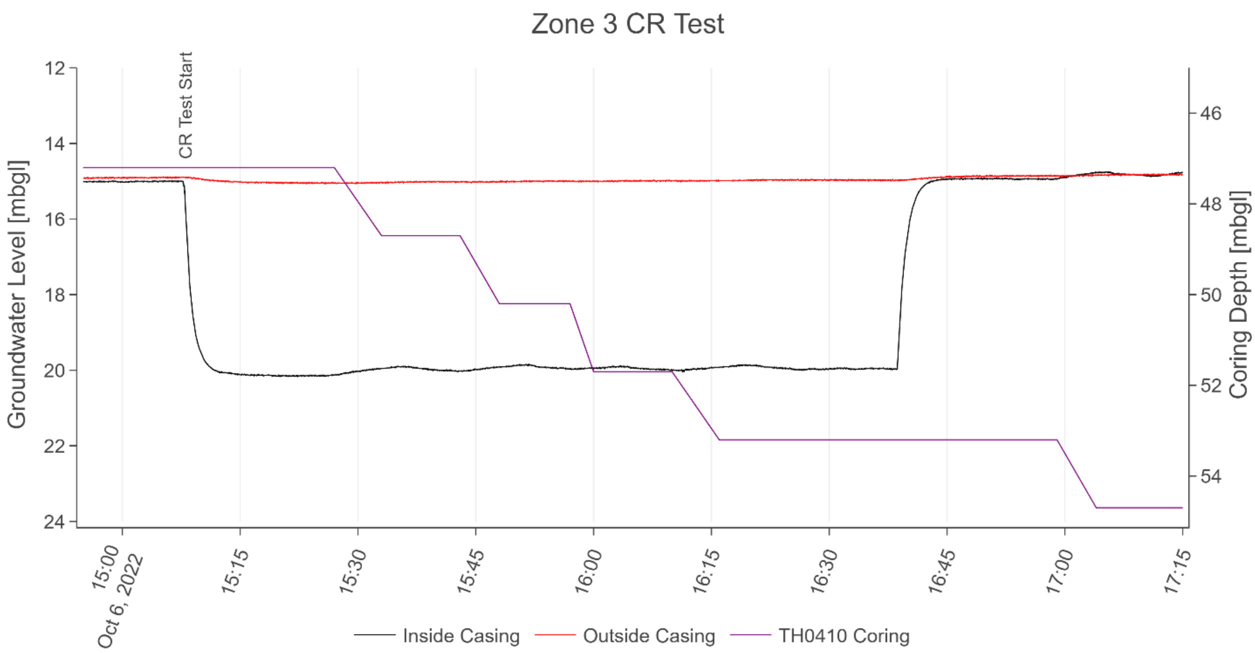


Figure 7.3 - Test 6 (Zone 3) constant rate test with depth of coring activity in TH0410. Coring timing taken from draft field data only. Data released with permission of AECOM/Marriot Drilling.

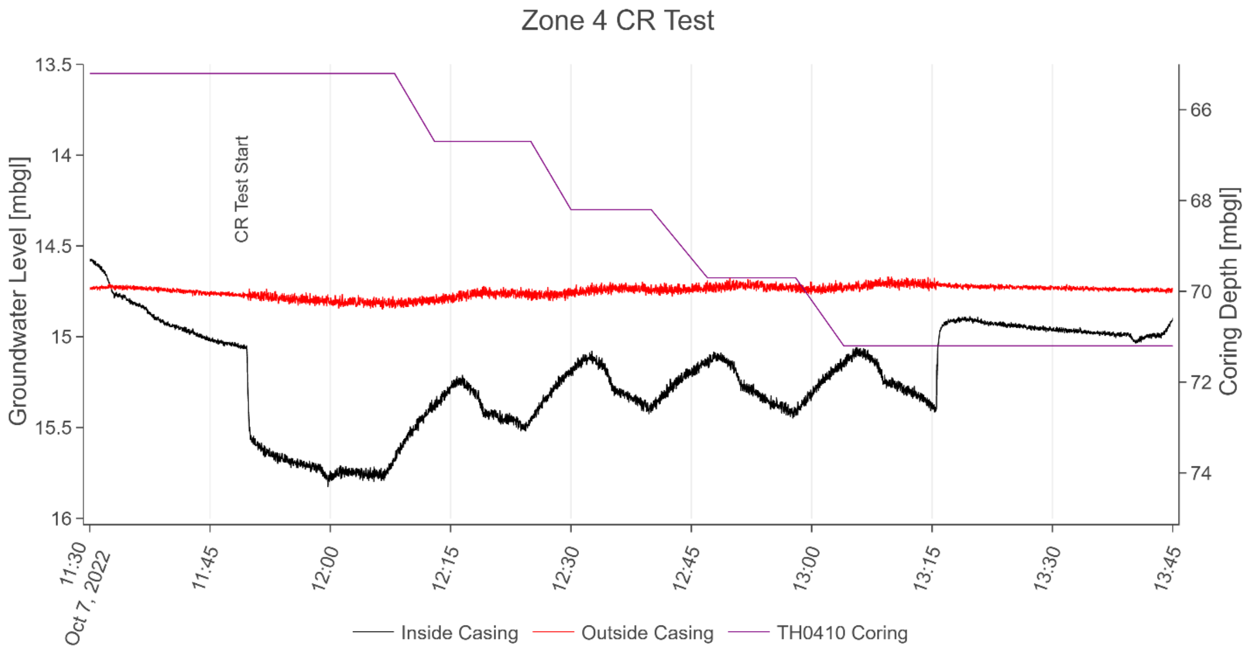


Figure 7.4 - Test 8 (Zone 4) constant rate test with depth of coring activity in TH0410. Coring and site activity timing taken from draft field data only. Data released with permission of AECOM/Marriot Drilling.

7.2 INFLUENCE OF LOCAL ABSTRACTIONS

The TSP abstraction borehole (SJ47NW25; NGR 344950 375500; 152 m depth), which lies c. 350m due south of the UKGeos array, was monitored for the months preceding hydraulic testing. Whilst it was not possible to install groundwater level monitoring equipment, a pressure logger was attached to the headworks to provide a record of when the borehole was being pumped. This data is available in the testing data pack. When combined with the long-term groundwater level record (Figure 7.5), it can be seen that during pumping (between 30 and 40 min duration on average) the level in TH0424 declines by ~0.2 m per pumping cycle. Time interval between pumping events (3 events per day on average) does not seem sufficient to allow the local groundwater level to fully recover to it “natural” baseline level. This may cause some difficulties when interpreting the data dependant on what phase the local groundwater is in (drawdown or recovery) and when combined with any pressure effects from local drilling activities increases the complexity of these effects.

