# Data release and initial interpretation of test pumping of boreholes at the Glasgow UK Geoenergy Observatory

UK Geoenergy Observatories

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BRITISH GEOLOGICAL SURVEY

UK GEOENERGY OBSERVATORIES PROGRAMME

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# Data release and initial interpretation of test pumping of boreholes at the Glasgow UK Geoenergy Observatory

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Test pumping in GGA08 at the Glasgow Observatory.

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# Summary

This report describes a programme of test pumping carried out on ten boreholes at the UK Geoenergy Observatory (Glasgow Observatory), Cuningar Loop in Rutherglen, Greater Glasgow in January and February 2020. It details the types of test undertaken, the datasets generated and how these datasets can best be used dependent on the data analysis being undertaken. Drawdown data for pumping boreholes and observation boreholes is presented in graphical form, together with an initial interpretation of test pumping results.

The main objectives of the pumping tests were to obtain data regarding: the physical aquifer properties, in particular transmissivity, of the different hydrogeological zones at the Observatory; to investigate borehole efficiency; and to gather data on the connectivity between different hydrogeological zones.

Successful step tests and five hour constant rate tests were carried out in all boreholes except GGB04 in the superficial deposits where a slug test was carried out instead due to the low yield. Time series data of water levels, temperature and conductivity were collected in the pumping and observation boreholes. The constant rate tests were analysed using Jacob's approximation and Theis recovery methods to give a preliminary interpretation of the transmissivity. The drawdown curves were visually inspected to help identify borehole inefficiency and significant responses from observation boreholes to pumping.

Transmissivity values for the superficial deposits are highly variable (0.04 and 225 $m^2$/day), the two bedrock test pumping responses also gave very different results (2.6 and 580 $m^2$/d), three boreholes in the Glasgow Upper mine workings give a consistent transmissivity estimate (950 – 1020 $m^2$/d) and the two boreholes intersecting the Glasgow Main mine workings give transmissivity estimates of 2000 – 2100 $m^2$/d.

There is clear connectivity between the bedrock boreholes and the Glasgow Upper mine workings during pumping, with strong responses between boreholes from most pumping tests. There is also clear connectivity within the individual mine workings. There is also evidence of some connectivity between the Glasgow Main mine workings and the Glasgow Upper mine workings.

There is an upward vertical hydraulic gradient at the Observatory, with rest water levels approximately 10 – 11 m relative to Ordnance Datum (OD) in the Glasgow Main mine workings; 9 – 10 m OD in the Glasgow Upper mine workings and bedrock boreholes, and 3 – 4.5 m OD in the superficial deposits.

Temperature measurements from observation boreholes monitored throughout the testing period show that the groundwater in the deeper Glasgow Main mine workings is warmer than the shallower workings, bedrock or superficial deposits with a value generally 12.4 – 12.8 ºC. Temperatures in the Glasgow Upper mine workings and the overlying bedrock are broadly similar, 11.5 – 12 ºC, apart from GGA04.

Specific electrical conductivity measurements from the mine workings and bedrock boreholes lie in the range 1350 - 1600 $\mu Scm^{-1}$ @25 ºC and are typical of measurements from water boreholes within mined Carboniferous rocks (MacDonald et al. 2017). The conductivity of the superficial deposits is high and variable at 1000 – 1400 $\mu Scm^{-1}$ @25 ºC, although within the range of those found in Glasgow (Ó Dochartaigh et al. 2018).

# 1 Introduction

## 1.1 OBJECTIVE OF THIS REPORT

This report provides information from a programme of test pumping carried out on ten boreholes at the UK Geoenergy Observatory (Glasgow Observatory), Cuningar Loop in Rutherglen, Greater Glasgow (Figure 1) in January and February 2020.

Further information on the boreholes can be found in Barron et al. (2020 a, b), Elsome et al. (2020), Monaghan et al. (2020 a, b), Shorter et al. (2020 a, b), Starcher et al. (2020 a, b) and Walker-Verkuil et al. (2020 a, b). Borehole information packs are available at https://ukgeos.ac.uk/data-downloads.

This report describes the test pumping data files released and includes an initial interpretation of test pumping results.

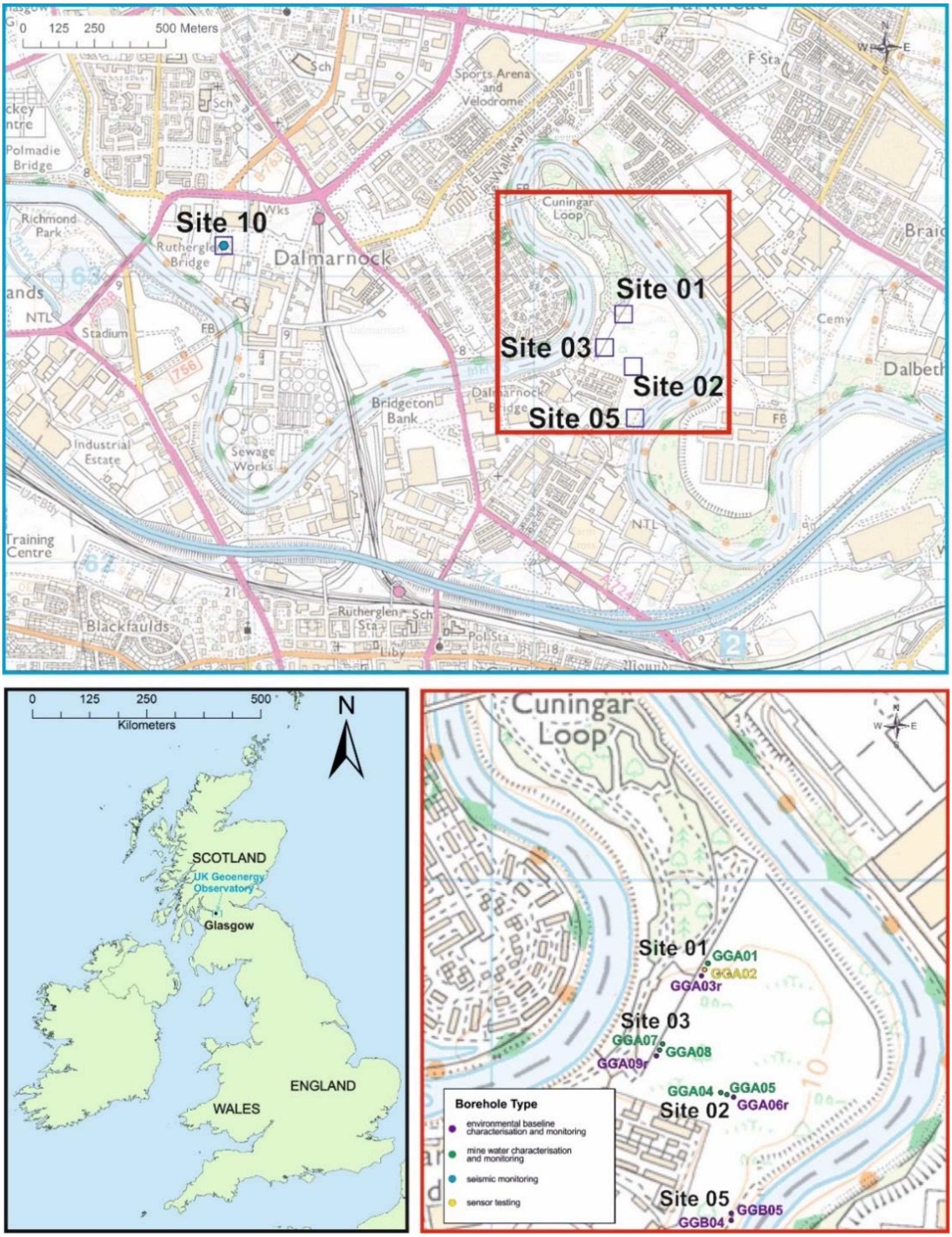


**Figure 1 Location map of the Glasgow Observatory, including detail of the mine water and environmental baseline boreholes at Cuningar Loop (in red box). Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved [2020] Ordnance Survey [100021290 EUL].**

## 1.2 CITATION GUIDANCE

| **_Any use of the data should be cited to:_** |
|---|
| DOI: K M Shorter, A M MacDonald, B E Ó Dochartaigh, J Elsome, S Burke (2021) UKGEOS Glasgow Hydrogeological Test Pumping Data Release. NERC EDS National Geoscience Data Centre. (Dataset). https://doi.org/10.5285/315c716a-8bc5-4071-ad67-62da22e4b6ab |
| **_and this report cited as:_** |
| Shorter K M, MacDonald A M, Dochartaigh B E Ó, Elsome J, Burke S. 2021. Data release and initial interpretation of test pumping of boreholes at the Glasgow UK Geoenergy Observatory. British Geological Survey Open Report, OR/21/016. |

## 1.3 SUMMARY OF GLASGOW OBSERVATORY AND THE TESTED BOREHOLES

### 1.3.1 Overview of the Glasgow Observatory

The Glasgow Observatory is located at Dalmarnock in the east of Glasgow City and the Cuningar Loop area of Rutherglen, South Lanarkshire (Figure 1). The aims of the Observatory include de-risking key technical barriers to low-temperature shallow mine-water heat energy and heat storage from groundwater in former coal mine workings; and providing environmental characterisation and monitoring to assess any change in ambient conditions.

The Glasgow Observatory includes 12 boreholes (Figure 1). Five are *mine water boreholes* that are drilled into, and screened against, individual former mine workings; five are *environmental baseline monitoring boreholes* that are drilled into, and screened against, targeted zones in bedrock above the Glasgow Upper mine working, or in superficial deposits overlying bedrock. Two boreholes were not available for hydrogeological testing: borehole GGA02 is a fully cased sensor testing borehole and GGC01 is a seismic monitoring borehole a few kilometres away at Dalmarnock. Table 1 summarises the 12 boreholes in the Glasgow Observatory.

**Table 1 Summary of sites, boreholes and lithologies of the 12 boreholes in the Glasgow Observatory**

| Site name | Borehole name | Borehole Type | Lithology screened |
|---|---|---|---|
| Site 1 | **GGA01** | Mine water | Glasgow Upper mine working |
| Site 1 | **GGA02** | Sensor testing | Not screened |
| Site 1 | **GGA03r** | Environmental baseline | Bedrock |
| Site 2 | **GGA04** | Mine water | Glasgow Upper mine working |
| Site 2 | **GGA05** | Mine water | Glasgow Main mine working |
| Site 2 | **GGA06r** | Environmental baseline | Superficial deposits |
| Site 3 | **GGA07** | Mine water | Glasgow Upper mine working |
| Site 3 | **GGA08** | Mine water | Glasgow Main mine working |
| Site 3 | **GGA09r** | Environmental baseline | Superficial deposits |
| Site 5 | **GGB04** | Environmental baseline | Superficial deposits |
| Site 5 | **GGB05** | Environmental baseline | Bedrock |
| Site 10 | **GGC01** | Seismic monitoring | Not screened |

Boreholes GGA02 and GGC01 were not included in the test pumping carried out at the Glasgow Observatory.

### 1.3.2 Outline of the tested boreholes

Table 2 summarises the 10 boreholes that were included in the test pumping and the dates testing was carried out. The screened target zone in each of the ten boreholes is between 1.8 and 3.6 m long. Above the screened section the remainder of each borehole is cased off to prevent inflow to the borehole from any other zone and the borehole annulus is sealed and cemented.

**Table 2 Description of test zone (screened section) and dates of test pumping carried out on the Glasgow Observatory boreholes**

| Borehole | Aquifer unit | Description of screened section (test zone) | Date of step drawdown test | Date of constant rate test | Date of falling/rising head test |
|---|---|---|---|---|---|
| GGA01 | Glasgow Upper mine working | Overlying sandstone roof and Glasgow Upper mine working waste | 14/01/2020 | 15/01/2020 | - |
| GGA03r | Bedrock | Sandstone below rockhead, above Glasgow Upper mine working | 17/01/2020 | First test: 20/01/2020<br>Second test: 18/02/2020 | - |
| GGA04 | Glasgow Upper mine working | Overlying sandstone roof and Glasgow Upper mine working position coal and mudstone | 27/01/2020 | 28/01/2020 | - |
| GGA05 | Glasgow Main mine working | Overlying sandstone roof and Glasgow Main mine working void, to mudstone floor | 22/01/2020 | 23/01/2020 | - |
| GGA06r | Superficial | Sand and gravel | 30/01/2020 | 31/01/2020 | - |
| GGA07 | Glasgow Upper mine working | Overlying mudstone and Glasgow Upper mine working, coal pillar and void | 06/02/2020 | 07/02/2020 | - |
| GGA08 | Glasgow Main mine working | Overlying sandstone/siltstone and Glasgow Main mine roadway (void and waste) | 03/02/2020 | 04/02/2020 | - |
| GGA09r | Superficial | Sand and gravel | 10/02/2020 | 11/02/2020 | - |
| GGB04 | Superficial | Sand and gravel | - | - | 17/02/2020 - 19/02/2020 |
| GGB05 | Bedrock | Sandstone below rockhead, above Glasgow Upper mine working | 13/02/2020 | 14/02/2020 | |

Figure 2 shows a simplified pre-drill cross-section of the geology across the Glasgow Observatory. Depicted in the figure are Site 1 and Site 3 which include boreholes that enter the superficial deposits, bedrock, Glasgow Upper and Glasgow Main mine workings.

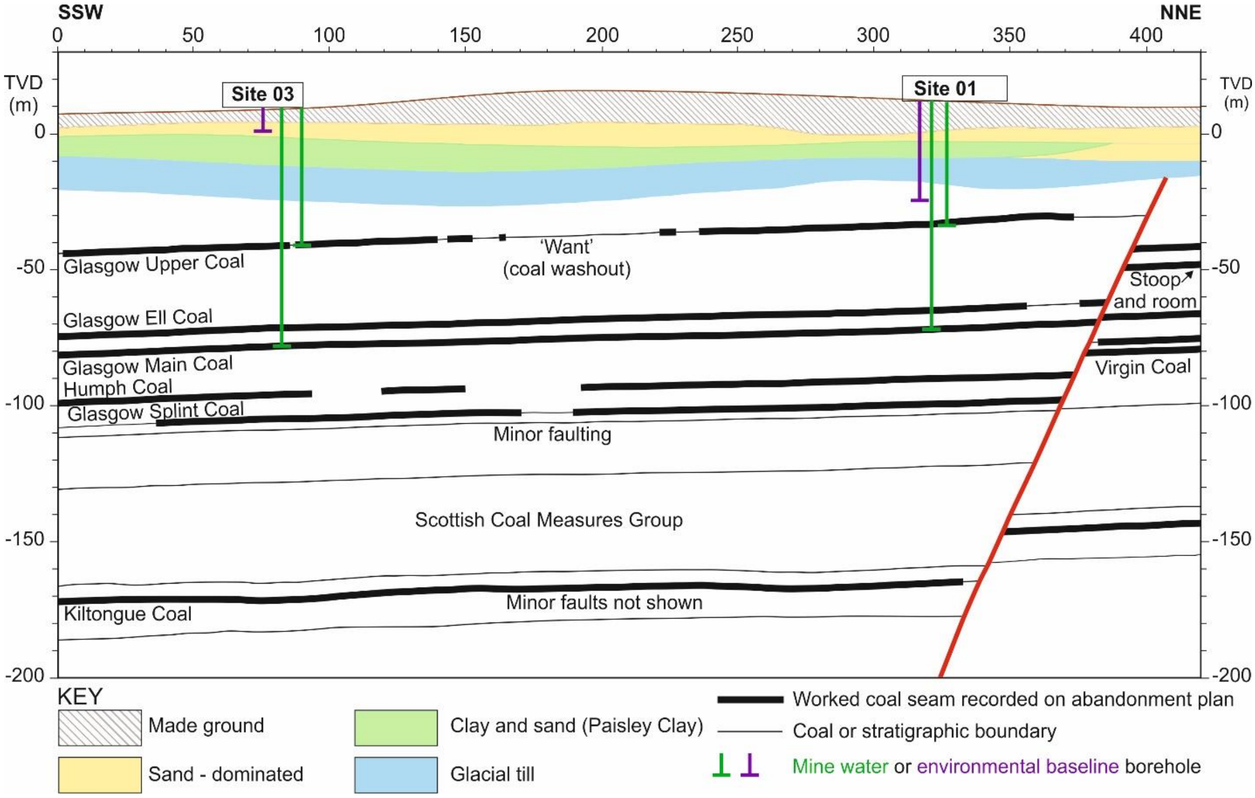


**Figure 2 Simplified cross-section of geology and target units for the boreholes at Sites 1 and 3 at the Glasgow Observatory**

### 1.3.3 Distance matrix

The 10 boreholes that formed part of the test pumping regime carried out in January and February 2020 at the Glasgow Observatory were all located within half a kilometre of each other. Table 3 summarises the straight line horizontal distance between the boreholes at surface and Table 4 summarises the vertical distance between the top of the screened section in each borehole.

**Table 3 Straight line horizontal distances between each borehole in metres**

| m | GGA01 | GGA03r | GGA04 | GGA05 | GGA06r | GGA07 | GGA08 | GGA09r | GGB04 | GGB05 |
|---|---|---|---|---|---|---|---|---|---|---|
| **GGA01** | | 20 | 191 | 195 | 200 | 135 | 145 | 155 | 379 | 369 |
| **GGA03r** | 20 | | 195 | 179 | 185 | 115 | 125 | 135 | 362 | 352 |
| **GGA04** | 191 | 174 | | 10 | 20 | 111 | 110 | 109 | 188 | 178 |
| **GGA05** | 195 | 179 | 10 | | 10 | 121 | 119 | 119 | 185 | 175 |
| **GGA06r** | 200 | 185 | 20 | 10 | | 130 | 129 | 129 | 181 | 171 |
| **GGA07** | 135 | 115 | 111 | 121 | 130 | | 10 | 20 | 278 | 269 |
| **GGA08** | 145 | 125 | 110 | 119 | 129 | 10 | | 10 | 272 | 263 |
| **GGA09r** | 155 | 135 | 109 | 119 | 129 | 20 | 10 | | 266 | 257 |
| **GGB04** | 379 | 362 | 188 | 185 | 181 | 278 | 272 | 266 | | 10 |
| **GGB05** | 369 | 352 | 178 | 175 | 171 | 269 | 263 | 257 | 10 | |

**Table 4 Vertical distance between the top of the screened section in each borehole in metres**

| m | GGA01 | GGA03r | GGA04 | GGA05 | GGA06r | GGA07 | GGA08 | GGA09r | GGB04 | GGB05 |
|---|---|---|---|---|---|---|---|---|---|---|
| GGA01 | | 8 | 3 | 39 | 33 | 6 | 40 | 33 | 35 | 2 |
| GGA03r | 8 | | 10 | 47 | 25 | 14 | 48 | 26 | 27 | 5 |
| GGA04 | 3 | 10 | | 36 | 36 | 4 | 38 | 36 | 37 | 5 |
| GGA05 | 39 | 47 | 36 | | 72 | 33 | 1 | 72 | 74 | 41 |
| GGA06r | 33 | 25 | 36 | 72 | | 39 | 73 | 0 | 2 | 31 |
| GGA07 | 6 | 14 | 4 | 33 | 39 | | 34 | 39 | 41 | 9 |
| GGA08 | 40 | 48 | 38 | 1 | 73 | 34 | | 74 | 75 | 43 |
| GGA09r | 33 | 26 | 36 | 72 | 0 | 39 | 74 | | 1 | 31 |
| GGB04 | 35 | 27 | 37 | 74 | 2 | 41 | 75 | 1 | | 32 |
| GGB05 | 2 | 5 | 5 | 41 | 31 | 9 | 43 | 31 | 32 | |

## 1.4 RATIONALE FOR TEST PUMPING

A borehole pumping test is a structured test in which groundwater is pumped from the borehole at known rates for specified time periods, and at the same time the groundwater levels in the pumping borehole and any observation boreholes are monitored in order to observe the response to pumping. After the pump is switched off, the groundwater levels continue to be monitored until recovery to pre-pumped level (the rest water level).