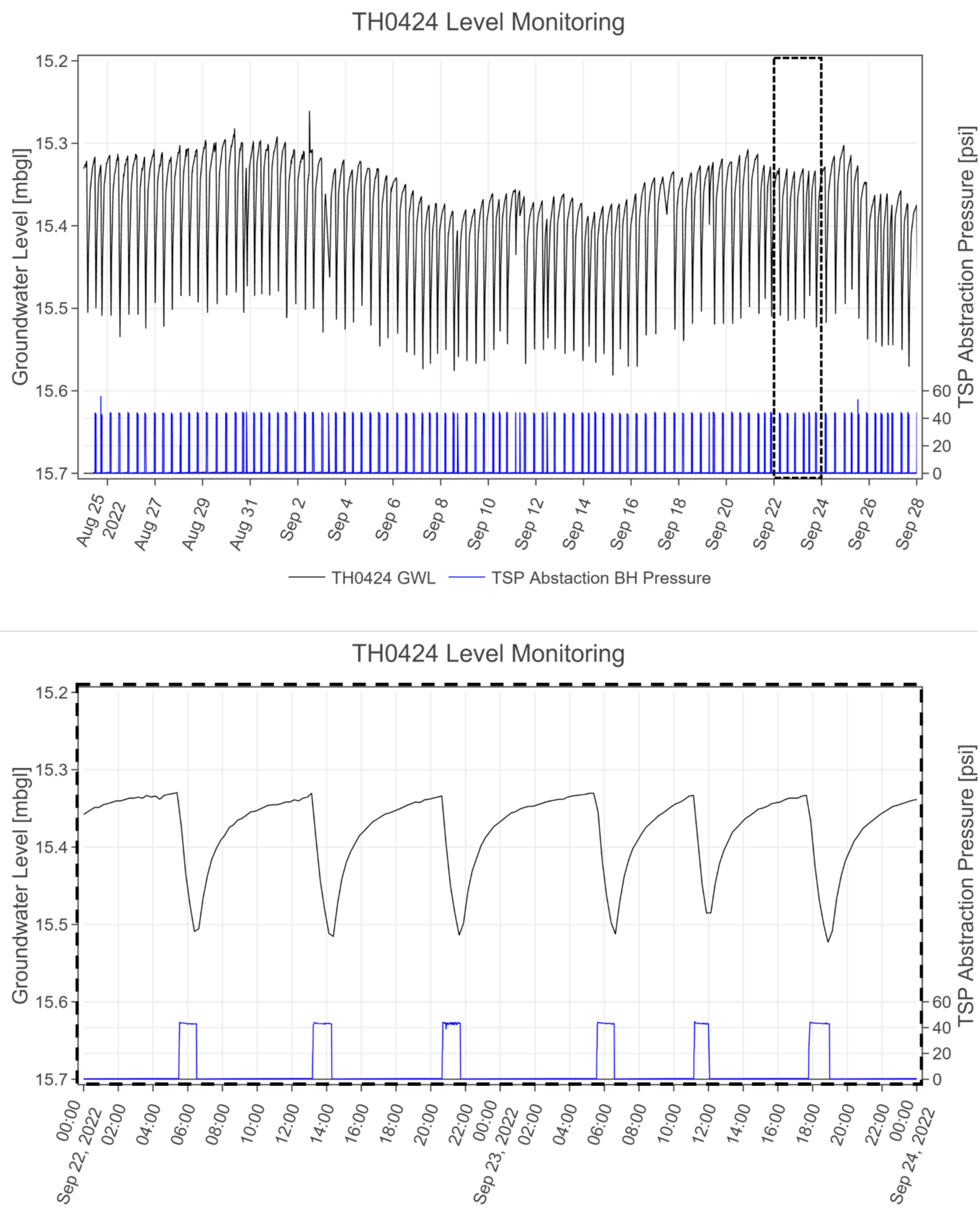


Figure 7.5 - Pumping record of TSP abstraction borehole and groundwater level record of TH0424. Data released with permission of University of Chester.

The influence of the local abstraction does offer a chance to monitor the response of isolated intervals. Where possible, intervals were left isolated with loggers installed overnight between testing days. Figure 7.6 - 7.1 show open hole and isolated zone response to local abstraction events. These periods of time also have the advantage of inactivity with no external influence of local drilling. Zone 3 and shallower display limited response in the outside logger, with the influence on groundwater level in the outside casing increasing with depth for zones 6 and 9. A method of logging the groundwater level in TSP abstraction borehole would allow for modelling of the cone of depression with isolated monitoring of intervals.

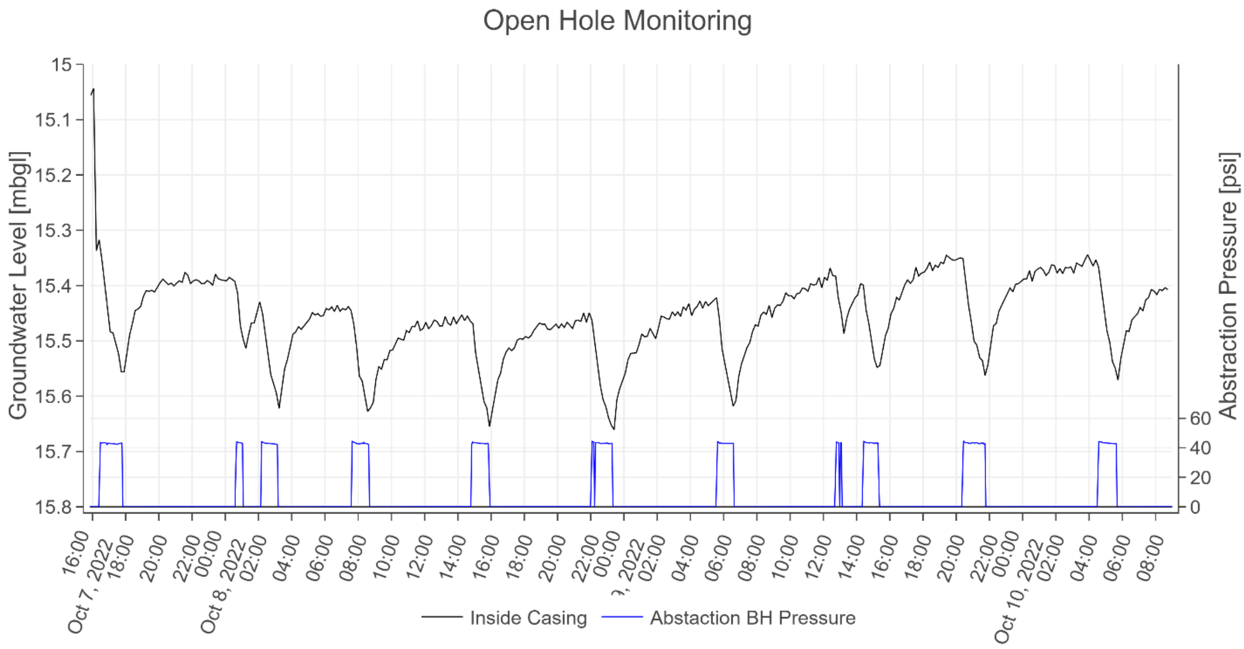


Figure 7.6 - TH0424 groundwater level in open hole and TSP abstraction pumping record 7 - 10th October 2022. Data released with permission of University of Chester.

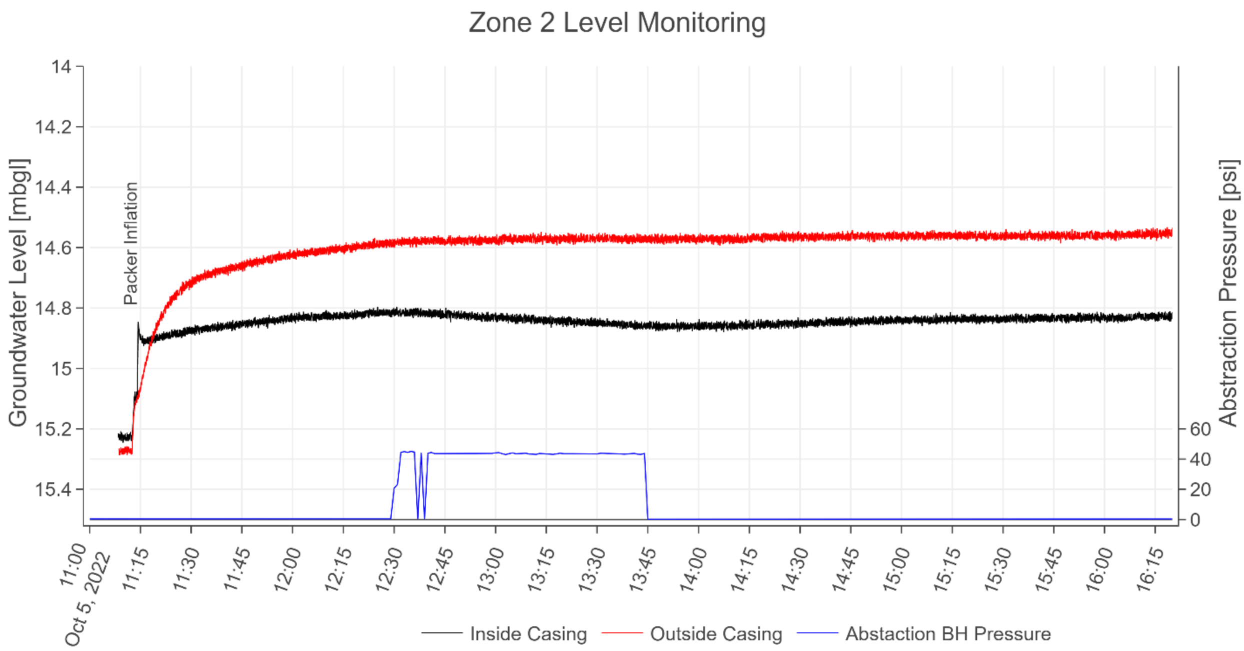


Figure 7.7 - Isolated zone 2 groundwater levels and TSP pumping record. Data released with permission of University of Chester.