The primary objective of test pumping is to obtain data about physical aquifer properties, in particular the transmissivity and storage capacity of the hydrogeological zones targeted by a borehole – i.e. the zone(s) that the borehole is screened against and which, therefore, contribute groundwater inflows to the borehole. Secondary objectives include obtaining information about the borehole efficiency and connectivity between different hydrogeological zones that may be present at different depths or laterally. The resulting data are vital in order to develop the hydrogeological understanding of the groundwater system, including, in this case, the mine water system; groundwater in the surrounding bedrock and overlying superficial deposits; and interactions between these hydrogeological zones and surface waters. This understanding is necessary in order to design and operate an effective mine water heat resource.

Test pumping was carried out at the Glasgow Observatory:

(i) to establish hydraulic characteristics of the aquifer;

(ii) to establish borehole performance and efficiency; and

(iii) to give an indication of hydraulic connectivity and groundwater flow behaviour between individual boreholes and target aquifer horizons (mine workings, bedrock, and superficial deposits) across the Observatory.

# 2 Methodology for test pumping

## 2.1 OVERVIEW

The test pumping programme was carried out after all boreholes had been drilled, installed with Boode® borehole casing (henceforth referred to as borehole casing) and cleaned. There was a minimum of five days between borehole cleaning and the test pumping starting. More details on borehole drilling, completion and cleaning are in the borehole data packs referred to in Section 1.1.

The programme was started on 14 January 2020 and completed on 21 February 2020. A sub-contractor, Drilcorp, were commissioned to carry out the test pumping. The Drilcorp team included a hydrogeologist to manage the test pumping alongside BGS hydrogeologists. Two types of tests were carried out on nine of the boreholes: a step drawdown test (SDT) and a constant rate test (CRT).

For nine of the ten boreholes, testing was carried out over two days: a SDT on the first day, and a CRT on the second day. The pump was installed in the borehole to be tested at least one day before the start of the SDT, to allow for setting up and calibrating the initial or constant pumping (flow) rate. Following pump installation and setup, the borehole was left overnight to recover to rest water level before the start of the SDT.

A SDT was carried out first, in order to:

- Investigate borehole performance under controlled variable flow rates;
- Establish yield-drawdown relationships in the borehole;
- Allow selection of an appropriate pumping rate for a CRT; and
- Allow estimations of borehole efficiency.

Suitable flow rates for each step were selected based on evidence collected during drilling and borehole cleaning. Each step was one hour long, except for the SDT on GGA03r. For five tests, five pumping steps were carried out, followed by monitoring the recovery of the borehole water level. On GGA04, GGA06r and GGA09r, four steps were carried out followed by monitoring the recovery of the borehole water level. For GGA03r a sustainable flow rate could not be achieved throughout the SDT resulting in four steps being carried out of varying lengths. The resultant drawdown during these four steps was too great causing the pump to cut off. These are detailed further in Section 5.1.

Following the SDT, the groundwater level in the borehole was allowed to recover fully overnight before a CRT was carried out to allow estimation of aquifer properties. A suitable constant flow rate was selected based on evidence from the SDT and on limitations imposed by waste water disposal licencing (See Section 2.1.1). For each test the borehole was pumped for five hours and recovery was manually monitored for a further one hour, whilst the data logger monitored recovery for up to 24 hours after the end of CRT.

Each SDT and CRT was carried out using an electrical submersible pump of suitable capacity to provide the desired pumping rate(s). The pump used for each test is specified in Table 6 to Table 15 below. The water level in the pumped borehole was manually monitored by BGS staff and digitally monitored by a data logger (more information in Section 2.2.2). An example of the field sheet used to manually monitor the water level can be found in Appendix A. Groundwater pumped from each borehole first went to a settling tank to allow sediment to settle out of suspension. The water was then pumped from the settling tank to a discharge pipe that discharged into the River Clyde. The discharge (CAR) licence allowed for a maximum of 369 $m^3$ to be discharged daily at a maximum rate of 20 L/s, further information on this is in Section 2.1.1.

On one borehole only (GGB04), a third type of test was carried out: a slug (falling/rising head) test due to very low yield observed on borehole cleaning meaning that a SDT and CRT were not considered feasible.

A summary of the test pumping carried out on each borehole is provided at the start of each borehole section. Details of tests and resulting data for each borehole are in the relevant sections, below. Appendix B lists the associated digital files of test pumping data available in this data release.

### 2.1.1 Limitation of the CAR licence

The maximum daily discharge volume of 369 $m^3$ and maximum discharge rate of 20 L/s stated in the CAR licence imposed limits on the test pumping of the mine water boreholes. An upper limit of 25 L/s in the SDT could only be maintained for one hour in order to remain within the CAR licence and limits of the storage facilities available on-site. Similarly, the mine water boreholes could be pumped at a maximum of 20 L/s for five hours during the CRT.

## 2.2 FIELD PARAMETERS MONITORED

### 2.2.1 Flow rate

The pumping (pump flow) rate during each step drawdown and constant rate test was continuously measured using an inline flow meter. The two types of meter used were:

- An Endress+Hauser Promag 50P1H DN100 electromagnetic flowmeter (Figure 3a) on five mine water boreholes which measured instantaneous pumping rate and cumulative pumped volume and;
- A Maddalena DS-TRP TCM-142/08-4604 DN40 multi-jet flowmeter (Figure 3b) on the four environmental baseline monitoring boreholes, which measured cumulative pumped volume.

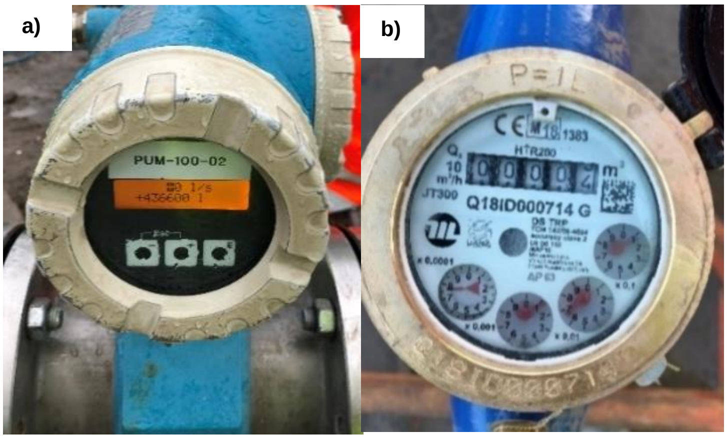


**Figure 3a) Endress + Hauser Promag flow meter. b) Maddalena DS-TRP flow meter**

Readings from the flowmeter were made at regular intervals and recorded by the Drilcorp hydrogeologist in the field.

### 2.2.2 Water level

Throughout each step drawdown, constant rate and slug test – including pumping and recovery phases – groundwater levels in the tested borehole were recorded at 15 second intervals using a Solinst Levelogger® Edge 3001 LT F300/M100 pressure transducer (data logger) installed by Drilcorp in the tested borehole. This data logger measured absolute water pressure in the borehole, which was converted to borehole water level by compensating for atmospheric pressure measured by a Solinst Barologger Edge Model 3001 LT F5/M1.5 barometric data logger, installed by Drilcorp 0.5 m above the base of the borehole manhole chamber. The borehole was vented throughout the tests. This data logger was installed in a temporary uPVC dip tube, 32 mm in diameter and slotted at its base.

Manual measurements of borehole water levels were also made at set intervals throughout the tests using a manual dipper in the same dip tube as the data logger. Data were recorded manually in the field and were used as a check on the data logger measurements. The time intervals at which manual groundwater level dip measurements were recorded are shown in the example field data capture forms in Appendix A. All manual groundwater level measurements were made from, and all data logger groundwater level measurements were calculated to, the same datum: the top of the temporary dip tube. For each test, the difference between the height of the top of the dip tube and the concrete base of the borehole manhole chamber was measured.

During each test, nine other boreholes in the Glasgow Observatory were used to observe the spatial response of groundwater levels at various distances from the pumped borehole, both in the same hydrogeological zone as the pumped borehole, and in the other targeted hydrogeological zones. Each borehole was installed with an Aquistar CT2X cableless conductivity logger (data logger) that recorded absolute water pressure in the borehole at five minute intervals continuously throughout each test and during the intervening periods. This was converted to borehole water level by compensating for atmospheric pressure measured by an Aquistar barometer: PT2X, installed on-site. Manual measurements of borehole water level in these boreholes were also made at occasional intervals using a manual dipmeter.

### 2.2.3 Physico-chemical parameters

Field measurements of selected physico-chemical parameters (groundwater temperature, specific electrical conductivity (SEC), pH, redox potential and dissolved oxygen concentration) were made during each step and constant rate test. Details of the types of probes and meters used to measure these parameters are summarised in Table 5.

**Table 5 Summary of the meters and probes used to measure physico-chemical parameters during test pumping**

| Parameter measured | Type of meter | Type of probe | Units measured |
|---|---|---|---|
| Specific electrical conductivity | Mettler Toledo Seven2Go Pro S7 | Mettler Toledo Epoxy/Graphite Conductivity Probe: InLab 738-ISM | $\mu Scm^{-1}$ automatically corrected to a reference temperature of 25°C |
| pH | Mettler Toledo SevenGo Pro S8 | Jenway gel probe | - |
| Redox potential | Mettler Toledo SevenGo Pro S8 | VWR Electrode Redox Gel BNC | mV |
| Dissolved oxygen | Mettler Toledo Seven2Go Pro S9 | InLab OptiOx optical DO sensor | mg/L |
| Temperature | Hanna HI-93510 Thermister Thermometer | Hanna HI-762BL stainless steel probe | °C |

Temperature data measured by the data logger installed in the pumped borehole is presented in Section 8. The data loggers installed in the observation boreholes measured conductivity and temperature, this data is briefly summarised in Section 8 but further analysis was outside the scope of this report.

Groundwater samples for laboratory analysis of bicarbonate concentration, selected hydrogeochemical, stable isotope and dissolved gas parameters were collected during each constant rate test. Details of field physico-chemical parameters and field bicarbonate concentrations measured and groundwater chemistry are provided in a separate data release.

## 2.3 DATA QUALITY CONTROL

The pumping rate was manually checked regularly throughout each test by the Drilcorp hydrogeologist, this is recorded in the Drilcorp Excel® files for each borehole. Data from the data logger installed in the pumping borehole and the Barologger was downloaded by the Drilcorp hydrogeologist after the completion of both the SDT and CRT at each borehole. After the tests the field data was collated, digitised and provided to BGS by Drilcorp.

Manual water level data was collected using a field sheet with predefined timings, ensuring consistency in data collection during test pumping (Appendix A). Manual data was digitised by BGS following the test pumping.

Data from the data loggers installed in the observation boreholes and Aquistar barometer: PT2X were downloaded at the end of the test pumping period. Downhole pressure data were compensated for atmospheric pressure, and were converted to water level in depth below datum (See Section 2.2.2). The data were collated in Excel® and are provided in the data release (https://doi.org/10.5285/315c716a-8bc5-4071-ad67-62da22e4b6ab).

All data were checked for errors, primarily by graphical plotting to identify any outliers.

### 2.3.1 Datums

#### 2.3.1.1 Ongoing borehole construction

The Glasgow Observatory was an active construction site throughout the test pumping period, with work being carried out to cut borehole casings down to final height and complete the borehole headworks and manhole chambers. All datum changes recorded during the construction period have been taken into account in the analysis of the pump test data, however remaining discrepancies in water level heights indicate that absolute groundwater levels may only be accurate to within 10 – 30 cm. The relative data for each test measured by the Solinst data logger, however, should be accurate within approximately 5 cm (Solinst 2020). The relative data for each observation borehole measured by the CT2X data logger, should be accurate within approximately 1 cm (Seametrics 2019).

#### 2.3.1.2 During test pumping

A 32 mm uPVC dip tube with a slotted section at its base was inserted into each borehole during the test pumping (Figure 4). A data logger was placed down the dip tube and manual water level measurements were also taken within the dip tube. Data logger water levels were originally measured from below the final floor level (FFL) of the manhole chamber and reported from this datum in the files provided by Drilcorp (see Appendix B). Manual dip water levels were measured from the top of the dip tube. A measurement of the height of the dip tube above the chamber floor is provided in the data logger files provided by Drilcorp. For consistency, all pumping borehole water levels (data logger and manual water levels) have been corrected to the height of the dip tube for each borehole *during test pumping*.

Figure 4 shows a general set up of equipment in the borehole for test pumping.

#### 2.3.1.3 Datums for observation boreholes

Water level measurements from the observation boreholes were also subject to changes in datum levels during construction. Appendix C details which datum to use for which data and corrected depth to water and water height data is provided in each individual borehole observation data file. However, it should be noted that although the change in groundwater levels within each borehole (measured by the Aquistar CT2X data logger) are accurate to within 1 cm, the absolute groundwater levels, and therefore comparison of levels with other boreholes, are less certain and should only be considered accurate to within 10 – 30 cm.

**When using the observation data logger data provided as part of this data pack, please refer to Appendix C for the correct datums to use for each borehole data set for absolute groundwater level.**

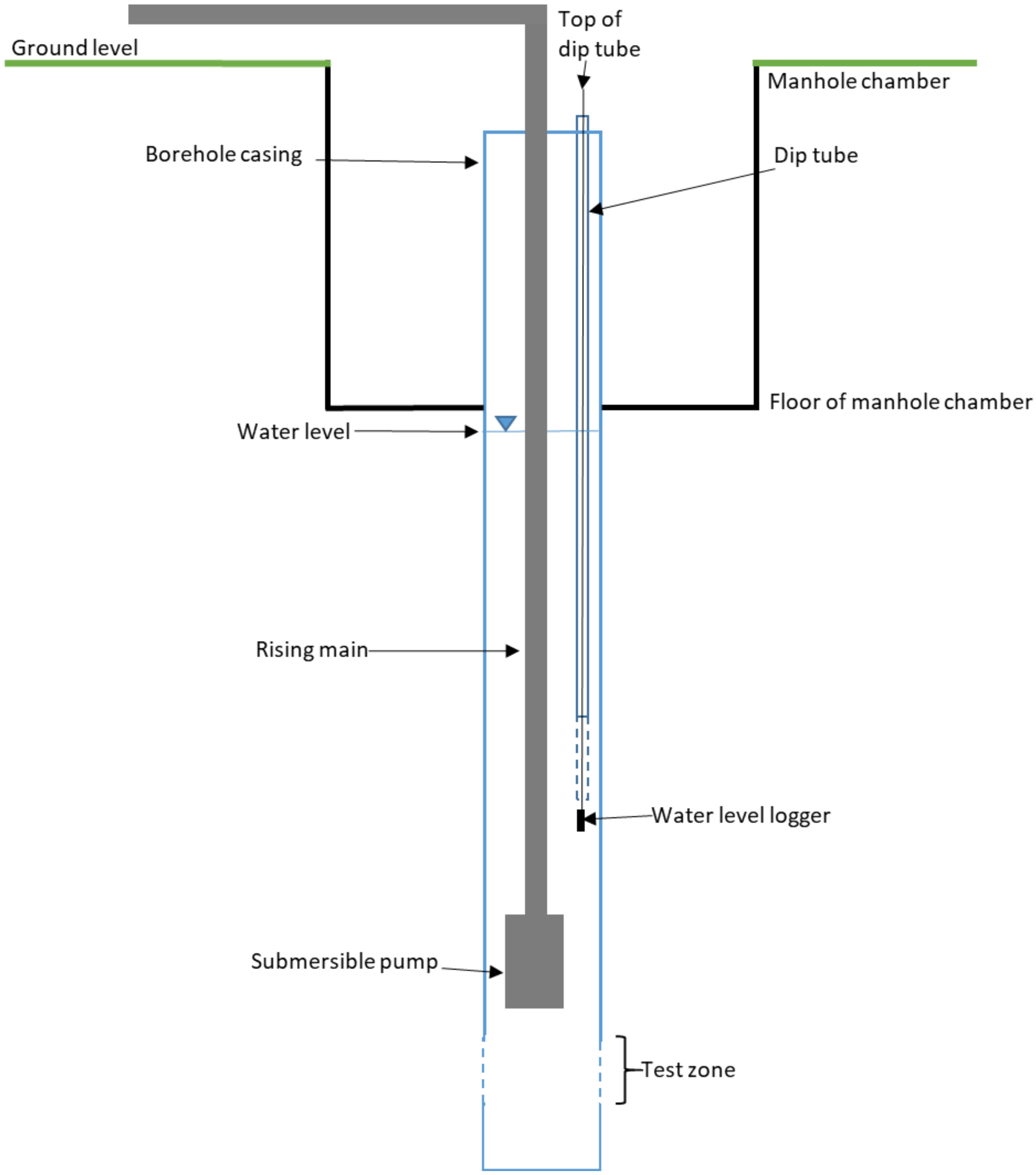


**Figure 4 Borehole design schematic including equipment used during test pumping. Made ground and superficial deposits steel casings are installed within the boreholes but not shown here for simplicity.**

### 2.3.2 Conversion of Aquistar CT2X data logger data

The Aquistar CT2X data logger installed into all observation boreholes during test pumping measured:

- Pressure (mbar)
- Temperature (°C)
- Conductivity (µScm$^{-1}$ @25°C)

The logger also reports salinity (PSU) and total dissolved solids (TDS) in mg/L calculated using the conductivity data. Once the data was downloaded, the following series of calculations were carried out on the pressure data.

**Compensation of water pressure (mbar $H_2O$) for atmospheric pressure (mbar):**

**Equation 1**

$$Water\ pressure\ (mbar\ H_2O) = Logger\ Pressure\ (mbar) - Barometric\ pressure\ (mbar)$$

**Conversion of water pressure to head of water above sensor (m):**

**Equation 2**

$$Head\ of\ water\ \ (m) = \ Water\ Pressure\ (mbars\ H_2O)\ x\ 0.010197$$

**Conversion of head of water above sensor to water level below datum.**

**Equation 3**

$$Water\ level\ (mbd) = Depth\ of\ sensor\ (mbd) - head\ of\ water\ (m)$$

The depth of the sensor was periodically adjusted to allow for vertical movement or drift over time, and to optimise the fit between the logged and manual water level data. Appendix C details changes to sensor deployment depths throughout the test pumping period. The water level depth was measured manually most times that the sensor was removed, and also periodically to validate and check against sensor drift. Please refer to Section 3.2.1for further information on how to use the data provided as part of this data pack.

## 2.4 RISK MANAGEMENT DURING TEST PUMPING

The flow rates proposed for each stage of the step drawdown test were set with regard to limiting the increase in drawdown in the mine water boreholes. This was done to reduce the risk of a sudden increase in turbulent flow and/or drawdown that might lower the pumped water level down to the borehole screen interval.

To mitigate the risk of damage to the borehole or mine working that could hypothetically be caused by drawdown of water level to below the Glasgow Upper mine working, a pre-determined level for maximum drawdown was set for each borehole. This was that the water level should remain above the Glasgow Upper mine workings, and not fall below 50% of the initial water column depth. Monitoring carried out to ensure the maximum drawdown limits were not exceeded.

The selected flow rate for each constant rate test was slightly below the maximum rate that the borehole could sustain. Ideally, the flow rate was chosen to allow accurate calculation of the relationship between flow rate and drawdown without the risk of breaching the pre-determined maximum allowable drawdown (British Standard 2003).

At GGA03r, the test was continued beyond the original plan, due to the low flow rates at which the test was carried out. Drawdown occurred greater than 50% of the starting water depth and the test was stopped when the water level was within 5 m of the pump depth.

## 2.5 INITIAL INTERPRETATION OF TEST PUMPING DATA

### 2.5.1 Type-curve matching analyses

Where possible, a preliminary analysis has been completed to derive estimated values for aquifer transmissivity by type curve matching to the constant rate test data using:

(i) The Jacob straight line method for drawdown data; and

(ii) The Theis recovery method for recovery data.

Each of these techniques relies on a set of assumptions about the aquifers, boreholes and tests that are rarely wholly matched in reality, and were not wholly matched for any of the tests on the Glasgow Observatory boreholes. Calculation of transmissivity from pumping boreholes using Jacob's approximation and Theis recovery method are well- used techniques (Kruseman and de Ridder 1970), and can give accurate results so long as the time of pumping is sufficient to overcome the effects of well storage ($t > 25\ r_c^2/T$, a condition met for all the tests). A large numerical study of 600 tests by Halford et al (2006) indicated estimates of transmissivity within

20% of “true” values. Theis recovery data are often preferred as small variations in pumping rate are smoothed out, and uncertainties due to non-linear well losses reduced.

For more information on the theoretical models on which each technique is founded see the papers by Cooper-Jacob (1946) and Theis (1935) and further explanation in Kruseman and de Ridder (1970). Whilst a systematic approach using these analyses has been conducted, further analysis and interpretation of the test pumping data from these boreholes is required and recommended.

#### 2.5.1.1 JACOB’S STRAIGHT-LINE METHOD FOR DRAWDOWN DATA

Jacob’s straight –line method for drawdown data is outlined in Kruseman and de Ridder (1970). The drawdown data is plotted with drawdown (s) on the y-axis and log time (log t) on the x-axis. Transmissivity is then derived using the following equation:

**Equation 4**

$$T = \frac{2.30Q}{4\pi\Delta s}$$

Where: $T$ = transmissivity of aquifer ($m^2$/d), $Q$ = discharge rate ($m^3$/day), $\Delta s$ = change in drawdown in metres measured over one log cycle.

The change in drawdown ($\Delta$s) is measured by drawing a best fit line excluding early data. This straight line is then used to measure the change in drawdown over one log cycle. Further analyses may lead to a broader range of transmissivity data.

#### 2.5.1.2 THEIS METHOD FOR RECOVERY DATA

Theis’ method (1935) for recovery data is outlined in Kruseman and de Ridder (1970). The recovery data is plotted onto a semi-log graph with residual drawdown (s’) on the y-axis and Log (t/t’) on the x-axis where t is the time since pumping started and t’ is the time since pumping stopped. Transmissivity is then derived using Equation 4 outlined above.

#### 2.5.1.3 NOTE ON TRANSMISSIVITY ESTIMATES

For this preliminary analysis of the test results, only data from the pumped boreholes have been used in the derivation of transmissivity values using the Jacob’s (1946) and Theis (1935) methods. Further analysis using the observation borehole data is recommended to better constrain the aquifer properties.

### 2.5.2 BGS PT

BGS PT is a set of two programmes (Barker & Macdonald 2000):

1. PTFIT: for analysing pumping tests
2. PTSIM: simulates time-drawdown behaviour for a specified set of parameters.

Although developed originally for use on large diameter boreholes (>1 m), these programmes account for well storage and can be used for any diameter borehole. For the purposes of this report, PTFIT was utilised to analyse the slug tests carried out on GGB04 as the curve type analyses outlined in Section 2.5.1 could not be applied to this borehole.

PTFIT fits a generalised well function to a set of observed drawdown data by automatically altering the aquifer parameters and accounts for well storage (Barker 1988; Barker & Macdonald 2000). For GGB04, PTFIT was used to calculate preliminary transmissivity values from the slug tests.

# 3 Data Presentation

## 3.1 DATA PRESENTED IN THIS REPORT

Data presented in Sections 4 - 7 are the results of the test pumping for each borehole. Each borehole section includes the following results:

- Summary table of test pumping for each borehole
- Graphs of the manually measured water level and data logger for the step drawdown test (SDT) and constant rate test (CRT)
- Graphs of the data logger water levels in the observation boreholes for the SDT and CRT of each borehole
- Graphed data used to derive the preliminary transmissivity values using the Jacob (1946), Theis (1935) or BGS PT (Barker & Macdonald 2000) methods.

The graphs of observation data display water level data from up to nine observation boreholes. Not all boreholes were accessible to place a data logger in during all the test pumping and therefore there may be fewer boreholes shown on some graphs. **For clarity, observation boreholes that showed no discernible water level change during the test pumping were excluded from the observation borehole graph.** Also, as the site was still under active construction, there may be some discrepancies in the datum for the observation borehole data, see Appendix C for further details. A graph showing water level change over the whole test pumping period is provided in Section 9.

The report is set out based on borehole lithology, starting with the shallowest boreholes on-site (superficial deposits boreholes) and proceeding towards the deepest boreholes (Glasgow Main mine working).

Some preliminary discussion and interpretation of the data is provided in Section 9.

## 3.2 DATA PRESENTED IN DATA FILES

Data files being released alongside this report fall into one of four categories:

1. Digital files provided by BGS covering the data collected during the test pumping of each borehole
    - Two files are provided for each borehole one file for the data collected during the SDT and another for the CRT.
    - In the case of GGB04 there is a file for the falling head test and a file for the rising head test.
    - Each of these files consists of three worksheets (except GGA03r CRT file where there are five sheets to cover the second CRT test on this borehole).
    - The first worksheet is 'Metadata' and contains general information on the test pumping carried out.
    - The second sheet is the 'Manual_dip_data' and the third 'Solinst_datalogger_data'
2. Digital files provided by Drilcorp covering the data collected during the test pumping of each borehole
    - Two files are provided for each borehole, one PDF and one Excel® file.
    - The PDF report outlines operational details of the background hydraulic monitoring, SDT and CRT
    - The Excel® file of hydraulic data consists generally of three worksheets.
    - The first worksheet is 'Schedule' and contains general information on both the SDT and CRT.

    - The second worksheet is 'ATMO' containing data from the Solinst barometer data collected by Drilcorp during the test pumping.
    - The third worksheet is 'GG###' containing data from the flow meter, dipmeter (manual dip data provided by BGS) and raw and compensated water level logger data for each borehole.
3. Digital files *provided by BGS* covering the data collected from the CT2X dataloggers *in the observation boreholes*
    - One Excel® file is provided for each borehole and contains one worksheet including: information on all the datum changes that apply to this data, raw, uncompensated data collected from the borehole, calculated data (compensated water levels as 'depth to water' and converted 'height of water'), manually dipped water levels
4. A digital file *provided by BGS* covering the *barometric pressure data* collected from the PT2X barometer
    - One file is provided with one worksheet containing the barometric pressure data and air temperature measured by the PT2X barometer.

A detailed list of all files is provided in Appendix B.

### 3.2.1 How to use the data files

Outlined below are a few starting points for users:

- If the user wishes to analyse the drawdown data for each pumping test:
    - Drawdown data for the pumping boreholes are presented in datafile categories 1 or 2 above.
    - Drawdown data for the observation boreholes is presented in datafile category 3 above.
- If the user wishes to review groundwater level changes across the site corrected to Ordnance Datum (OD):
    - Groundwater level in meters Ordnance Datum (m OD) is presented for each observation borehole in the CT2X datalogger datafiles (category 3 above). **Note:** Whilst all datum changes that were recorded during the construction work, or changes that could be derived from the data have been taken into account in the calculated OD elevation, there may be some discrepancies in water level heights, meaning that absolute groundwater levels may only be accurate to within 10 – 30 cm.
    - Groundwater level data for the pumping borehole for any given test (datafile categories 1 or 2 above) can be converted to m OD as follows:
        - **Category 1:** Water level in m OD = (Final height of floor of manhole chamber (m OD) + height of dip tube above manhole chamber floor (m)) – reported water level (m below top of dip tube)
        - **Category 2:** Water level in m OD = Final height of floor of manhole chamber (m OD) – reported water level (m below final floor level (FFL) [of manhole chamber])
        - **Note:** Only the final height of floor of manhole chamber is reported, this may differ from the height of the floor at the time of test pumping individual boreholes, therefore there may be some discrepancies in water level heights, meaning that absolute groundwater levels may only be accurate to within 10 – 30 cm.
    - Further information on measurement datum points and correction to m OD can be found in Section 2.3.1, 2.3.2 and Appendix C.

Users should be aware that all data for the observation boreholes from the CT2X data loggers has been provided in full. Therefore, if graphing this data there will be spikes in the data when the data logger was removed from the borehole or when it was replaced by the Solinst data logger for the duration of the test pumping at that borehole. The diary in Table 23, Appendix C, provides detail to understand when the CT2X data logger was removed from the borehole. It should be referred to when using this data.

The PT2X barometer recorded data from 14:42 on 16/01/2020 to 15:37 on 20/02/2020. Barometric pressure was also recorded by the Solinst Barologger Edge Model 3001 LT F5/M1.5 barometric data logger, installed by Drilcorp for the duration of the test pumping at each borehole. Barometric pressure from both the PT2X and Solinst Barologger have been used to convert the water pressure data provided in the CT2X logger data files.

**For more detailed information on using the data provided as part of this data pack see Appendix C.**

# 4 Superficial boreholes

Presented in Sections 4.1 to 4.3 are the results of test pumping carried out on the three superficial boreholes of the Glasgow Observatory, GGA06r (located at Site 2), GGA09r (located at Site 3) and GGB04 (located at Site 5).

## 4.1 TEST PUMPING: GGA06R

### 4.1.1 Overview of GGA06r

An overview of the test pumping carried out on GGA06r is in Table 6. Further details on the geology and borehole construction can be found in the GGA06r borehole information pack, which can be downloaded here: https://doi.org/10.5285/ccb1aabe-6062-4cb7-9731-535229316246.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA06r_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGA06r_FINAL.xlsx
- CRT_ GGA06r_FINAL.xlsx
- GGA06r_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA06r provided by Drilcorp is in file:

- GGA06r_Welltesting_Jan-2020_Report_v2.pdf

**Table 6 Overview of test pumping on GGA06r**

| | Step drawdown test | Constant rate test |
|---|---|---|
| Target aquifer horizon | Superficial deposits | |
| Description of screened section | Sand and gravel | |
| Depth of top of screened interval (m below top of borehole casing) | 11.79 | |
| Length of screened section (m) | 1.97 | |
| Type of pump | Grundfos SQ 1-35 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 11.67 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.82 | |
| Height of final floor level of manhole chamber (m OD) | 11.53 | |
| Date of test | 30/01/2020 | 31/01/2020 |
| Start time of pumping | 09:00 | 08:30 |
| End time of pumping | 13:00 | 13:30 |
| Number of pumping steps | 4 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 4 | 5 |
| Average pumping rates for each step (L/s) | 0.12/0.26/0.4/0.62 | 0.52 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 5 | 9 |
| Rest water level (m below top of dip tube) | 8.70 | 8.63 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 9.92 | 9.64 |
| Maximum drawdown during pump test (m) | 1.23 | 1.01 |

### 4.1.2 Manual dip and logger data for GGA06r

During the test pumping, manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A logger also monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 5 and Figure 6 plot the manual and data logger data from the SDT and CRT on GGA06r.

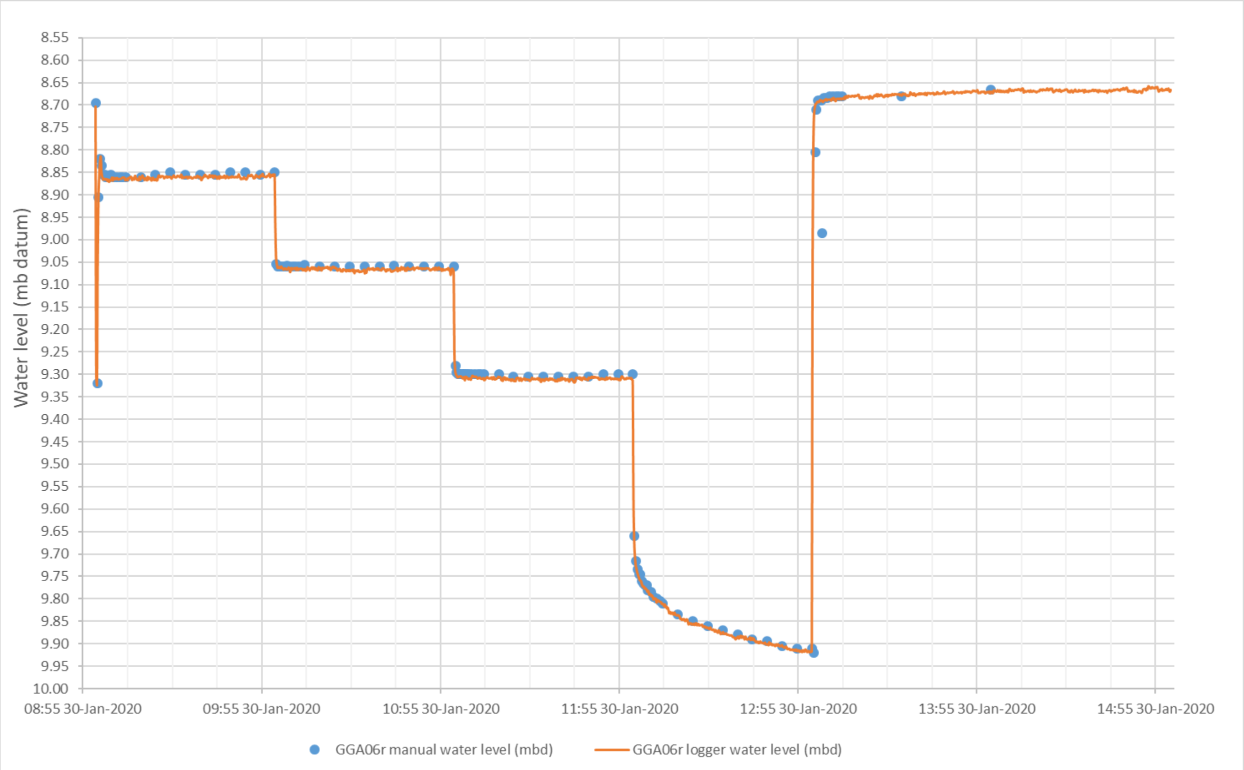


**Figure 5 Borehole water levels in GGA06r during SDT (data logger and manual dip). It took two minutes at the start of the test for the flow rate to be adjusted to the correct stable rate for the first step.**

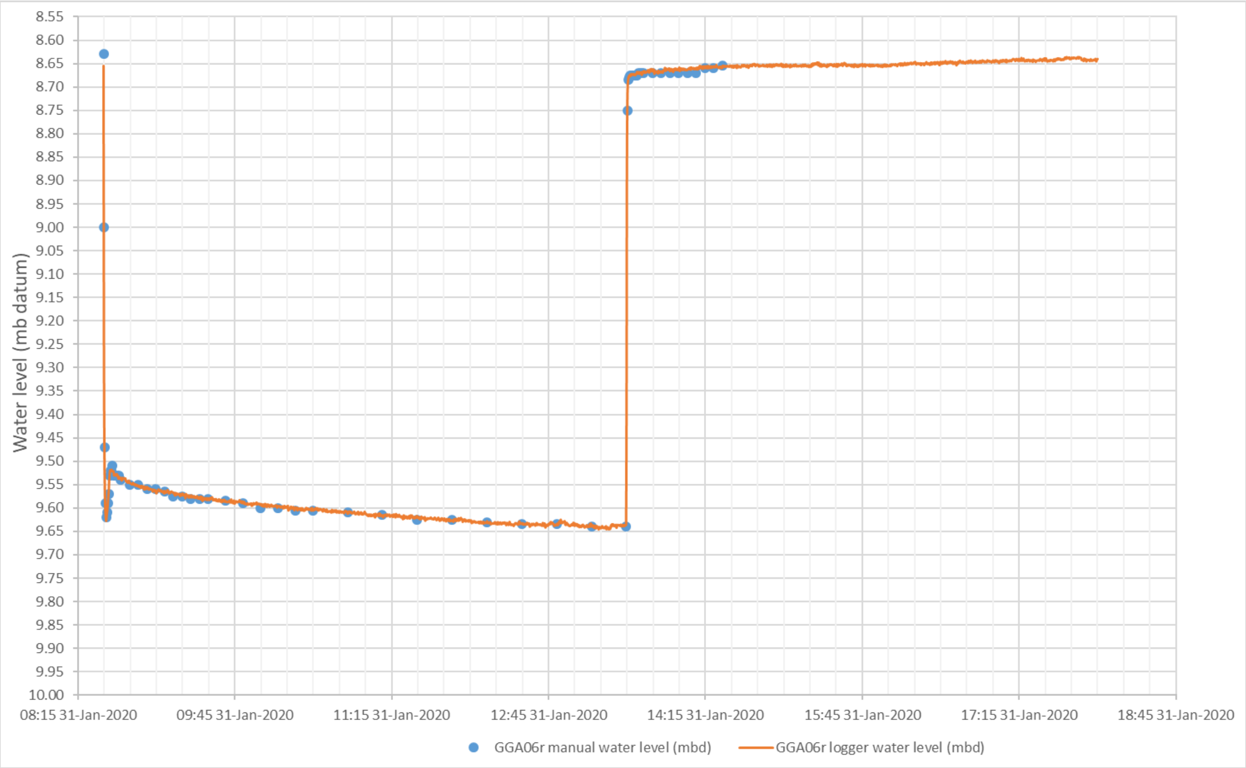


**Figure 6 Borehole water levels in GGA06r during CRT (data logger and manual dip). It took two minutes at the start of the test for the flow rate to be adjusted to the correct stable rate.**

### 4.1.3 Observation data during GGA06r test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA06r pump tests. Figure 7 and Figure 8 show the water levels in the two other superficial deposits boreholes, GGA09r and GGB04, during the test pumping on GGA06r. The other six boreholes have not been included as there was no obvious change in water level in response to the test pumping and for clarity.