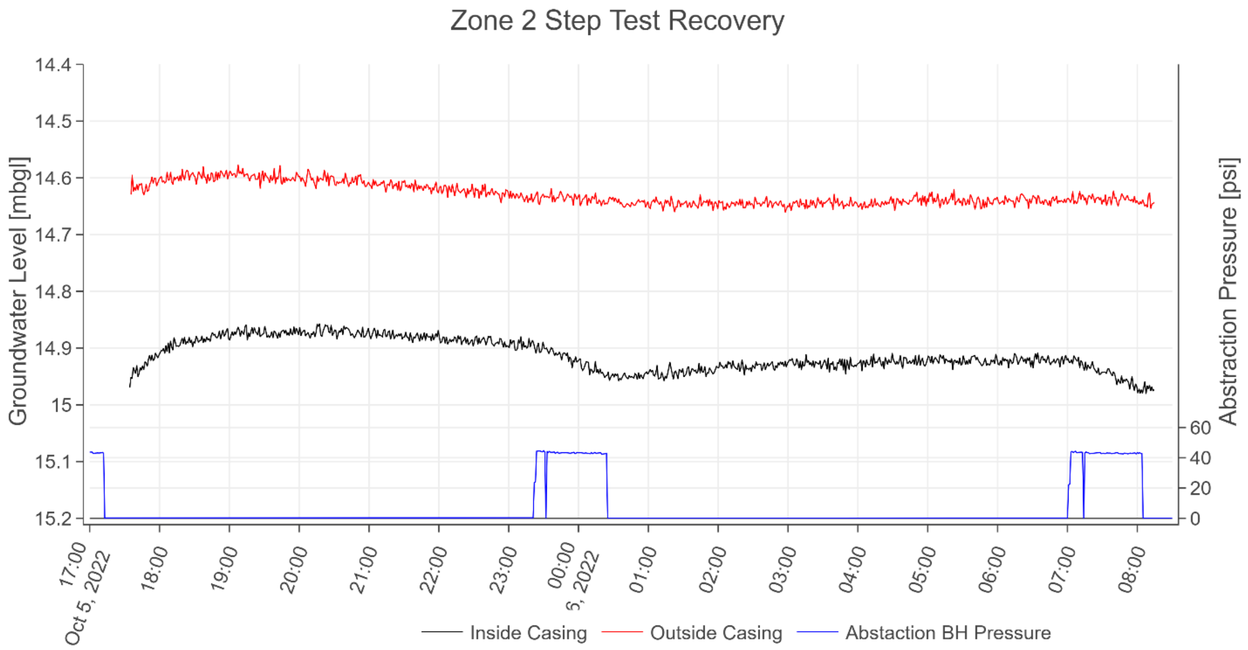


Figure 7.8 - Isolated zone 2 groundwater levels following step test and TSP pumping record. Data released with permission of University of Chester.

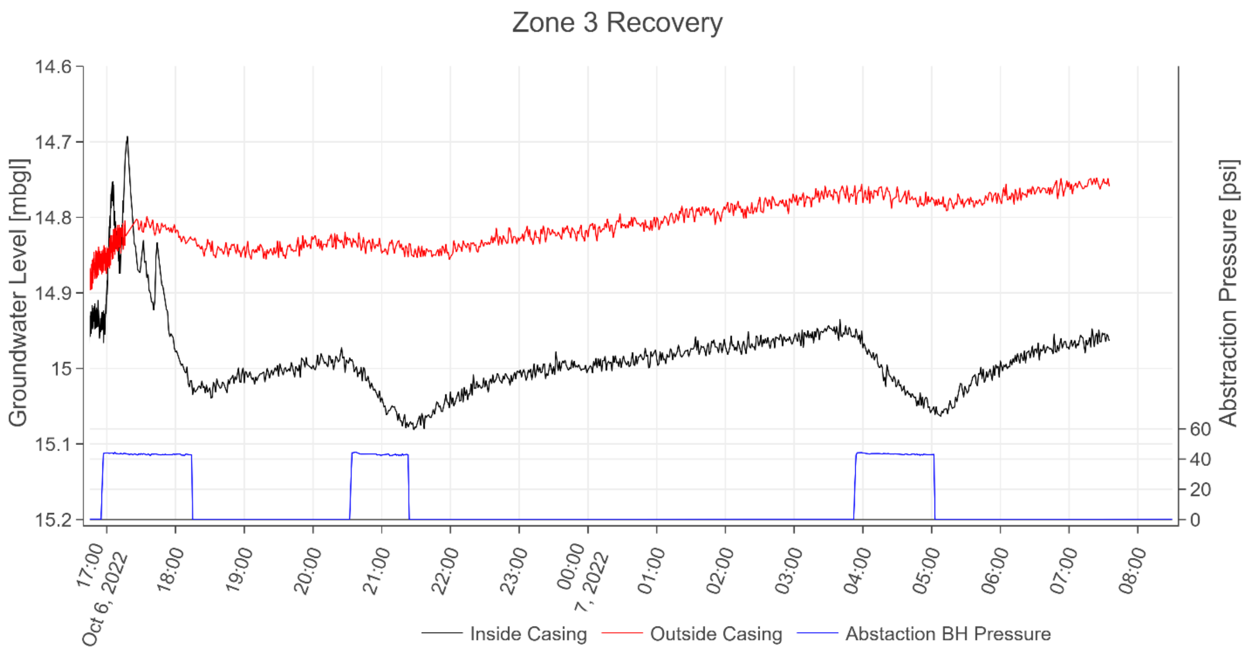


Figure 7.9 - Isolated zone 3 groundwater levels following CR test and TSP pumping record. Data released with permission of University of Chester.

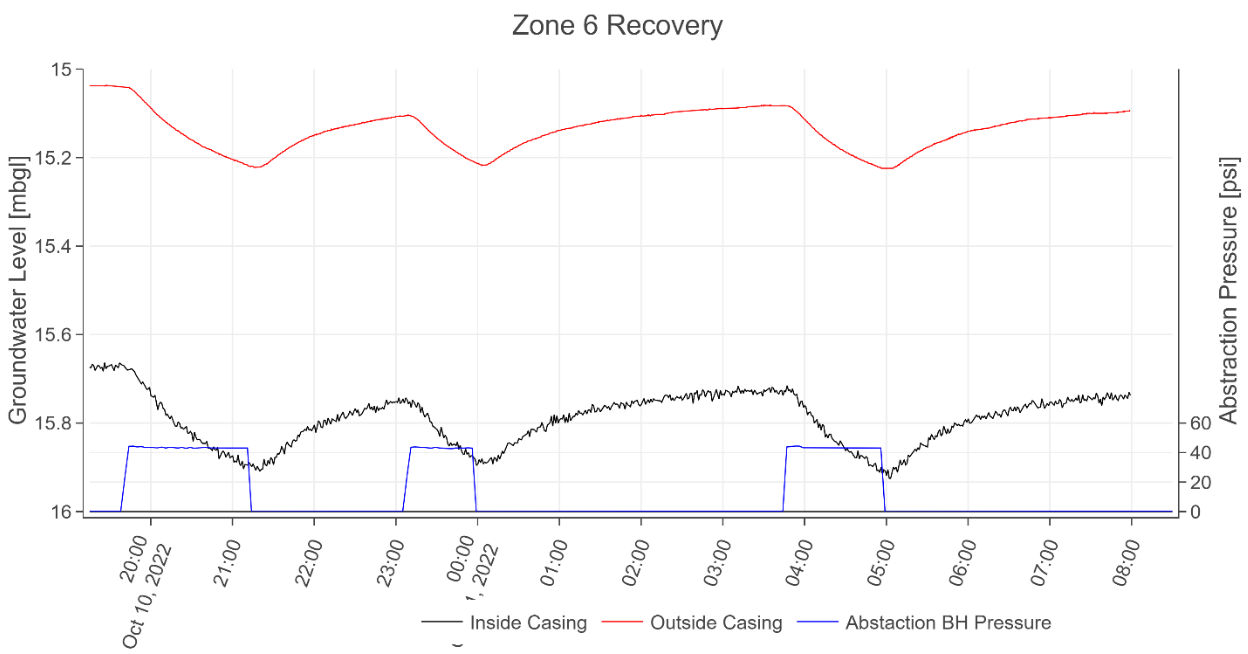


Figure 7.10 - Isolated zone 6 groundwater levels following CR test and TSP pumping record. Data released with permission of University of Chester.