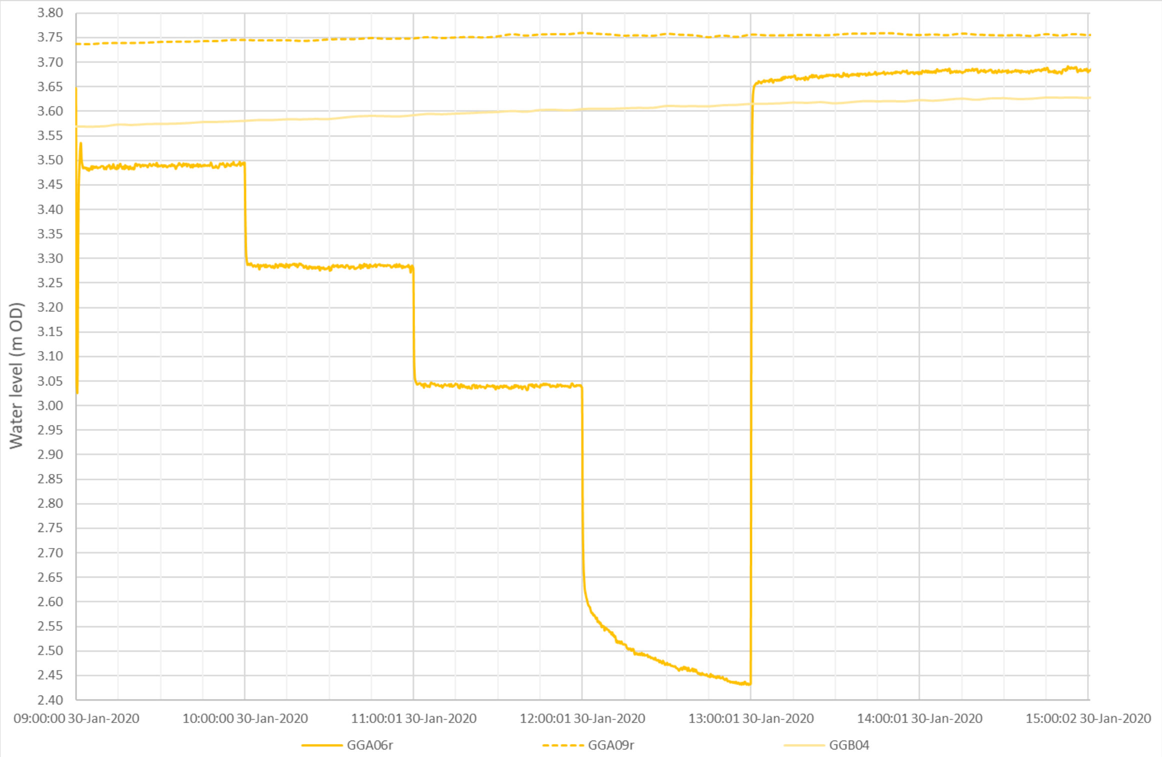


**Figure 7 Borehole water levels (from data logger) in pumping borehole and observation boreholes during the SDT on GGA06r.**

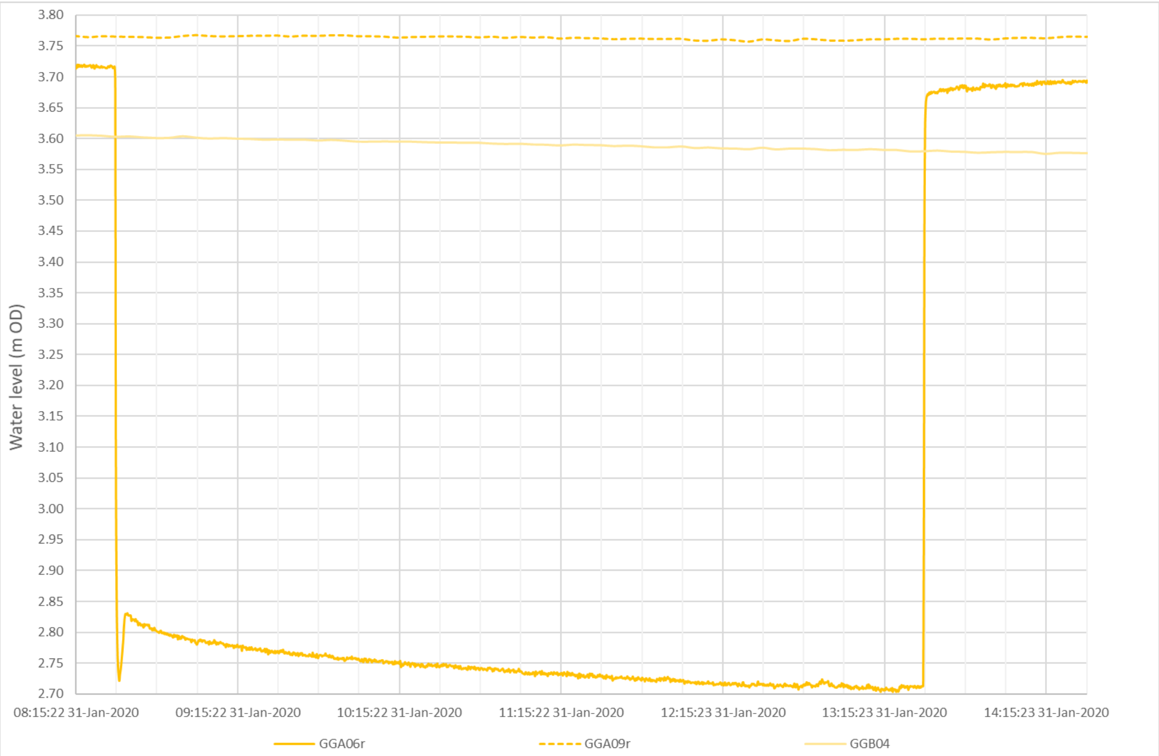


**Figure 8 Borehole water levels (from data logger) in pumping borehole and observation boreholes during the CRT on GGA06r.**

### 4.1.4 Preliminary time-drawdown curves of GGA06r

Drawdown and recovery curves used to estimate transmissivity during the CRT of GGA06r are shown in Figure 9 and Figure 10 (see Section 2.5 for more detail on the analyses methods used). A transmissivity value of 79 $m^2$/day was derived using the Jacob straight line method for drawdown data and 225 $m^2$/day the Theis recovery method for recovery data. Figure 9 and Figure 10 show the plotted data used in the derivation of the transmissivity values.

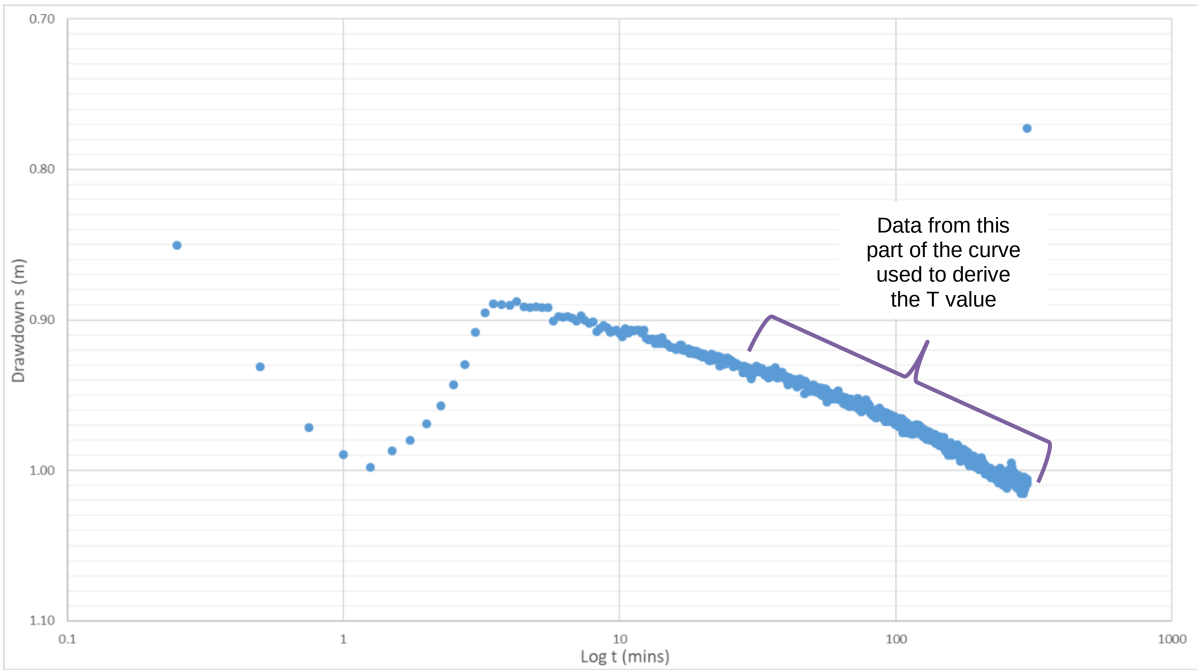


**Figure 9 Time-drawdown (from data logger) for drawdown phase of CRT on GGA06r**

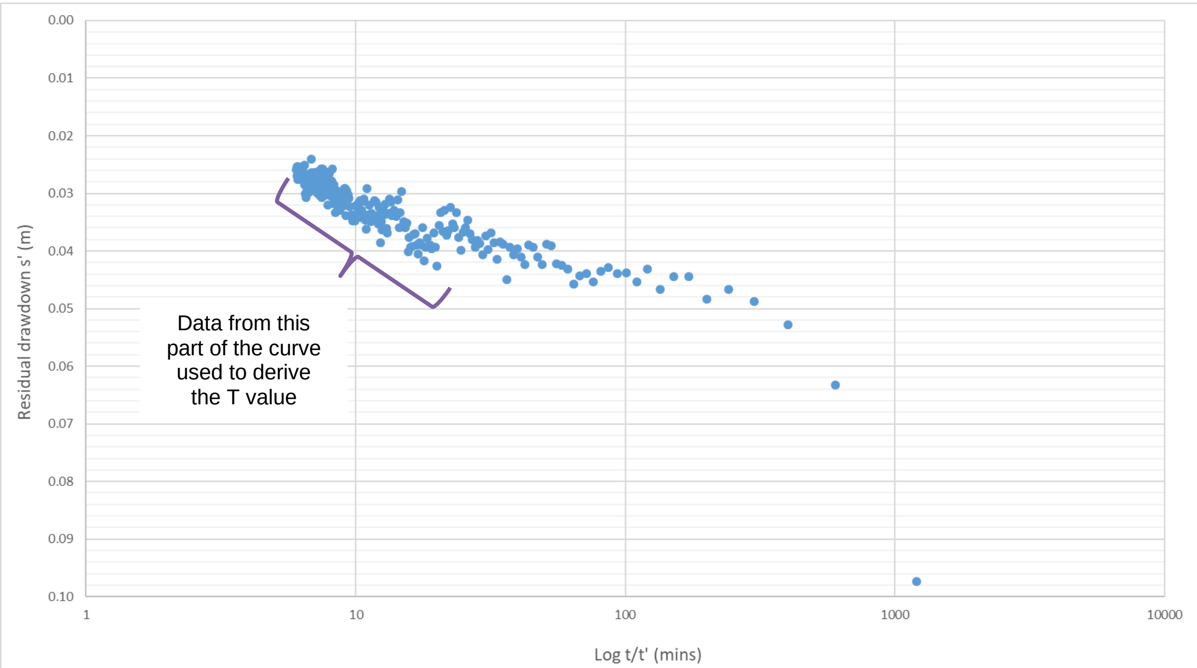


**Figure 10 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA06r**

## 4.2 TEST PUMPING: GGA09R

### 4.2.1 Overview of GGA09r

An overview of the test pumping carried out on GGA09r is in Table 7. Further details on the geology and borehole construction can be found in the GGA09r borehole information pack, which can be downloaded here: https://dx.doi.org/10.5285/baf7cc61-4a46-423f-a491-23d107b25001

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA09r_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGA09r_FINAL.xlsx
- CRT_ GGA09r_FINAL.xlsx
- GGA09r_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA09r provided by Drilcorp is in file:

- GGA09r_Welltesting_Feb-2020_Report_v1.pdf

**Table 7 Overview of test pumping on GGA09r**

| | **Step drawdown test** | **Constant rate test** |
|---|---|---|
| Target aquifer horizon | Superficial deposits | |
| Description of screened section | Sand and gravel | |
| Depth of top of screened interval (m below top of borehole casing) | 11.43 | |
| Length of screened section (m) | 1.9 | |
| Type of pump | Grundfos SQ 1-35 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 12.85 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.81 | |
| Height of final floor of manhole chamber (m OD) | 10.78 | |
| Date of test | 10/02/2020 | 11/02/2020 |
| Start time of pumping | 10:00 | 09:00 |
| End time of pumping | 14:00 | 14:00 |
| Number of pumping steps | 4 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 4 | 5 |
| Average pumping rates for each step (L/s) | 0.12/0.22/0.42/0.62 | 0.51 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 4.9 | 9 |
| Rest water level (m below top of dip tube) | 7.69 | 7.53 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 9.05 | 8.51 |
| Maximum drawdown during pump test (m) | 1.36 | 0.99 |

### 4.2.2 Manual dip and logger data for GGA09r

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Larger water level drawdowns at the beginning of steps one and two are the results of the pumping rate being adjusted and set. Figure 11 and Figure 12 plot the manual and logger data from the SDT and CRT on GGA09r.

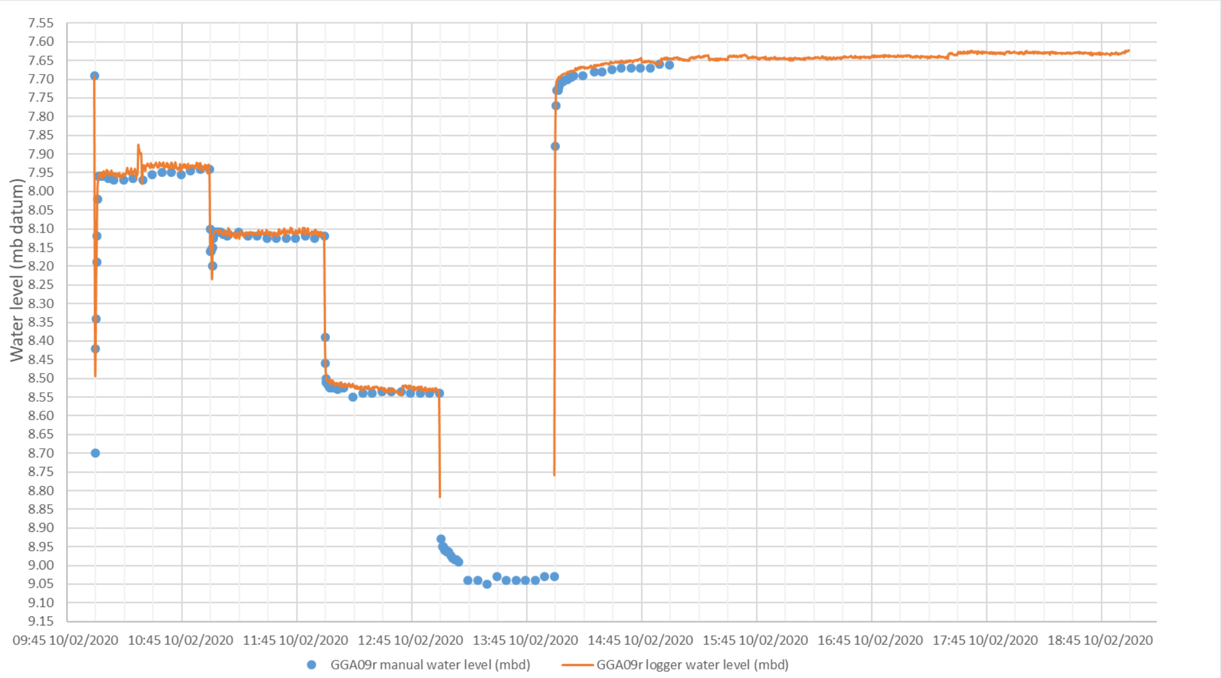


**Figure 11 Borehole water levels in GGA09r during SDT (data logger and manual dip). During the fourth step the water level dropped below the level of the data logger.**

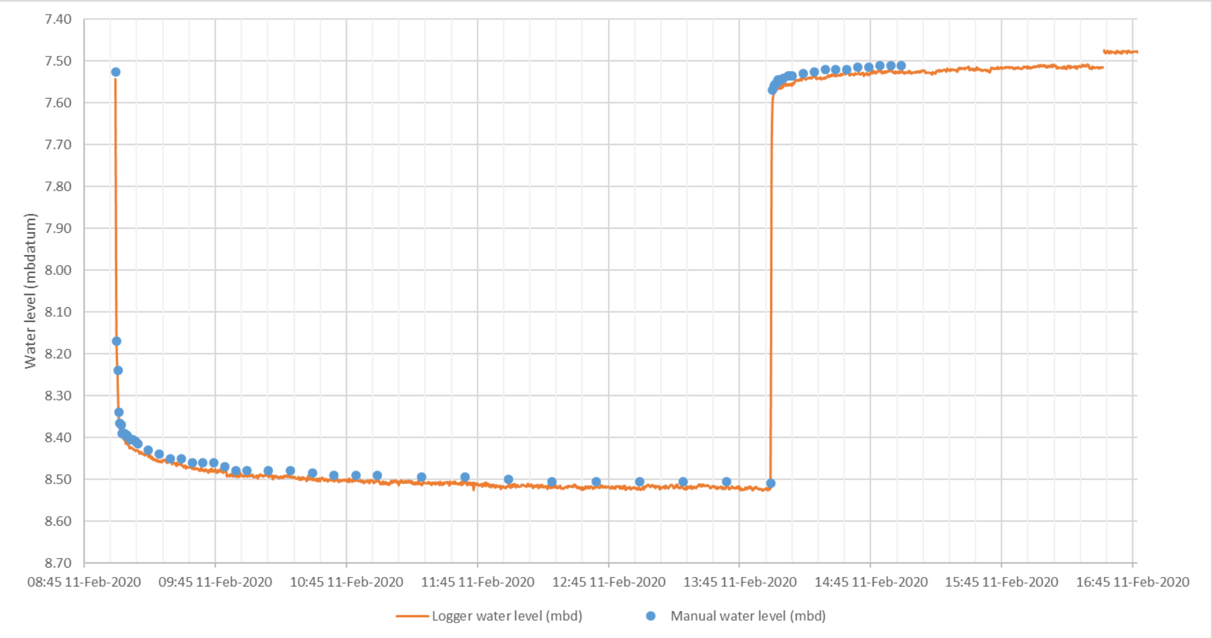


**Figure 12 Borehole water levels in GGA09r during CRT (data logger and manual dip). First manual dip of recovery was written down incorrectly and therefore removed from the graph for clarity.**

### 4.2.3 Observation data during GGA09r test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA09r pump tests. Figure 13 and Figure 14 show the water levels in the two other superficial deposits boreholes, GGA06r and GGB04, during the test pumping on GGA09r. The other six boreholes have not been included as there was no obvious change in water level in response to the test pumping and for clarity.

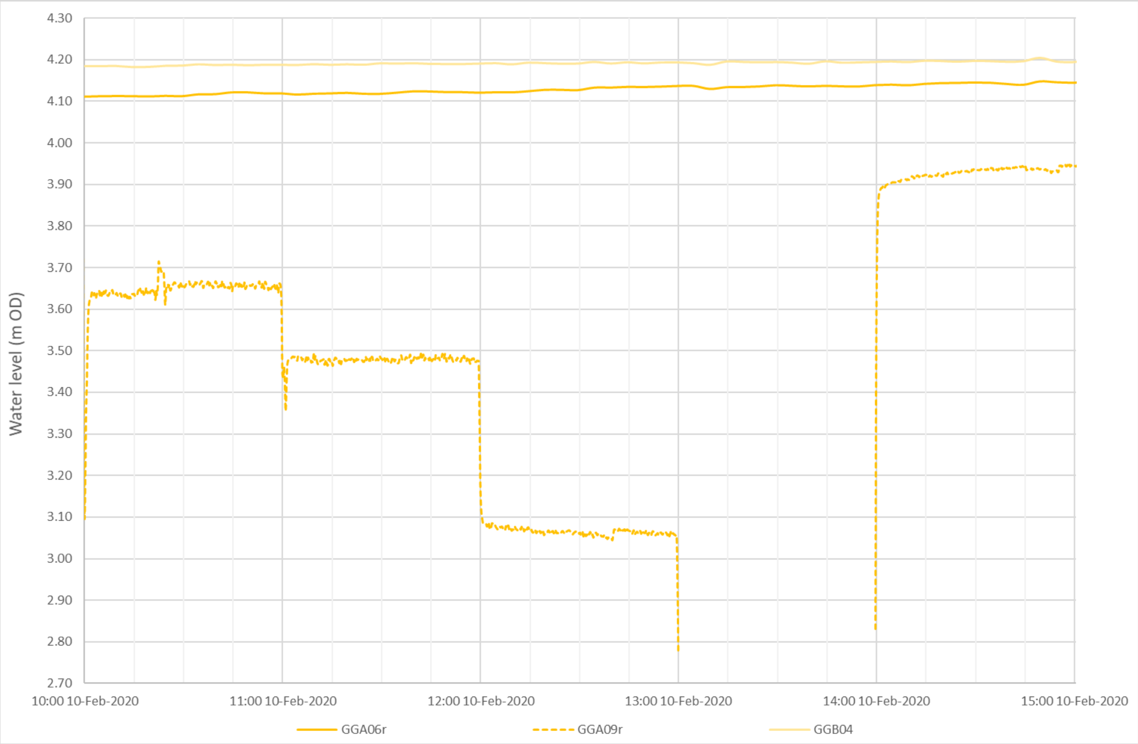


**Figure 13 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA09r**

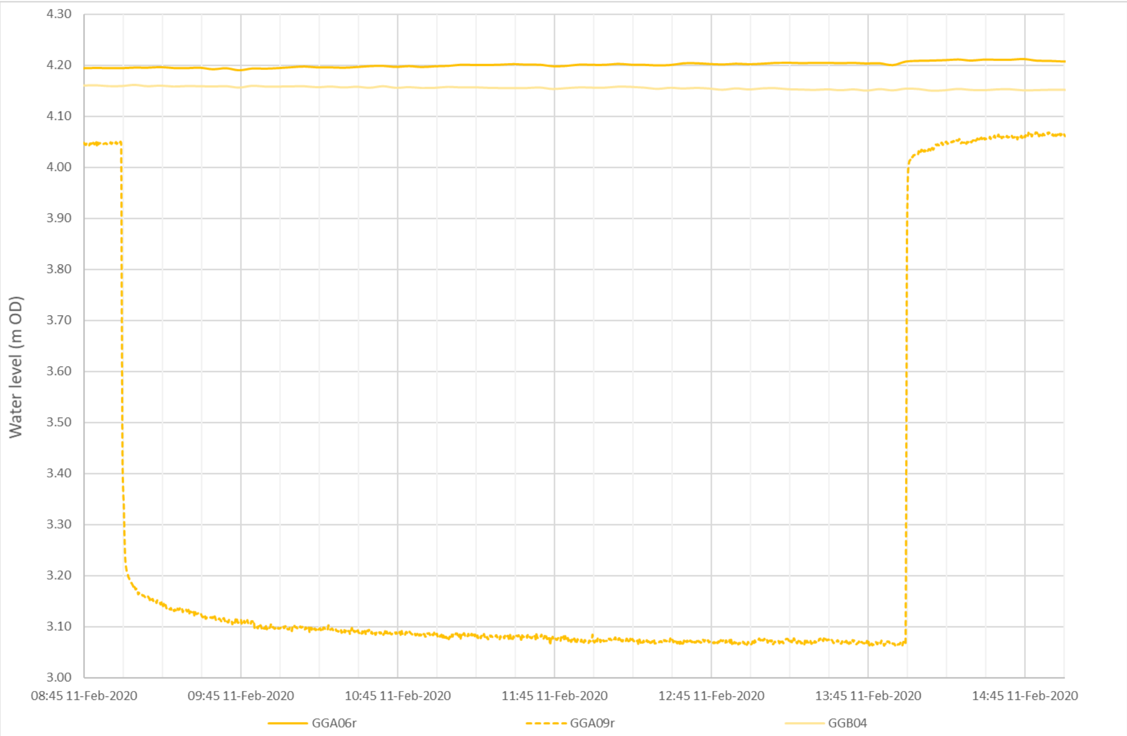


**Figure 14 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA09r**

### 4.2.4 Preliminary time-drawdown curves of GGA09r

Figure 15 and Figure 16 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA09r, see Section 2.5 for more detail on the analyses used. A value of 225 $m^2$/day was derived using both the Jacob straight line method for drawdown data and the Theis recovery method for recovery data.

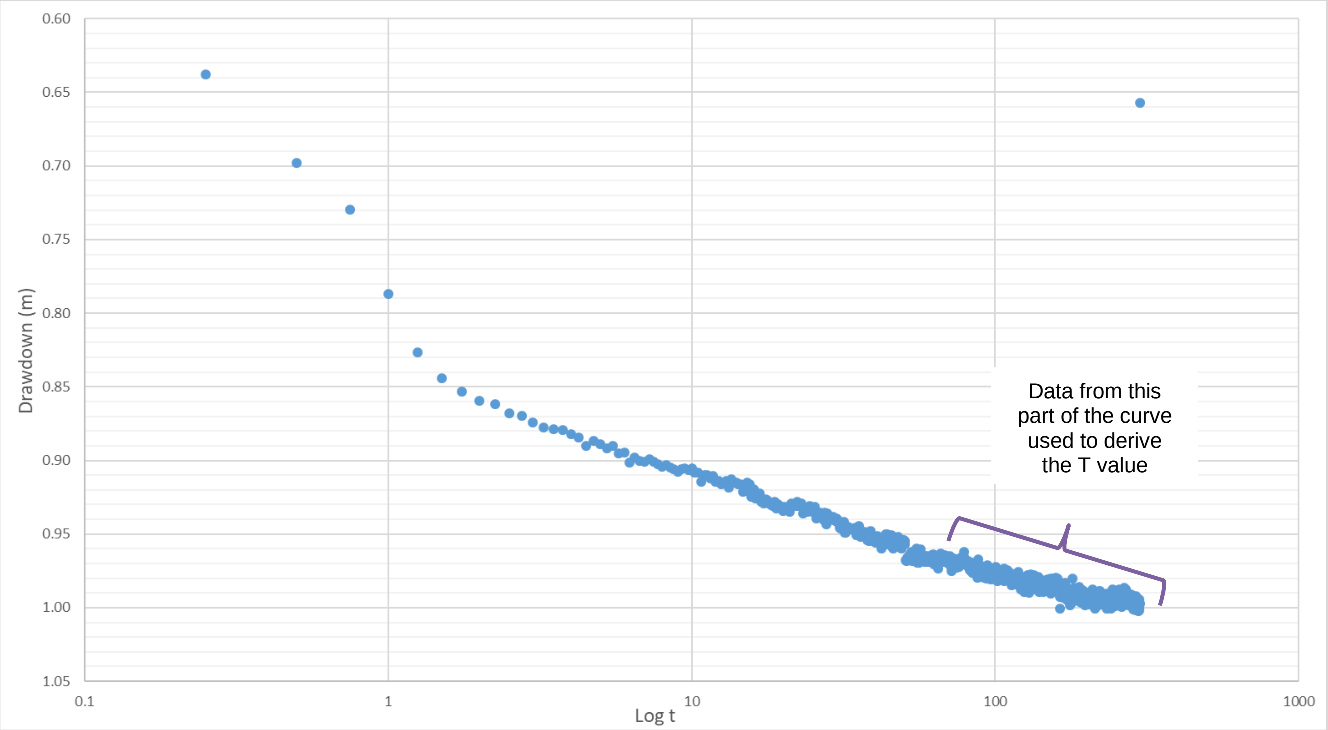


**Figure 15 Time-drawdown (from data logger) for drawdown phase of CRT on GGA09r**

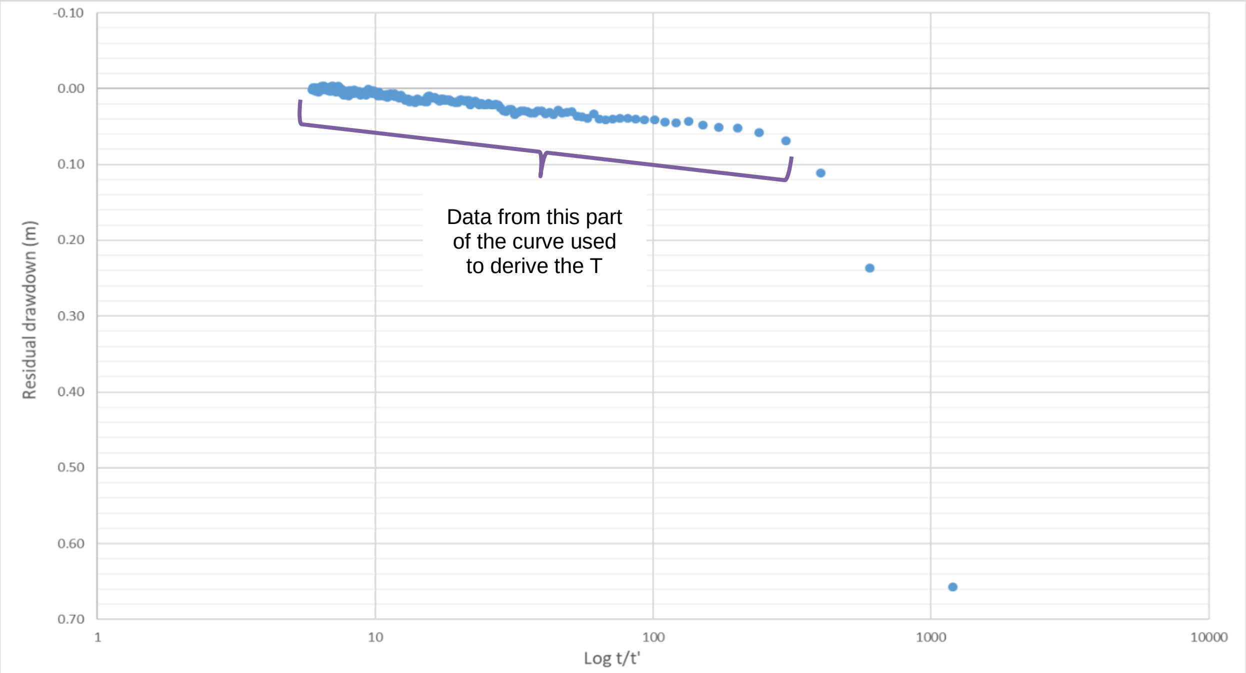


**Figure 16 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA09r**

## 4.3 TEST PUMPING: GGB04

### 4.3.1 Overview of GGB04

An overview of the test pumping carried out on GGB04 is in Table 8. Further details on the geology and borehole construction can be found in the GGB04 borehole information pack, which can be downloaded here: https://doi.org/10.5285/d31f33b8-b34a-4843-b2d2-545722bf94ae.

Test pumping data (including measurements of borehole water levels throughout the test) are available in the following files:

- GGB04_falling&risingtest_Hydraulic data_v1.xlsx
- FallingHead_Test_ GGB04_FINAL.xlsx
- RisingHead_Test_ GGB04_FINAL.xlsx
- GGB04_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA09r provided by Drilcorp is in file:

- GGB04_Welltesting_Feb-2020_Report_v1.pdf

**Table 8 Overview of test pumping on GGB04**

| | Falling head test | Rising head test |
|---|---|---|
| Target aquifer horizon | Superficial deposits | |
| Description of screened section | Sand and gravel | |
| Depth of top of screened interval (m below top of borehole casing) | 10.09 | |
| Length of screened section (m) | 1.9 | |
| Volume of slug (L) | 4.0 | |
| Dimensions of slug (m) | 1.04 x 0.07 | |
| Depth of slug (m below top of borehole casing) | 2.0 | |
| Datum for water level measurements | Top of dip tube | |
| Height of borehole casing above base of borehole manhole chamber (m) | 1.11 | |
| Height of floor of manhole chamber (m OD) | 11.199 | |
| Date of test | 17/02/2020 | 18/02/2020 |
| Time of slug input/removal | 11:35 | 08:10 |
| Length of test (hours) | 20 hrs 35 mins | 26 hrs 45 mins |
| Total length of test (hours) | 47.36 | |
| Manually dipped water level at start of test (m below top of borehole casing) | 8.04 | 8.01 |
| Maximum change in water level at start of test (m) | +0.47 | -0.48 |

### 4.3.2 Manual dip and logger data for GGB04

During the slug test, manual water level measurements were taken for the first five hours of the falling head test. Sporadic manual measurements were taken during the rising head test as well. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 17and Figure 18 plot the manual and logger data from the falling head test and rising head test on GGB04.

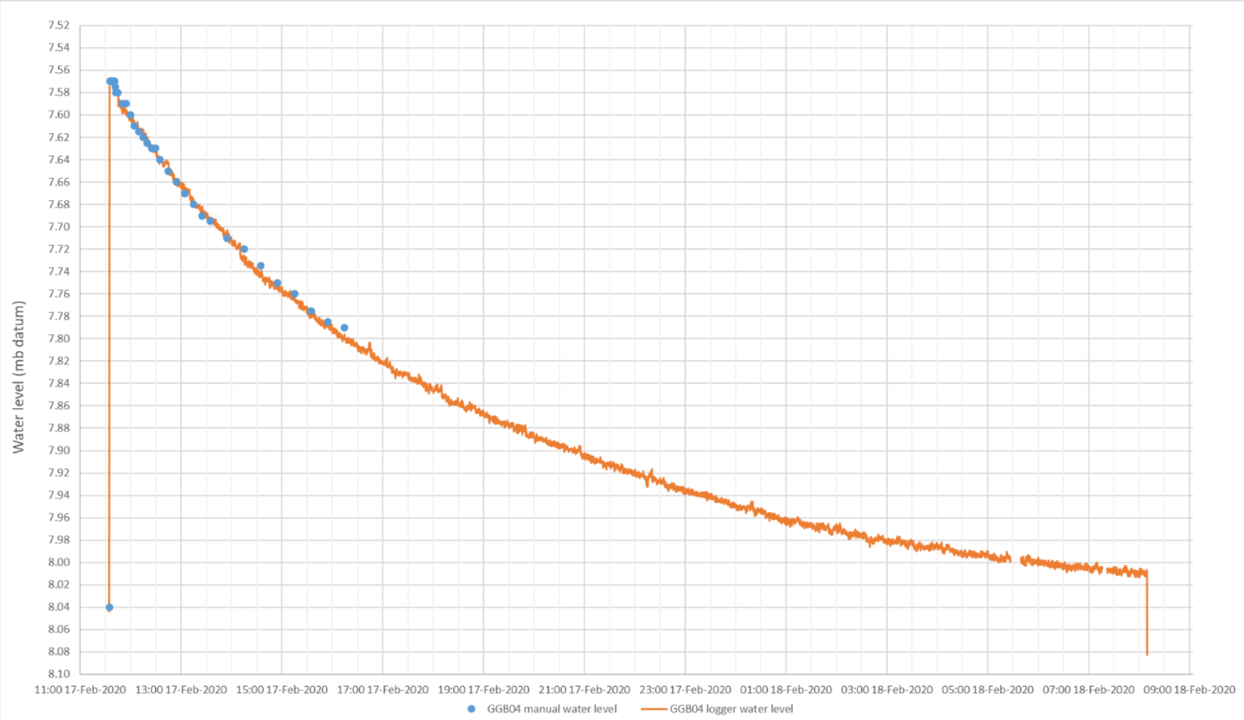


**Figure 17 Borehole water levels in GGB04 during falling head test (data logger and manual dip)**

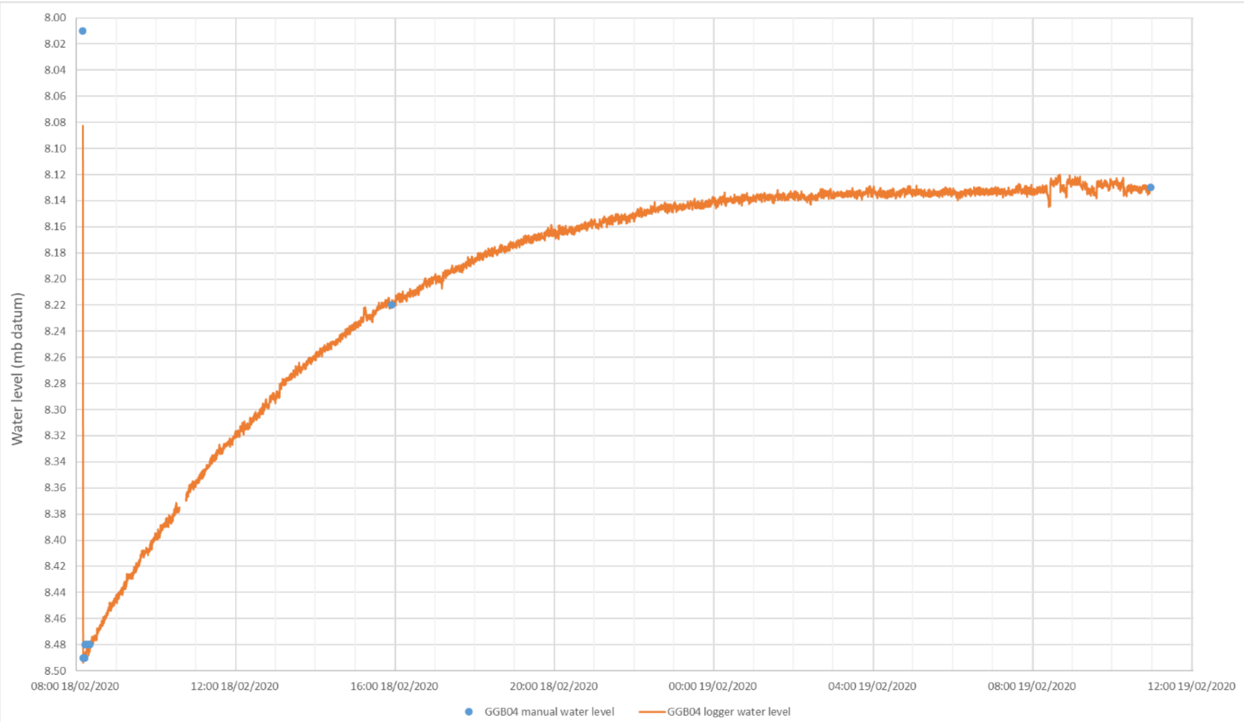


**Figure 18 Borehole water levels in GGB04 during rising head test (data logger and manual dip)**

### 4.3.3 Observation data during GGB04 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGB04 pump test. Figure 19 and Figure 20 show the water levels in the two other superficial deposits boreholes, GGA06r and GGA09r, during the test pumping on GGB04. The other six boreholes have not been included as there was no obvious change in water level in response to the test pumping and for clarity.