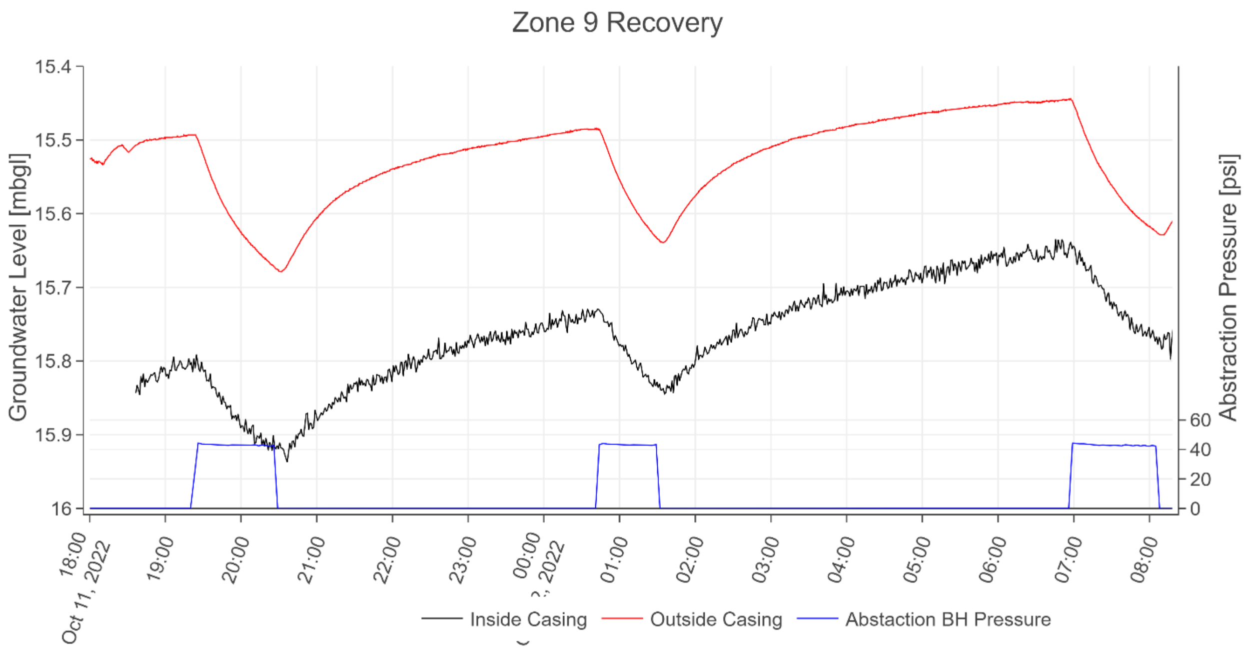


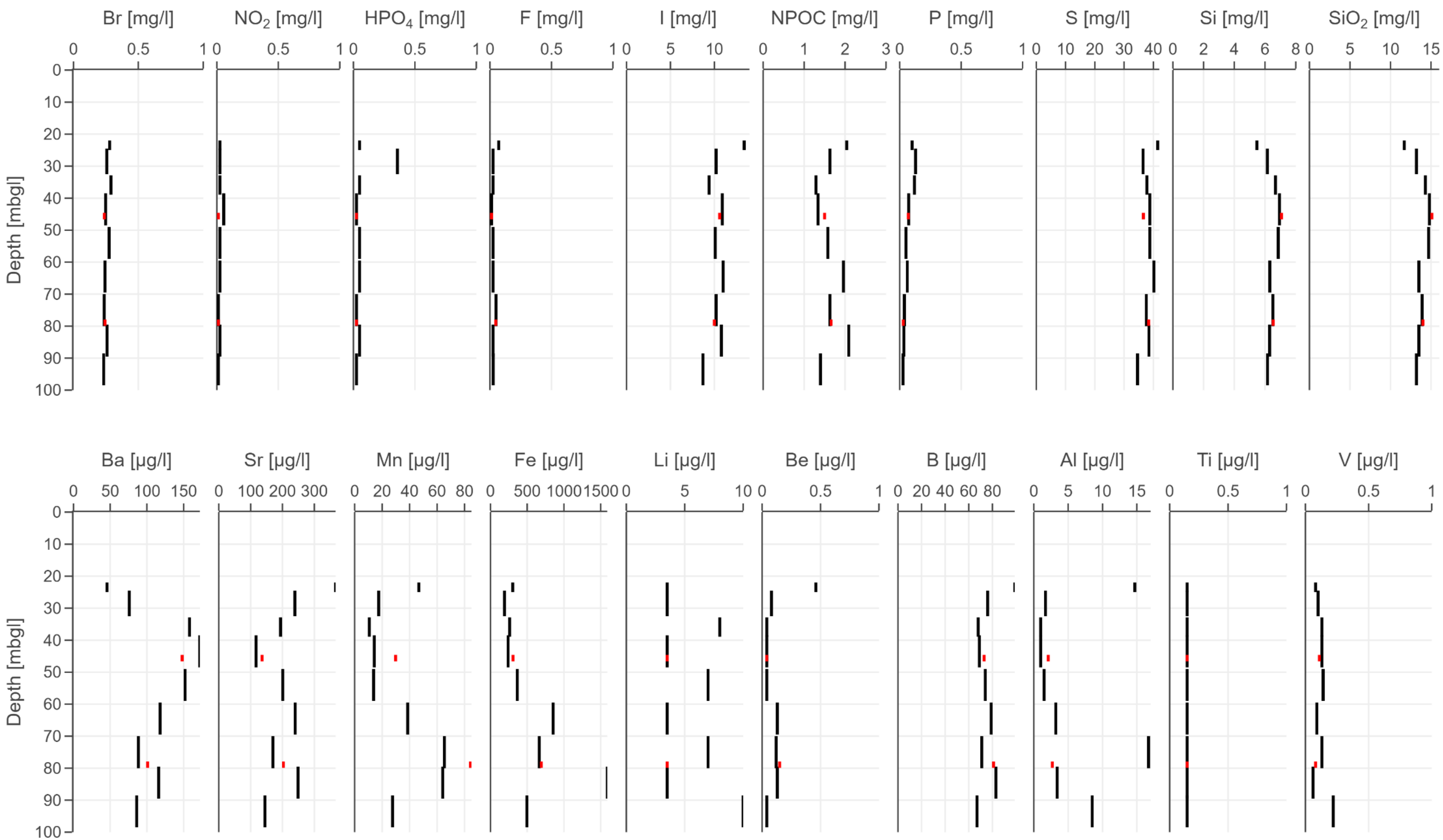
Figure 7.11 - Isolated zone 9 groundwater levels following CR test and TSP pumping record. Data released with permission of University of Chester.

Some tests data may have been affected by local abstractions which should be considered when interpreting groundwater levels. Table 7.2 displays tests that were likely affected by abstraction events from the TSP abstraction borehole.

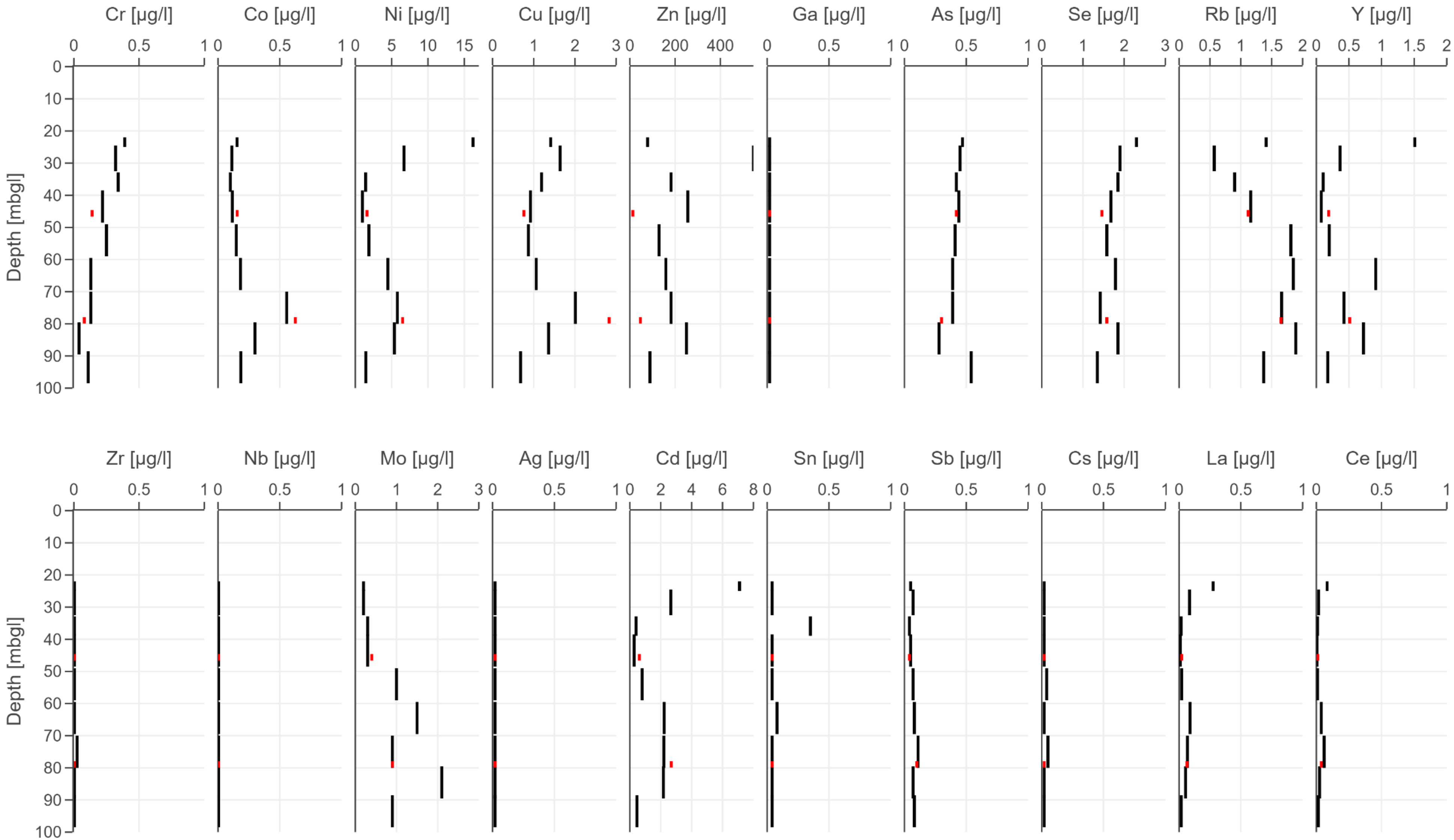
Table 7.2 - Tests affected by local groundwater abstraction events. Data released with permission of University of Chester.

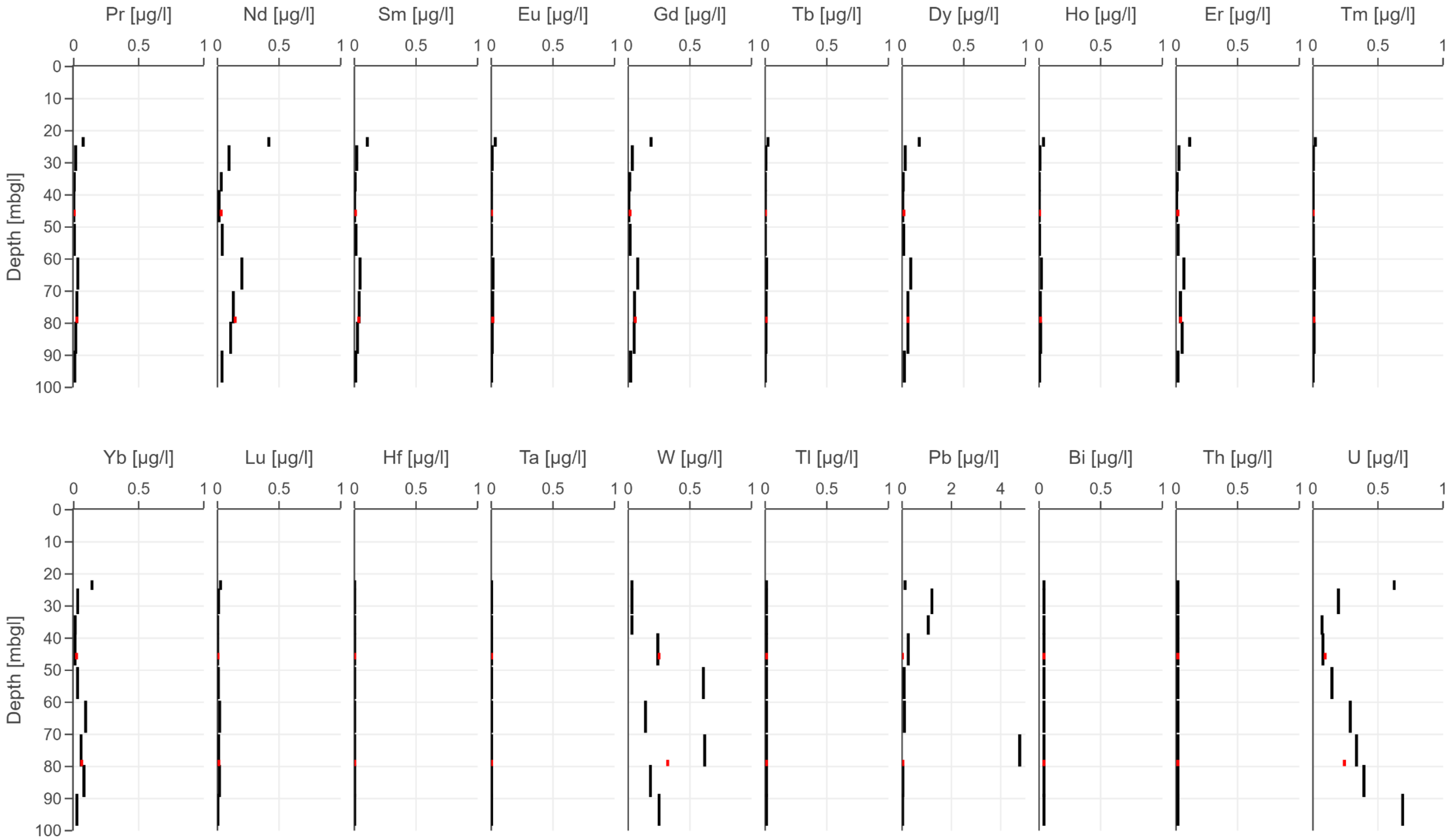
Test	Zone	TSP Borehole Status
Test 3	Zone 2 Step Test	Pumping during test
Test 4	Zone 2 CR Test	Pump cycle stopped ~45mins prior to test. Levels in recovery phase
Test 5	Zone 3 Step Test	Pump cycle stopped ~30 mins prior to test. Levels in recovery phase.
Test 7	Zone 4 Step Test	Pumping during test
Test 8	Zone 4 CR Test	Pump on at start of test. Pumping cycle stopped ~7 mins into test.
Test 12	Zone 6 CR Test	Pumping during test
Test 13	Zone 7 Step Test	Pumping during test
Test 14	Zone 7 CR Test	Pumping cycle stopped as test started. Levels in recovery phase.
Test 15	Zone 8 CR	Pumping during test. Pumping cycle stopped ~30 mins into test.
Test 20	Zone 12 CR Test	Pumping during test.

Appendix 1 Minor & Trace Analyte Plots



Br [mg/l]
NO$_2$ [mg/l]
HPO$_4$ [mg/l]
F [mg/l]
I [mg/l]
NPOC [mg/l]
P [mg/l]
S [mg/l]
Si [mg/l]
SiO$_2$ [mg/l]
Depth [mbgl]
Ba [µg/l]
Sr [µg/l]
Mn [µg/l]
Fe [µg/l]
Li [µg/l]
Be [µg/l]
B [µg/l]
Al [µg/l]
Ti [µg/l]
V [µg/l]
Depth [mbgl]

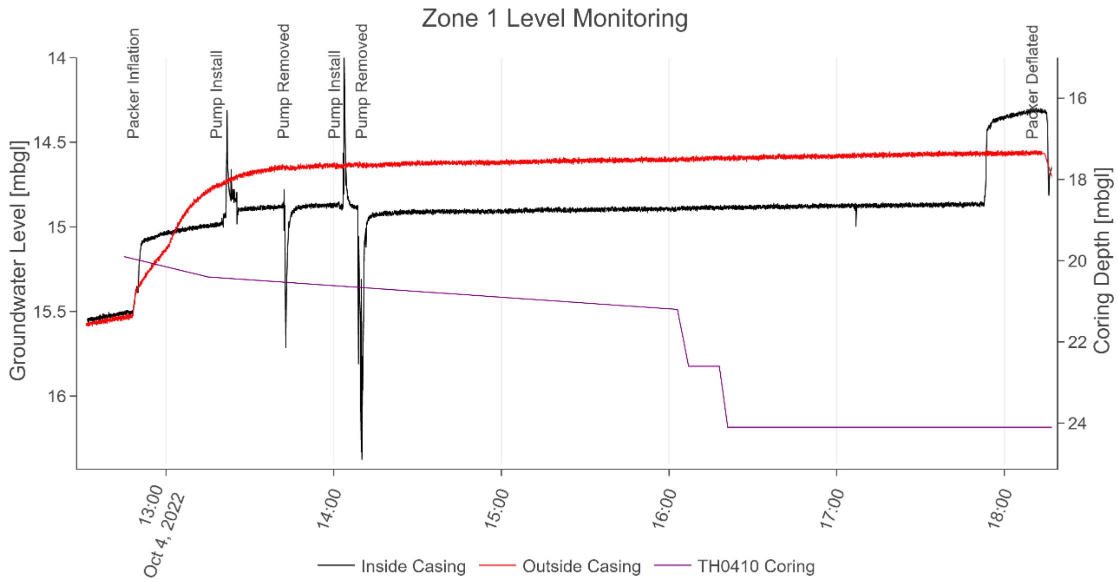

Cr [µg/l]
Co [µg/l]
Ni [µg/l]
Cu [µg/l]
Zn [µg/l]
Ga [µg/l]
As [µg/l]
Se [µg/l]
Rb [µg/l]
Y [µg/l]
Zr [µg/l]
Nb [µg/l]
Mo [µg/l]
Ag [µg/l]
Cd [µg/l]
Sn [µg/l]
Sb [µg/l]
Cs [µg/l]
La [µg/l]
Ce [µg/l]
Depth [mbgl]
0 10 20 30 40 50 60 70 80 90 100