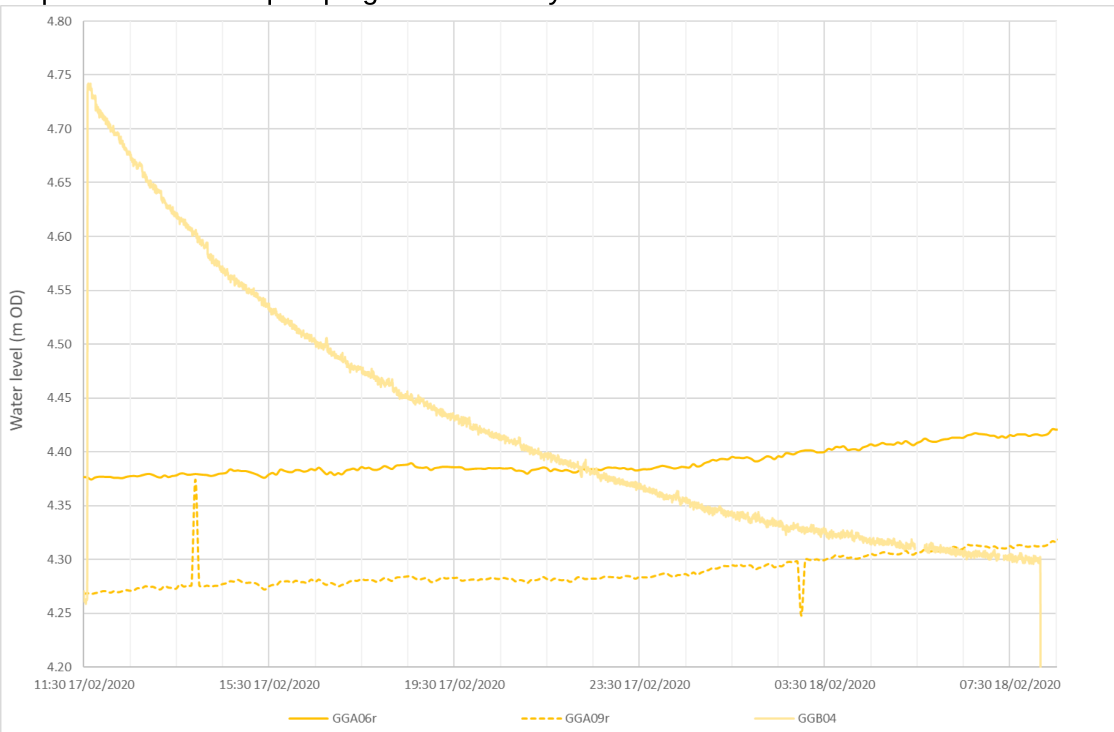


**Figure 19 Borehole water levels (from data logger) in pumping and observation boreholes during the falling head test on GGB04**

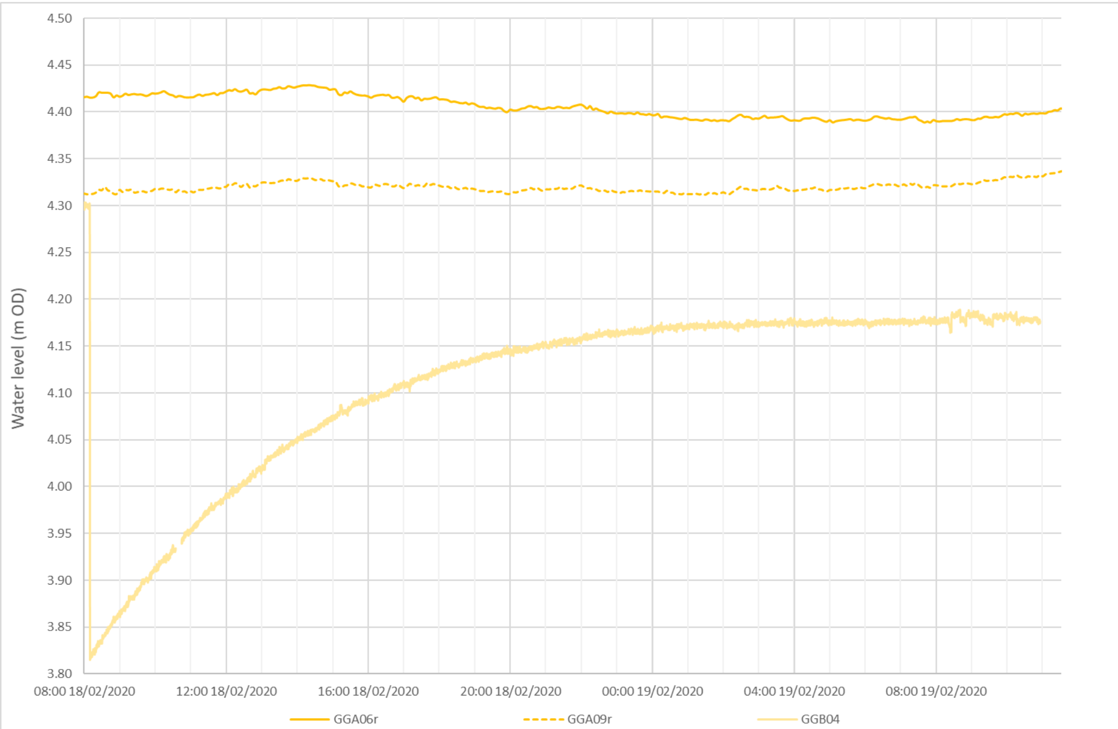


**Figure 20 Borehole water levels (from data logger) in pumping and observation boreholes during the rising head test on GGB04**

### 4.3.4 Preliminary BGSPT analysis

As described in Section 2.5.2, the PTFIT programme, part of BGSPT, was used to derive preliminary T values for GGB04. Several runs of the programme were carried out, in order to identify a best fit for both the falling head and rising head drawdown data. Figure 21 shows the best fit calculated drawdown data from the falling head test from which a transmissivity value of 0.04 $m^2$/day was calculated. Figure 22 shows the best fit calculated from the rising head test from which a transmissivity value of 0.018 $m^2$/day was calculated.

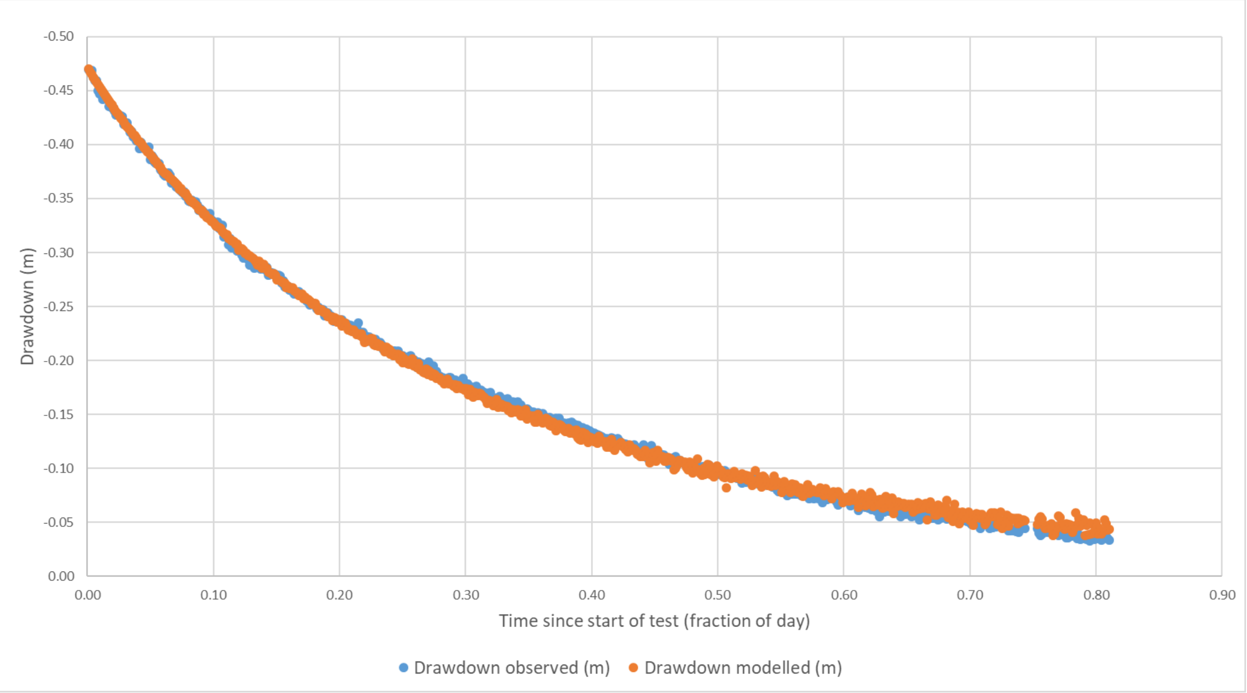


**Figure 21 BGS PT data from falling head test**

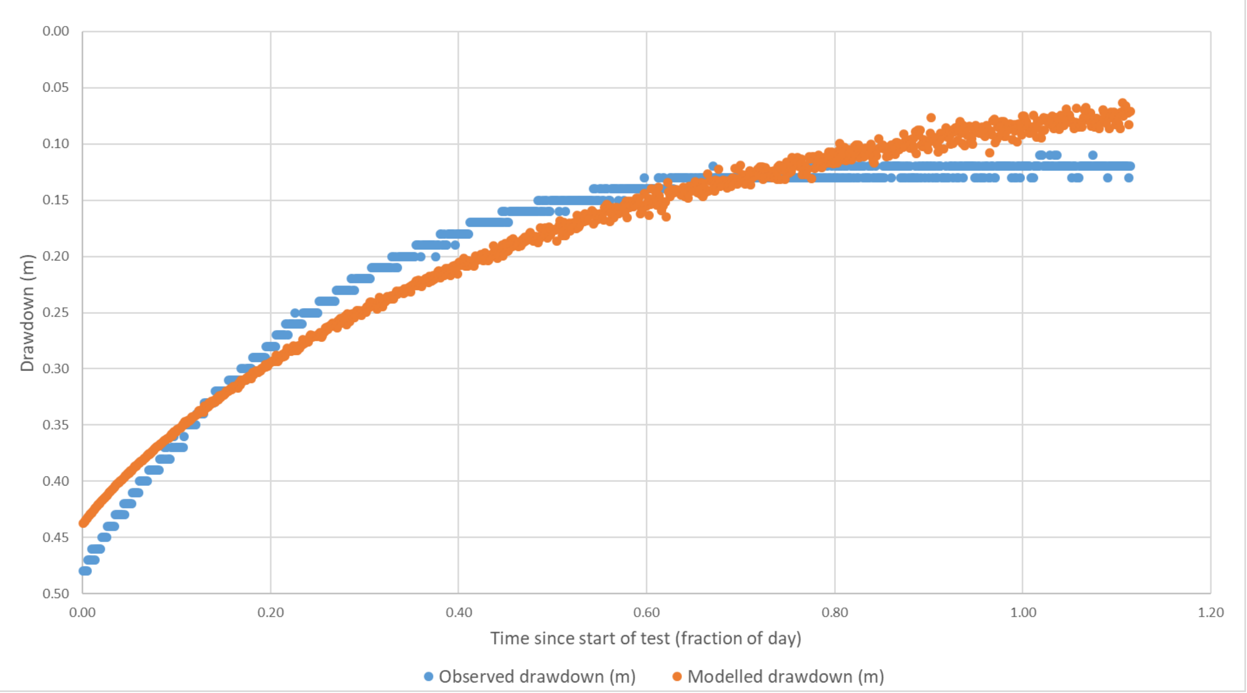


**Figure 22 BGS PT data from rising head test**

# 5 Bedrock boreholes

Presented in Sections 5.1 and 5.2 are the results of test pumping carried out on the two bedrock boreholes of the Glasgow Observatory, GGA03r (located at Site 1) and GGB05 (located at Site 5).

## 5.1 TEST PUMPING: GGA03R

### 5.1.1 Overview of GGA03r

An overview of the test pumping carried out on GGA03r is in Table 9. Further details on the geology and borehole construction can be found in the GGA03r borehole information pack, which can be downloaded here: https://doi.org/10.5285/7971dbc3-d4a3-4f74-90a9-89b46d39ad49.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA03r_SDT&CRT_Hydraulicdata_v1.xlsx
- GGA03r_CRT_Feb20_Hydraulicdata_v1.xlsx
- SDT_ GGA03r_FINAL.xlsx
- CRT_ GGA03r_FINAL.xlsx
- GGA03r_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA03r provided by Drilcorp is in file:

- GGA03r_Welltesting_Jan-2020&Feb-2020_Report_v1.pdf

**Table 9 Overview of test pumping on GGA03r**

| | Step drawdown test | Constant rate test 1 | Constant rate test 2 |
|---|---|---|---|
| Target aquifer horizon | Sandstone bedrock | | |
| Description of screened section | Sandstone below rockhead, above Glasgow Upper mine working | | |
| Depth of top of screened interval (m below top of borehole casing) | 37.0 | | |
| Length of screened section (m) | 2.81 | | |
| Type of pump | E-tech VS2/7 submersible pump | | Grundfos SQ 1-35 submersible pump |
| Depth of pump intake (m below top of borehole casing) | 35.31 | | 25.61 |
| Datum for water level measurements | Top of dip tube | | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.66 | | 0.74 |
| Height of final floor level of manhole chamber (m OD) | 9.42 | | |
| Date of test | 17/01/2020 | 20/01/2020 | 18/02/2020 |
| Start time of pumping | 08:50 | 10:30 | 10:00 |
| End time of pumping | 12:50 | 12:55 | 15:00 |
| Number of pumping steps | 4 | 1 | 1 |
| Length of pumping steps (hours) | 1 – 1.5 | 2.5 | 5 |
| Total length of pumping (hours) | 4 | 2 hours 25 minutes | 5 |
| Average pumping rates for each step (L/s) | 0.13/0.17/0.28/0.28 | 0.16 – 0.19 | 0.1 |
| Length of manually monitored recovery period (hours) | 1 | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 2.3 | 1.5 | 2.0 |
| Rest water level (m below top of dip tube) | 0.46 | 0.68 | Artesian (see attached files for explanation) |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 30.62 | 28.61 | 8.37 |
| Maximum manually measured drawdown during pump test (m) | 30.16 | 27.93 | 8.04 |

### 5.1.2 Manual dip and logger data for GGA03r

During the test pumping, manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger also monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 23 to Figure 25 plot the manual and logger data from the SDT and CRTs on GGA03r.

Problems were encountered in the third step of the SDT resulting in the pump stopping due to excessive drawdown (Figure 23). After 25 minutes the pump was able to be switched back on for a further 30 minutes before the decision was taken to stop the fourth step as the water level was getting close to the level of the pump. For further details see Drilcorp's report associated with this borehole (Appendix B).

Similar problems were encountered 90 minutes into the CRT, the pump switched off due to the excessive drawdown (Figure 24). After 30 minutes the pump was restarted for another 30 minutes of pumping before the test pumping was halted due to excessive drawdown. For further details see Drilcorp's report associated with this borehole attached to this report (Appendix B). Due to slight timing discrepancies when recording the manual dips onsite, the manual water levels are not always aligned with the data logger water levels. Where possible these have been cross-checked and updated.

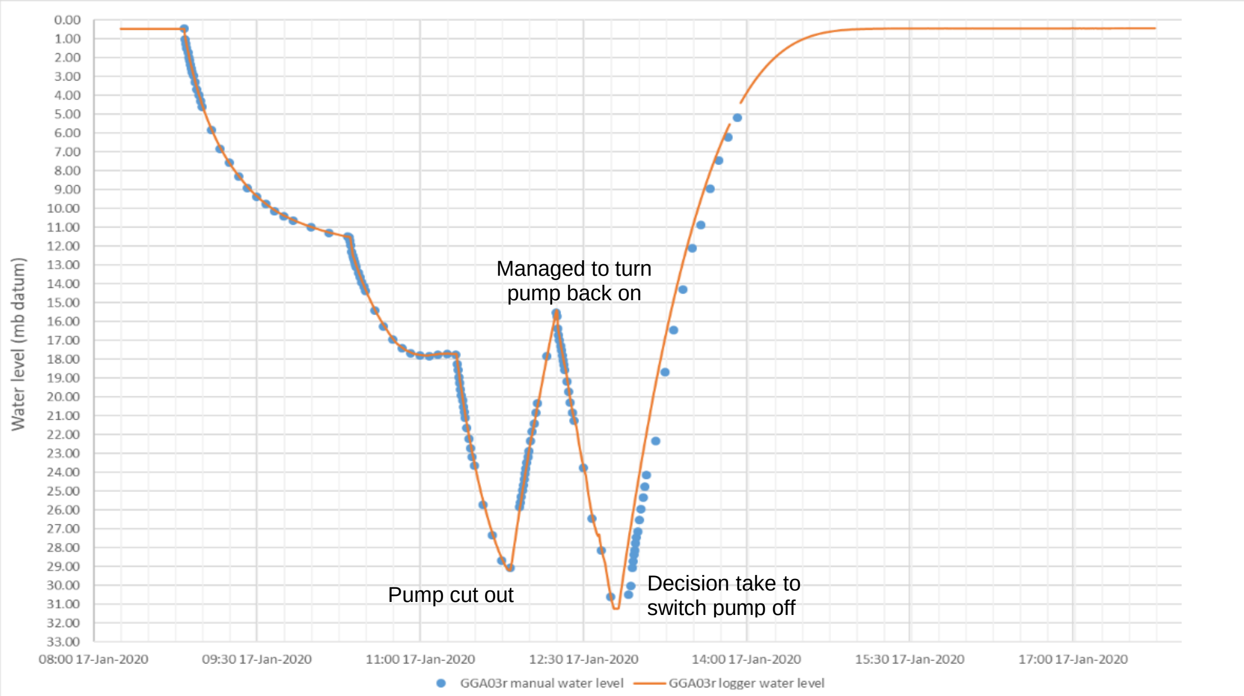


**Figure 23 Borehole water levels in GGA03r during SDT (data logger and manual dip).**

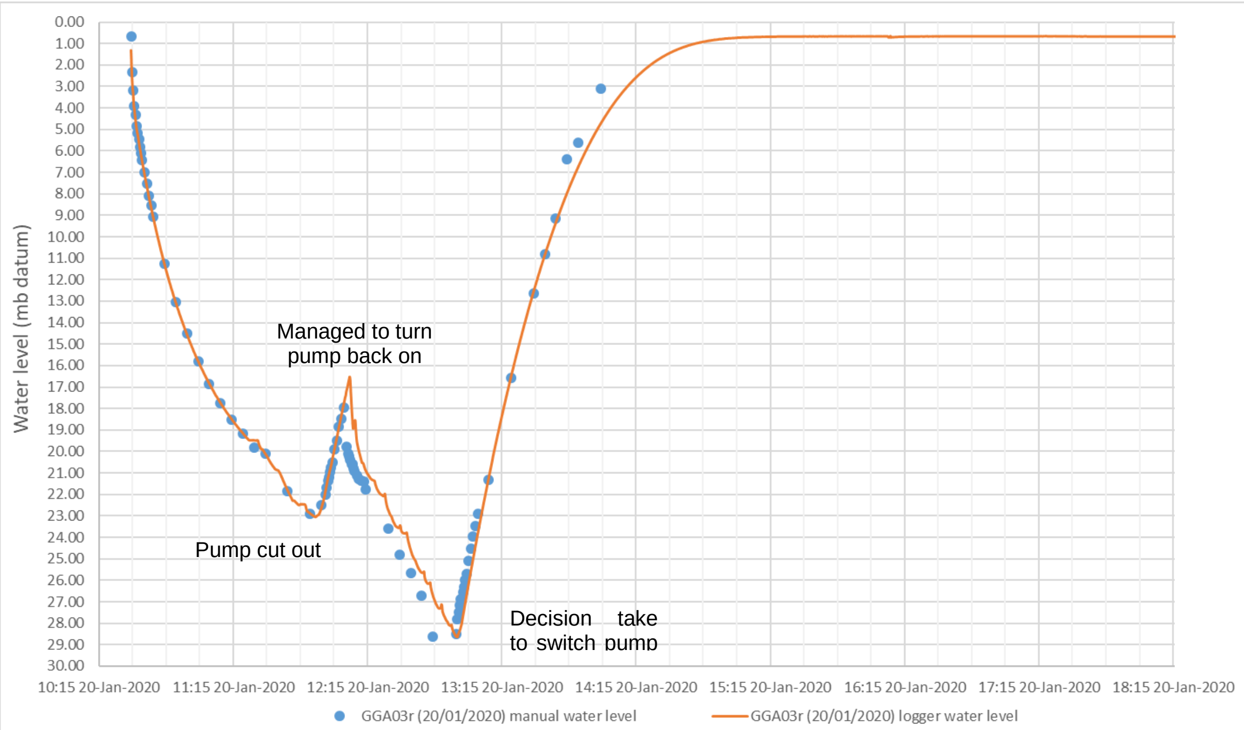


**Figure 24 Borehole water levels in GGA03r during first CRT on 20/01/2020 (data logger and manual dip).**

On the 18 February 2020 a second CRT was carried out on GGA03r using a smaller pump than during the SDT and first CRT (Details see Table 9). The second CRT was carried out successfully for five hours at 0.1 L/s, Figure 25.

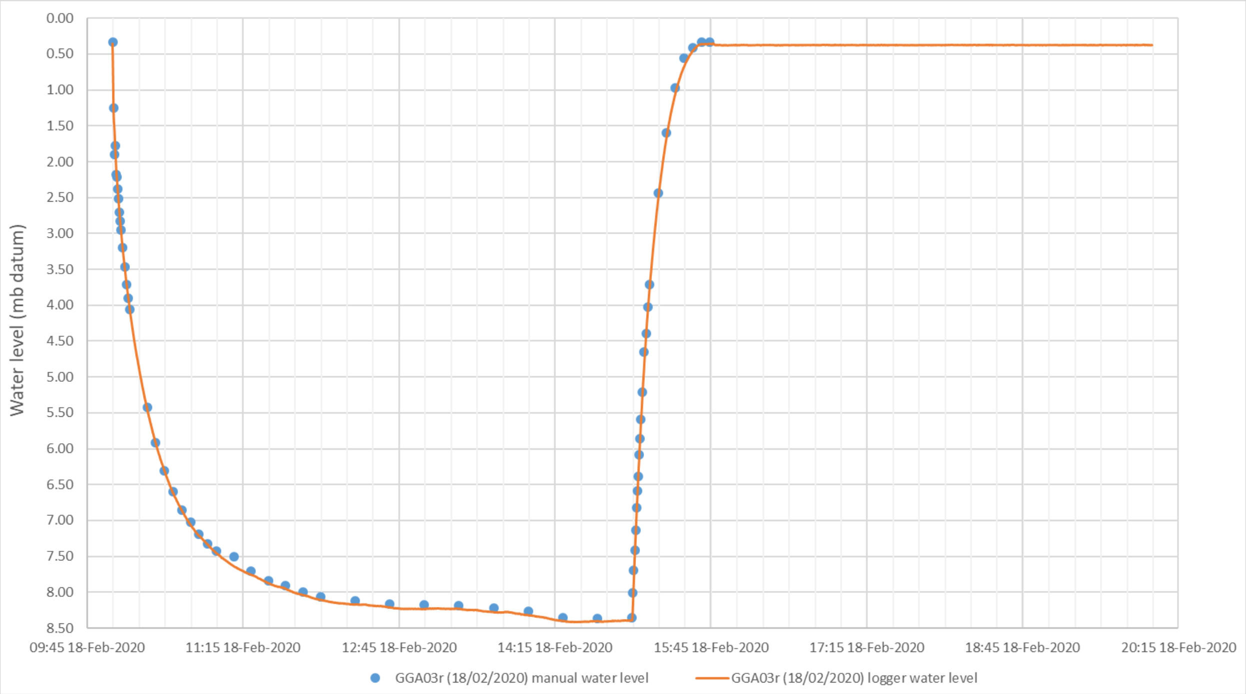


**Figure 25 Borehole water levels in second GGA03r during second CRT on 18/02/2020 (data logger and manual dip)**

### 5.1.3 Observation data during GGA03r test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA03r pump tests. Figure 26 is the observation data during the SDT on 17/01/2020 and Figure 27 during the second CRT on 18/02/2020 of GGA03r. Data from the Glasgow Main and superficial deposits boreholes have been omitted for clarity.

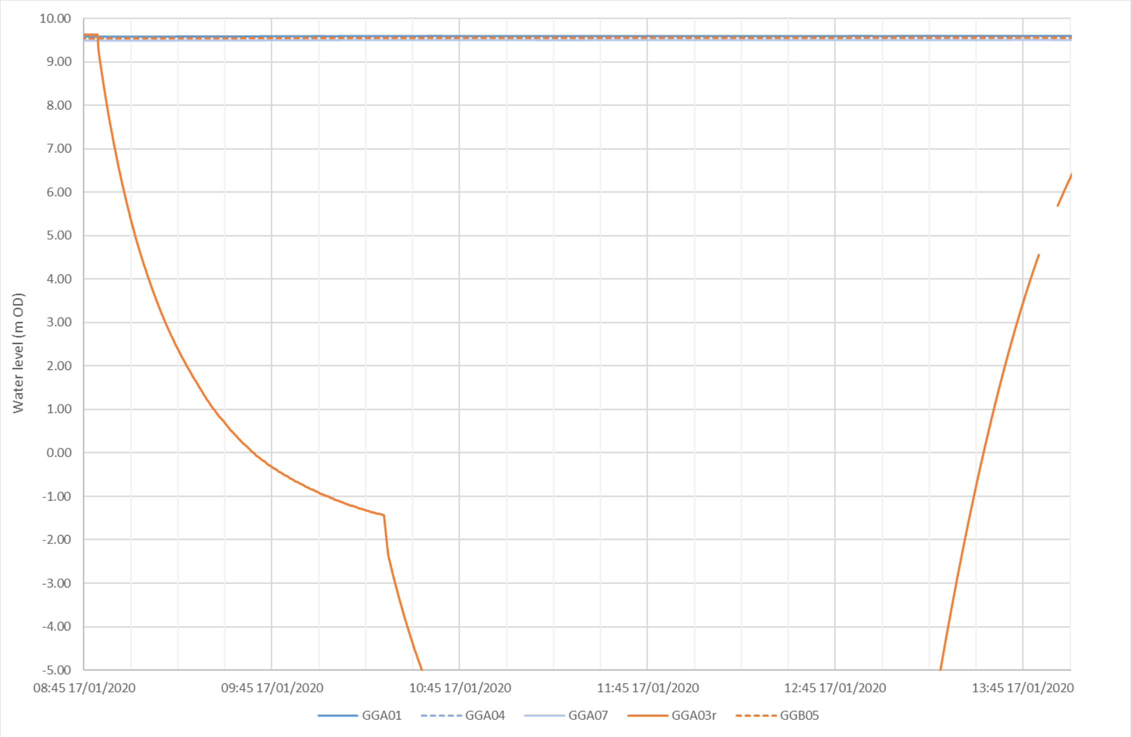


**Figure 26 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA03r**

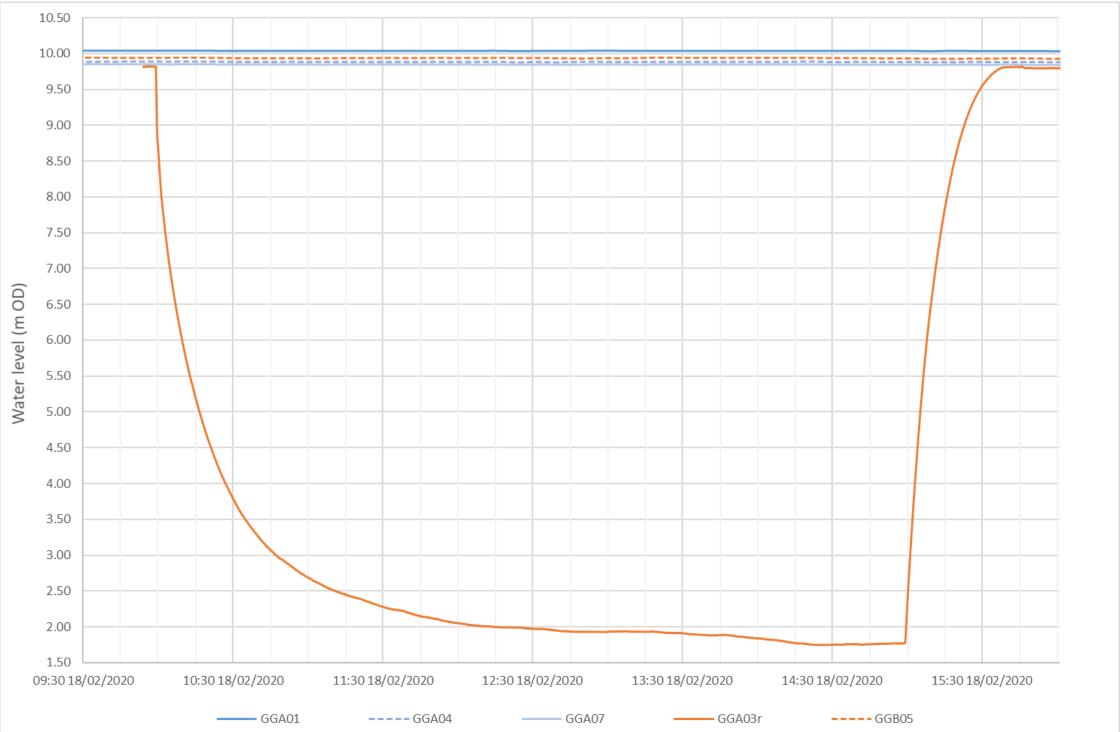


**Figure 27 Borehole water levels (from data logger) in pumping and observation boreholes during the second CRT on GGA03r**

### 5.1.4 Preliminary time-drawdown curves of GGA03r

Figure 28 and Figure 29 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA03r, see Section 2.5 for more detail on the analyses used.

A range of 2.6 m$^2$/day was derived using the Jacob straight line method for drawdown data Figure 28. A value could not be calculated using the Theis recovery method for recovery data, see Figure 29.

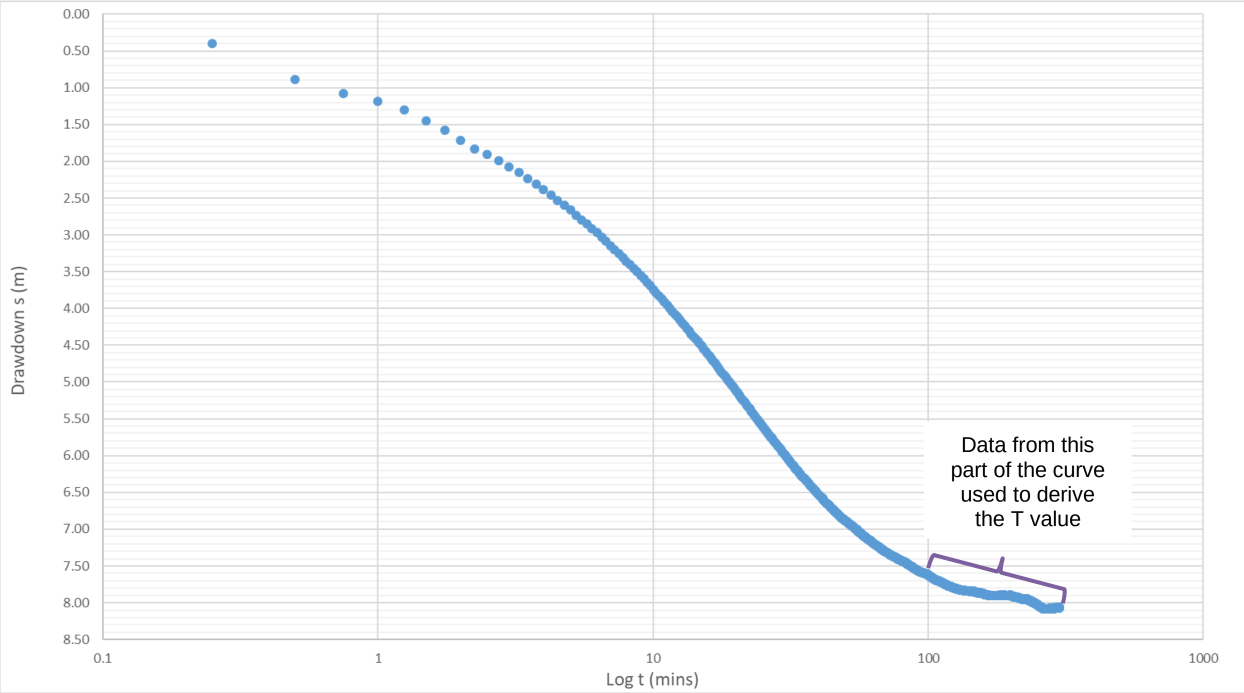


**Figure 28 Time-drawdown (from data logger) for drawdown phase of CRT on GGA03r**

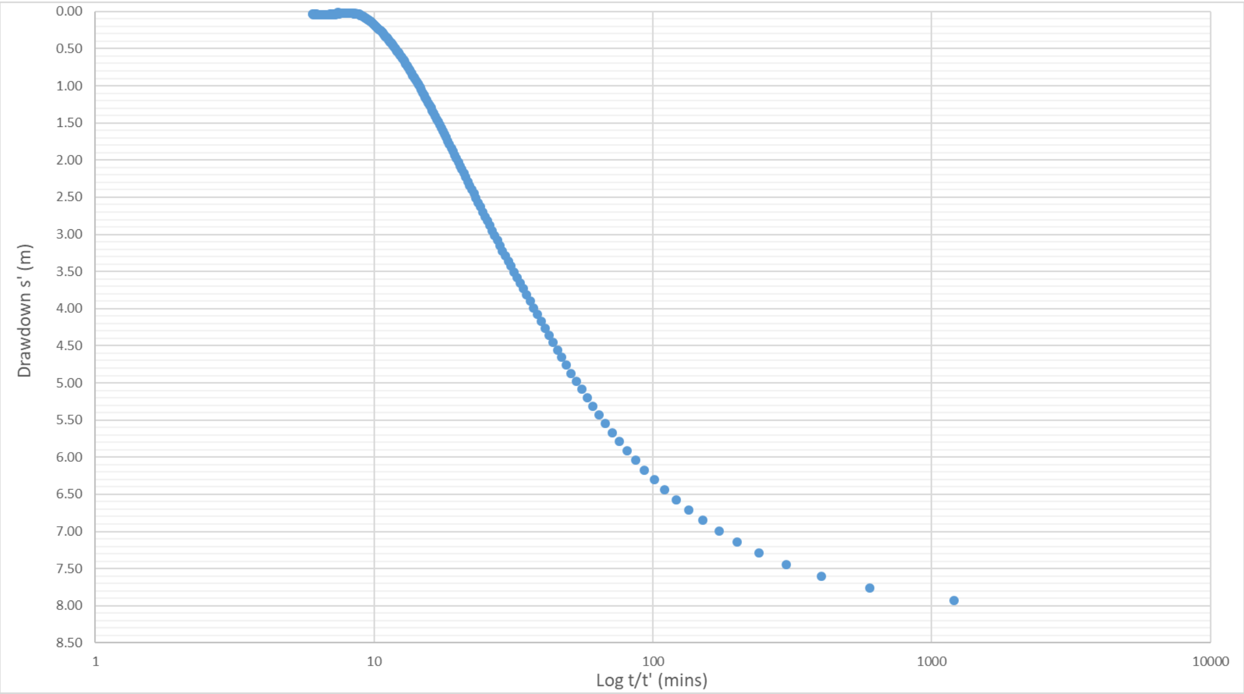


**Figure 29 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA03r**

## 5.2 TEST PUMPING: GGB05

### 5.2.1 Overview of GGB05

An overview of the test pumping carried out on GGB05 is in Table 10. Further details on the geology and borehole construction can be found in the GGB05 borehole information pack, which can be downloaded here: https://doi.org/10.5285/e0ec7462-b731-47c6-93d6-e4613fb44be0.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGB05_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGB05_FINAL.xlsx
- CRT_ GGB05_FINAL.xlsx
- GGB05_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGB05 provided by Drilcorp is in file:

- GGB05_Welltesting_Feb-2020_Report_v1.pdf

**Table 10 Overview of test pumping on GGB05**

| | **Step drawdown test** | **Constant rate test** |
|---|---|---|
| Target aquifer horizon | Bedrock | |
| Description of screened section | Sandstone below rockhead, above Glasgow Upper mine working | |
| Depth of top of screened interval (m below top of borehole casing) | 42.39 | |
| Length of screened section (m) | 1.8 | |
| Type of pump | E-Tech VS15/8 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 39.98 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 1.41 | |
| Height of final floor level of manhole chamber (m OD) | 11.16 | |
| Date of test | 13/02/2020 | 14/02/2020 |
| Start time of pumping | 08:30 | 08:15 |
| End time of pumping | 13:30 | 13:15 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Pumping rates for each step (L/s) | 1/2/2.8/3.5/4.3 | 4.3 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 49 | 79 |
| Rest water level (m below top of dip tube) | 2.66 | 2.66 |
| Water level at end of pumping phase (m below top of dip tube) | 4.84 | 4.99 |
| Maximum drawdown during pump test (m) | 2.18 | 2.25 |

### 5.2.2 Manual dip and logger data for GGB05

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger also monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 30 and Figure 31 plot the manual and logger data from the SDT and CRT on GGB05.