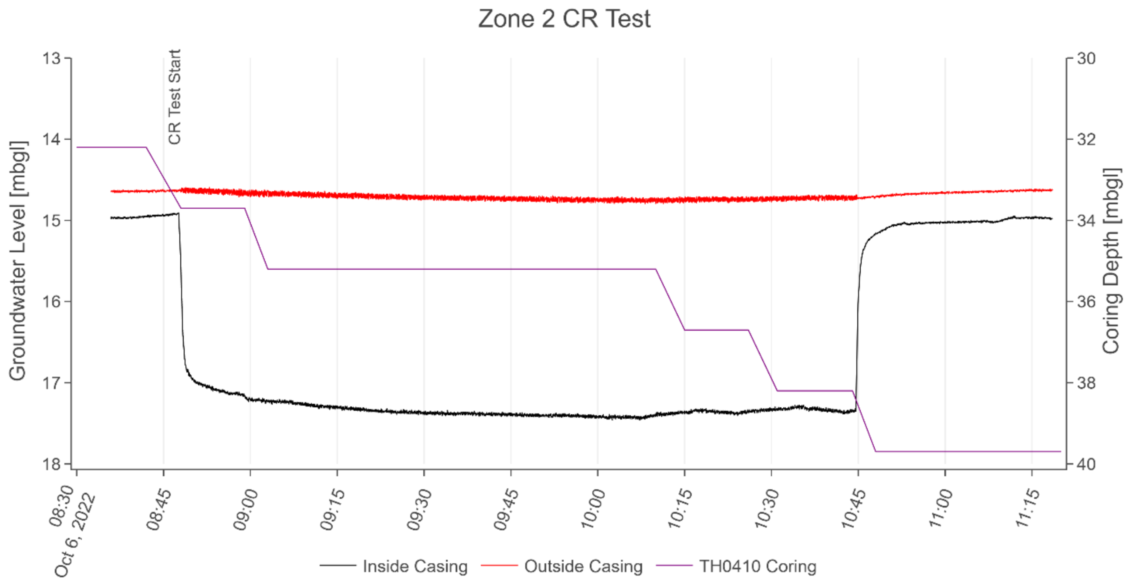


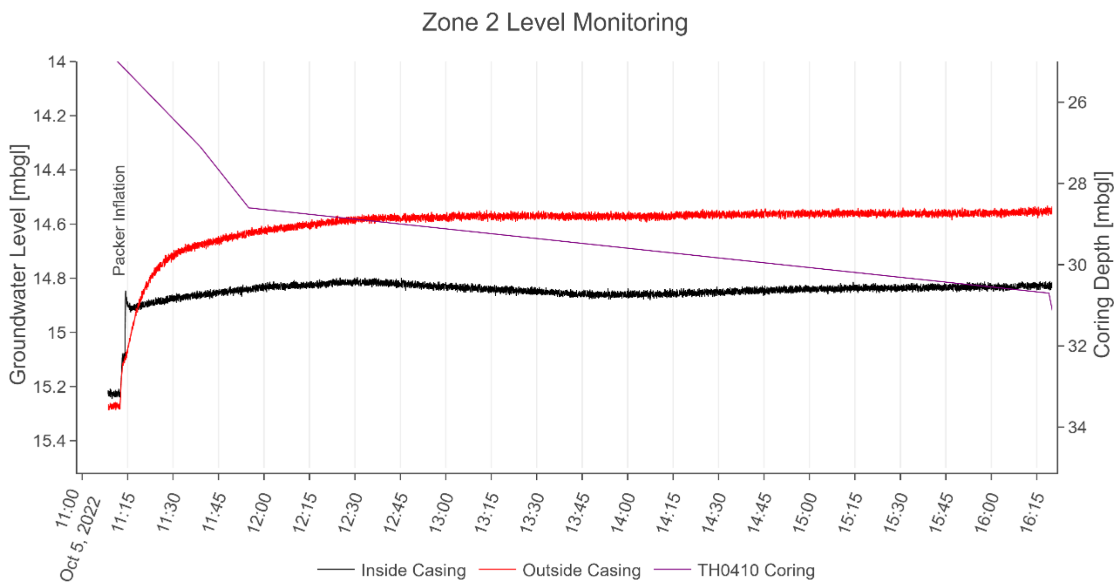
Pr [µg/l]
Nd [µg/l]
Sm [µg/l]
Eu [µg/l]
Gd [µg/l]
Tb [µg/l]
Dy [µg/l]
Ho [µg/l]
Er [µg/l]
Tm [µg/l]
Yb [µg/l]
Lu [µg/l]
Hf [µg/l]
Ta [µg/l]
W [µg/l]
Tl [µg/l]
Pb [µg/l]
Bi [µg/l]
Th [µg/l]
U [µg/l]
Depth [mbgl]

Appendix 2 Drilling Perturbation Plots

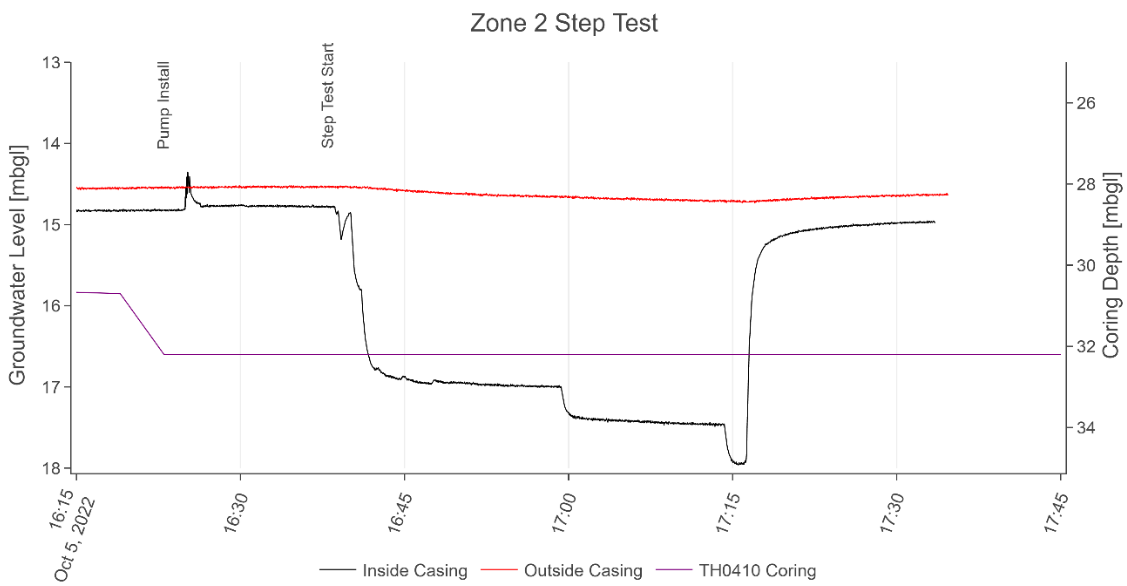
All figures in Appendix 2 contains data released with permission of University of Chester.



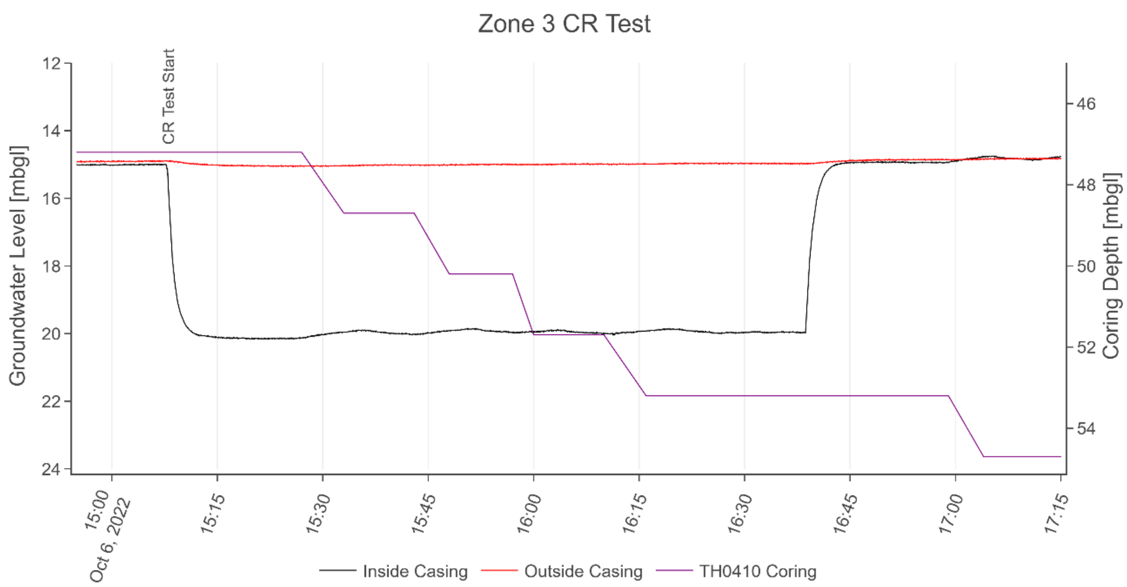




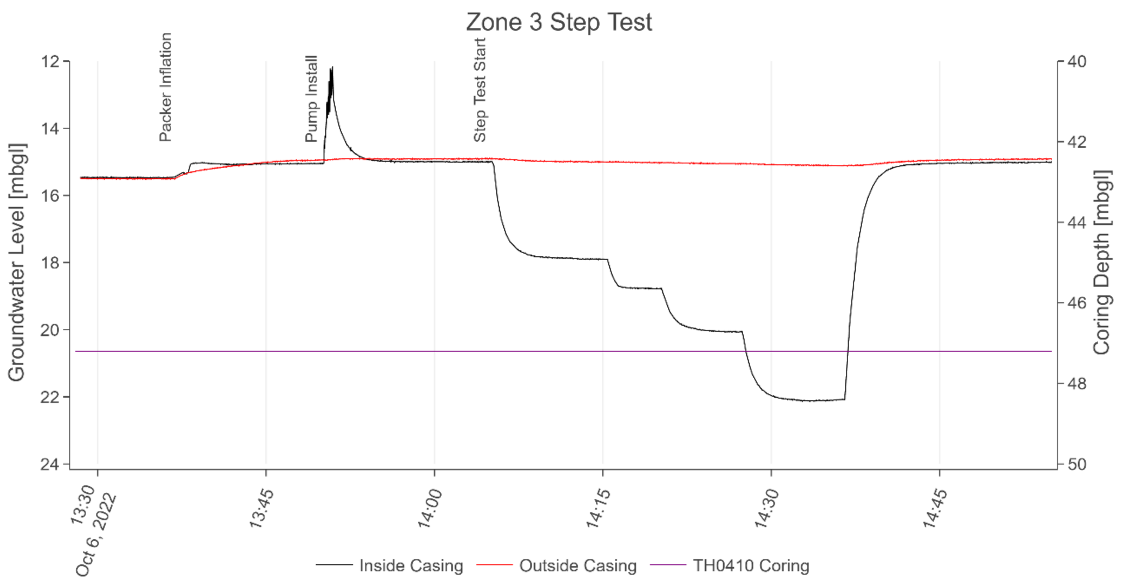
Zone 2 Level Monitoring
Groundwater Level [mbgl]
Coring Depth [mbgl]
Packer Inflation
14
14.2
14.4
14.6
14.8
15
15.2
15.4
26
28
30
32
34
11:00
Oct 5, 2022
11:15
11:30
11:45
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
16:15
Inside Casing
Outside Casing
TH0410 Coring



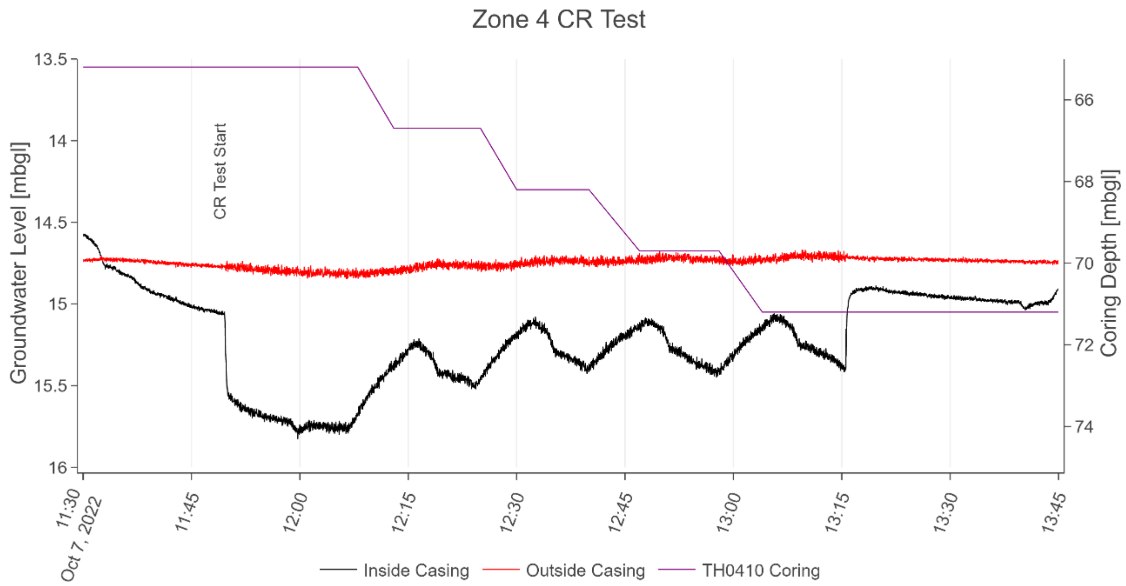
Zone 2 Step Test
Groundwater Level [mbgl]
Coring Depth [mbgl]
Pump Install
Step Test Start
13
14
15
16
17
18
26
28
30
32
34
16:15
Oct 5, 2022
16:30
16:45
17:00
17:15
17:30
17:45
Inside Casing
Outside Casing
TH0410 Coring



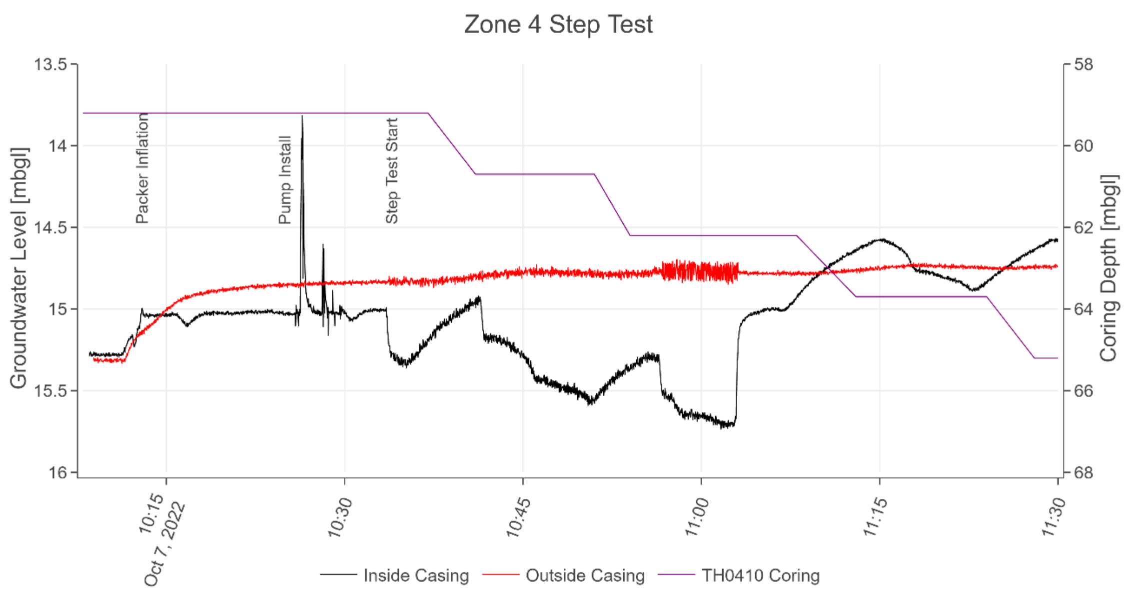
Zone 3 CR Test
Groundwater Level [mbgl]
Coring Depth [mbgl]
CR Test Start
12
14
16
18
20
22
24
46
48
50
52
54
15:00
Oct 6, 2022
15:15
15:30
15:45
16:00
16:15
16:30
16:45
17:00
17:15
Inside Casing
Outside Casing
TH0410 Coring



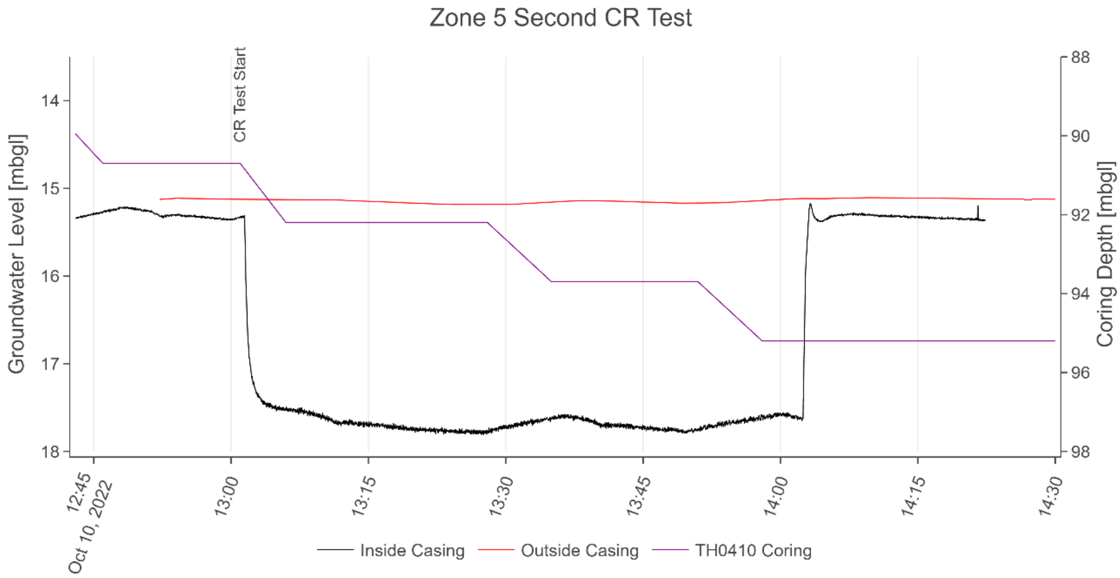
Zone 3 Step Test
Groundwater Level [mbgl]
Coring Depth [mbgl]
Packer Inflation
Pump Install
Step Test Start
Oct 6, 2022
Inside Casing
Outside Casing
TH0410 Coring

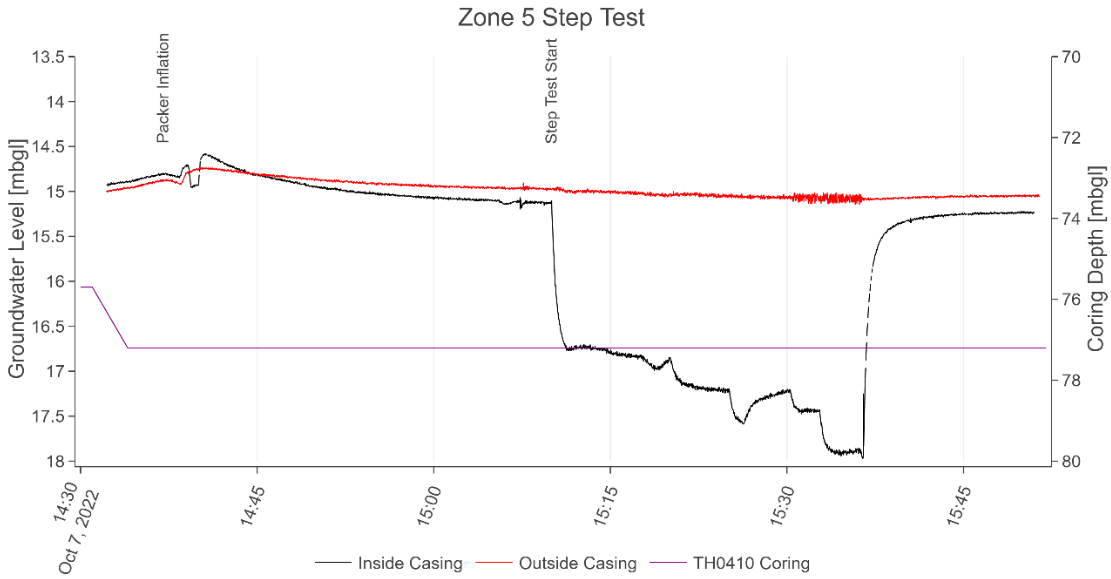


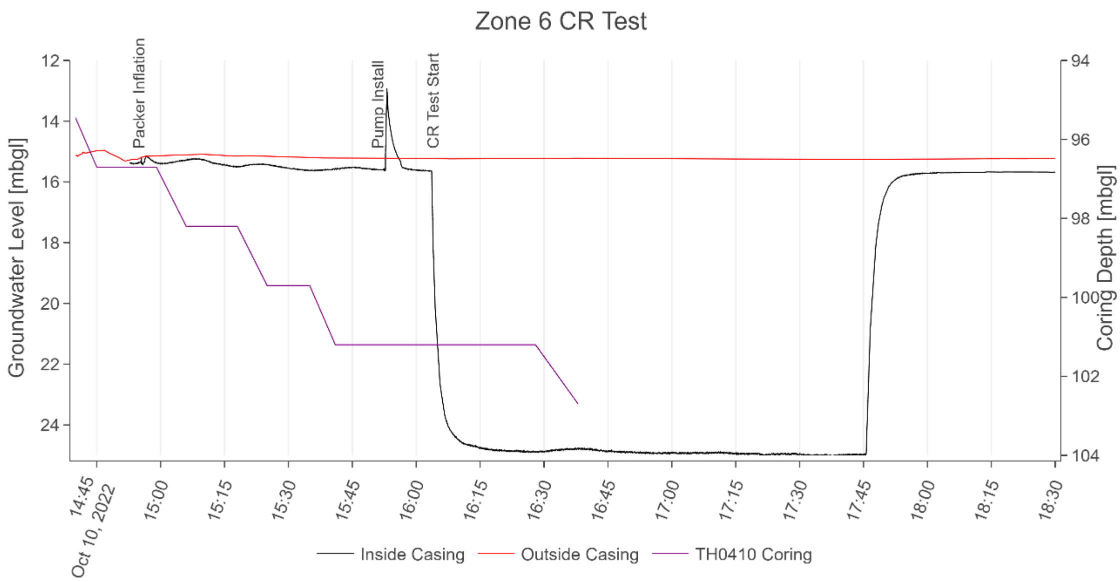
Zone 4 CR Test
Groundwater Level [mbgl]
Coring Depth [mbgl]
CR Test Start
Oct 7, 2022
Inside Casing
Outside Casing
TH0410 Coring



Zone 4 Step Test
Groundwater Level [mbgl]
Coring Depth [mbgl]
Packer Inflation
Pump Install
Step Test Start
Oct 7, 2022
Inside Casing
Outside Casing
TH0410 Coring


Zone 5 Second CR Test
CR Test Start
Groundwater Level [mbgl]
Coring Depth [mbgl]
14
15
16
17
18
88
90
92
94
96
98
12:45
Oct 10, 2022
13:00
13:15
13:30
13:45
14:00
14:15
14:30
Inside Casing
Outside Casing
TH0410 Coring


Zone 5 Step Test
Packer Inflation
Step Test Start
Groundwater Level [mbgl]
Coring Depth [mbgl]
13.5
14
14.5
15
15.5
16
16.5
17
17.5
18
70
72
74
76
78
80
14:30
Oct 7, 2022
14:45
15:00
15:15
15:30
15:45
Inside Casing
Outside Casing
TH0410 Coring


Zone 6 CR Test
Packer Inflation
Pump Install
CR Test Start
Groundwater Level [mbgl]
Coring Depth [mbgl]
12
14
16
18
20
22
24
94
96
98
100
102
104
14:45
Oct 10, 2022
15:00
15:15
15:30
15:45
16:00
16:15
16:30
16:45
17:00
17:15
17:30
17:45
18:00
18:15
18:30
Inside Casing
Outside Casing
TH0410 Coring

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The British Geological Survey Library holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://of-ukrinerc.olib.oclc.org/folio/.

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