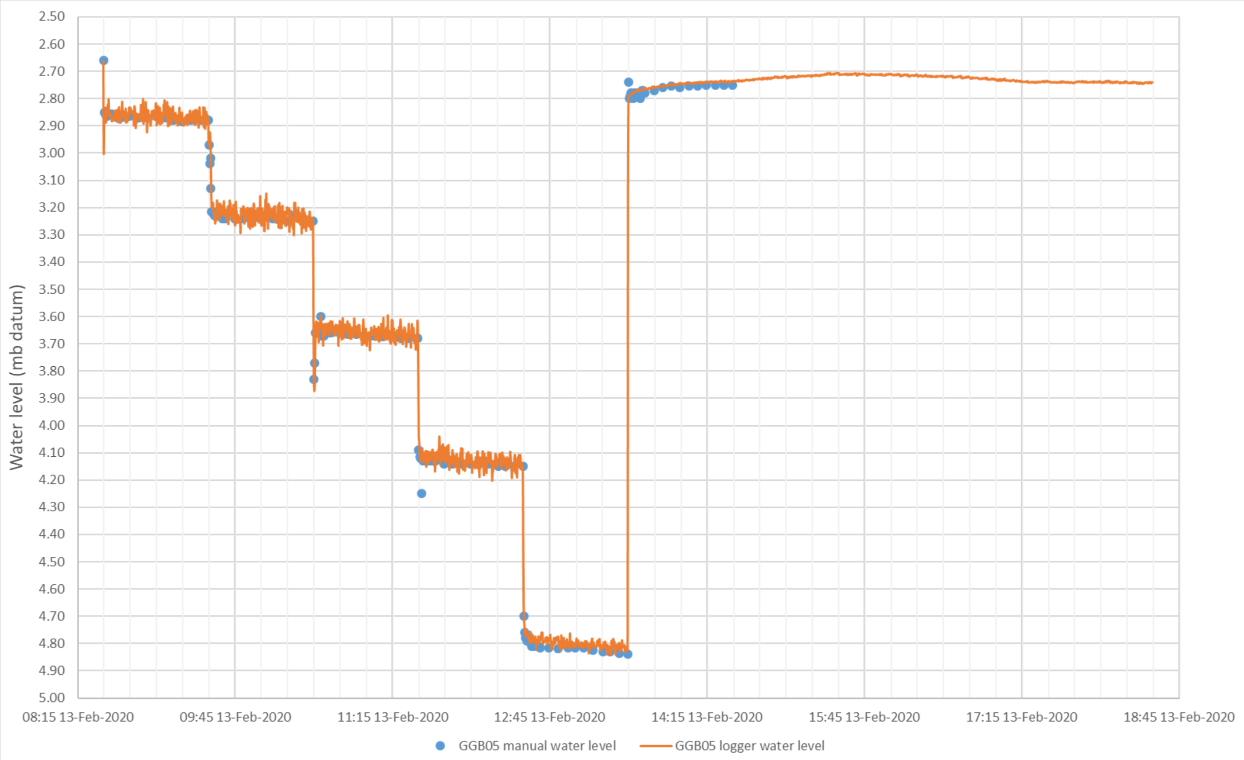


**Figure 30 Borehole water levels in GGB05 during SDT (data logger and manual dip)**

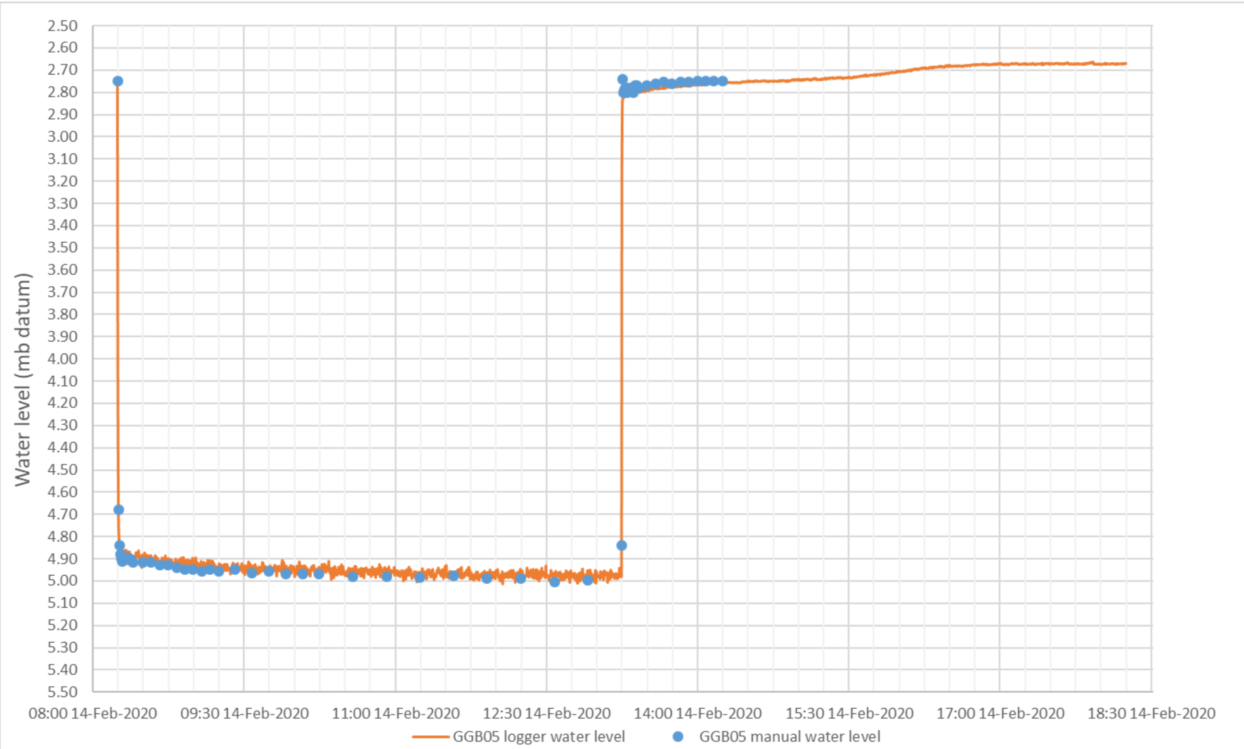


**Figure 31 Borehole water levels in GGB05 during CRT (data logger and manual dip)**

### 5.2.3 Observation data during GGB05 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGB05 pump tests. For clarity only those boreholes that exhibited obvious water level drawdown have been included in Figure 32 and Figure 33. Data from the Glasgow Main and superficial deposits boreholes have been omitted for clarity.

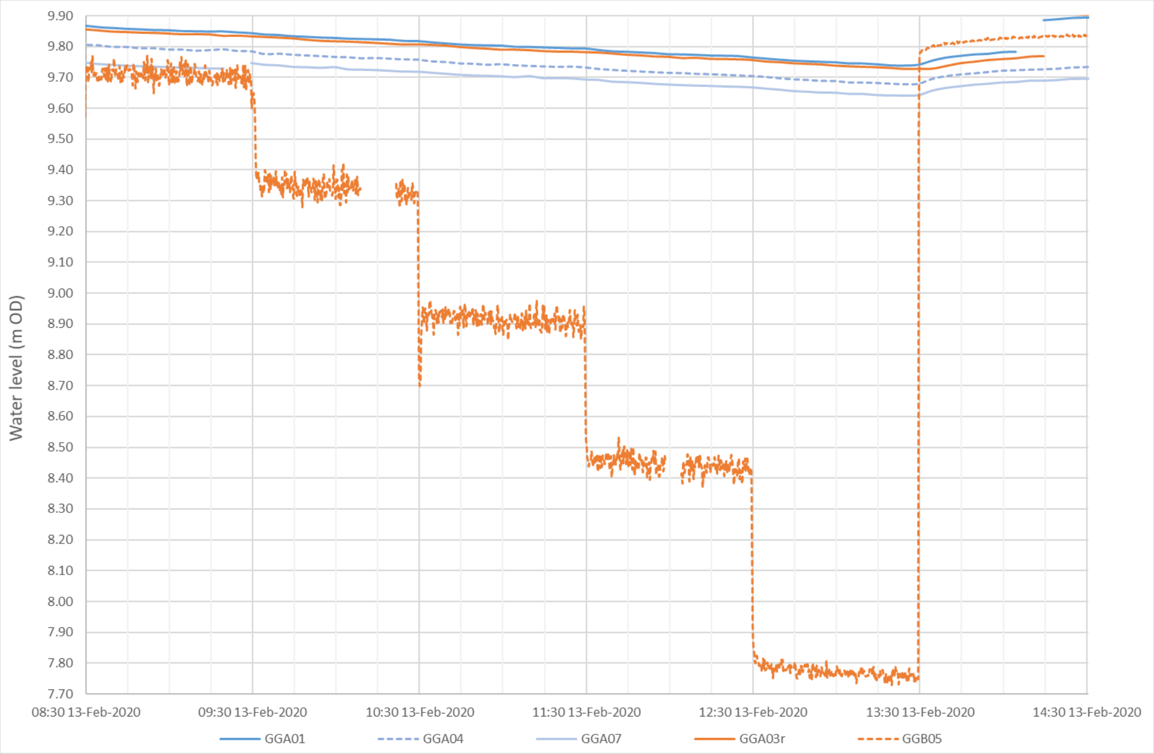


**Figure 32 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGB05**

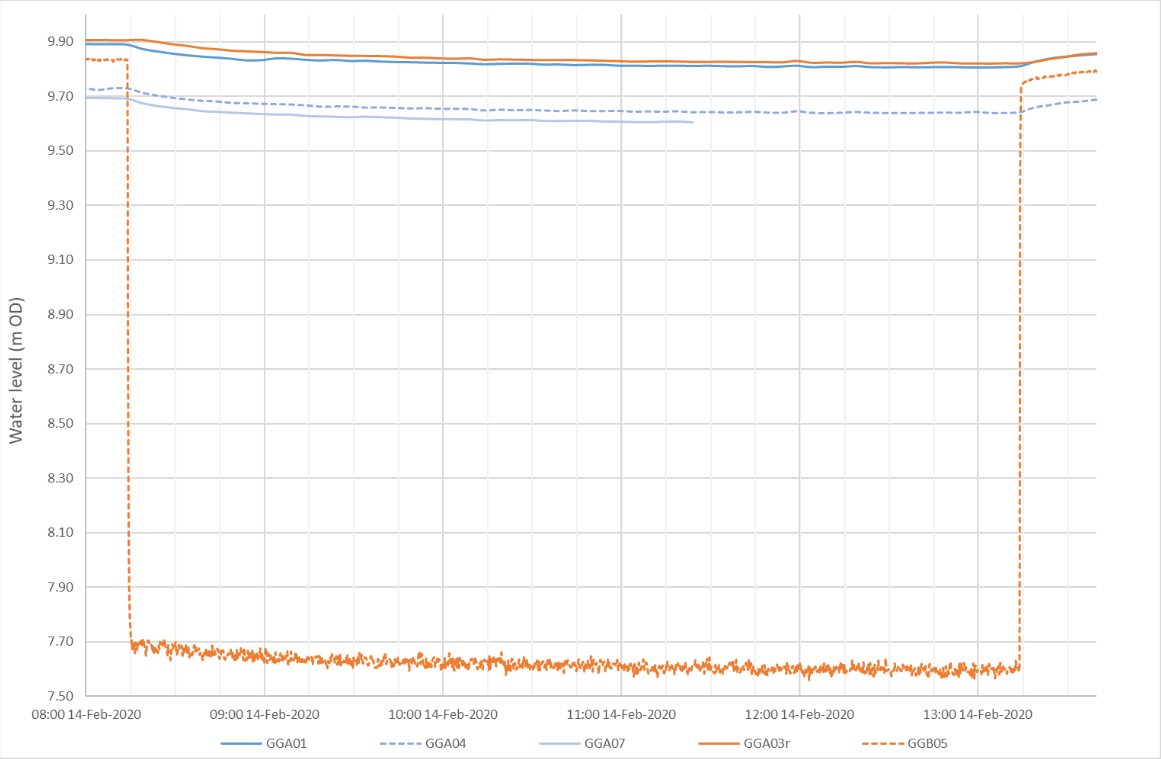


**Figure 33 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGB05**

### 5.2.4 Preliminary time-drawdown curves of GGB05

Figure 34 and Figure 35 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGB05, see Section 2.5 for more detail on the analyses used. A transmissivity value of 990 $m^2$/day was derived using the Jacob straight line method for drawdown data and 580 $m^2$/day the Theis recovery method for recovery data.

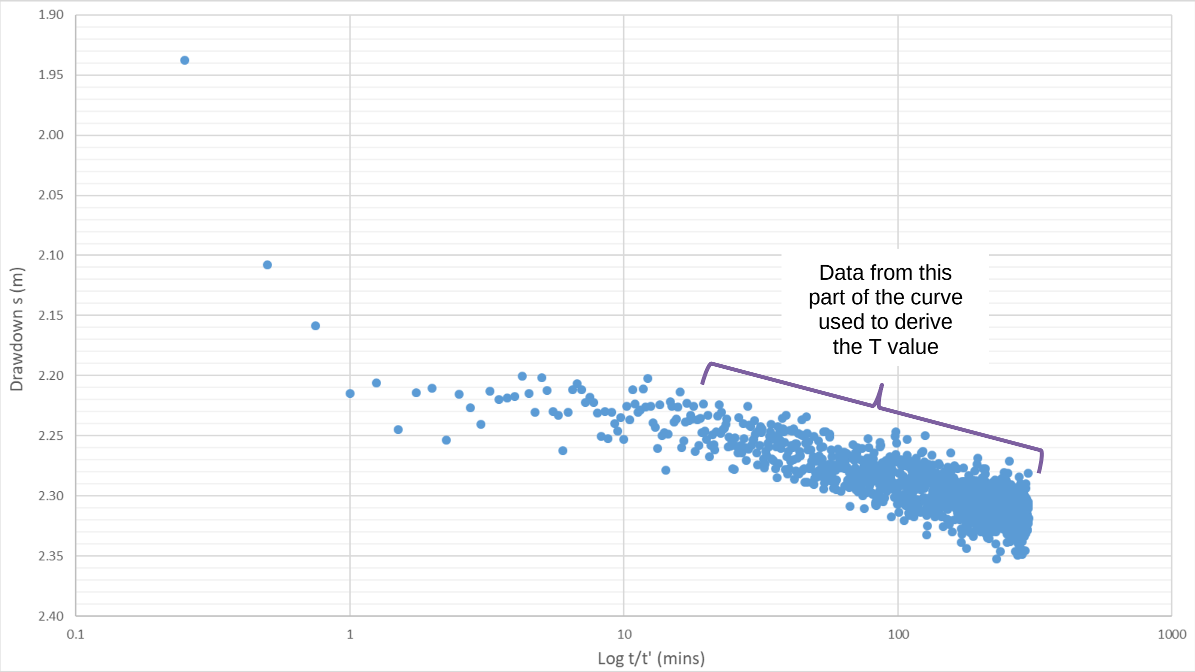


**Figure 34 Time-drawdown (from data logger) for drawdown phase of CRT on GGB05**

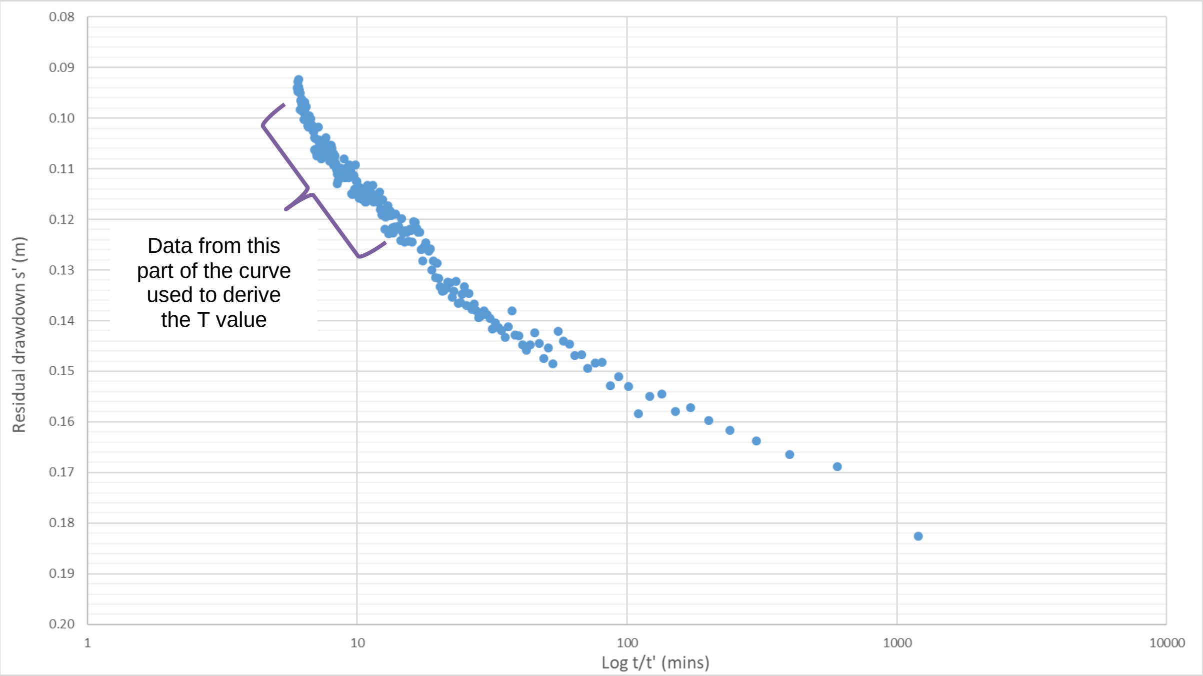


**Figure 35 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGB05**

# 6 Glasgow Upper mine working boreholes

Presented in Sections 6.1 to 0 are the results of test pumping carried out on the three boreholes installed in the Glasgow Upper mine working of the Glasgow Observatory, GGA01 (located at Site 1), GGA04 (located at Site 2) and GGA07 (located at Site 3).

## 6.1 TEST PUMPING: GGA01

### 6.1.1 Overview of GGA01

An overview of the test pumping carried out on GGA01 is in Table 11. Further details on the geology and borehole construction can be found in the GGA01 borehole information pack, which can be downloaded here: https://doi.org/10.5285/0d496c68-f79b-4956-8cd2-4970d1e86145.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA01_SDT&CRT_Hydraulicdata.xlsx
- SDT_ GGA01_FINAL_V2.xlsx
- CRT_ GGA01_FINAL_V2.xlsx
- GGA01_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA01 provided by Drilcorp is in file:

- GGA01_Welltesting_Jan-2020_Report_v5.pdf

**Table 11 Overview of test pumping on GGA01**

| | **Step drawdown test** | **Constant rate test** |
|---|---|---|
| Target aquifer horizon | Glasgow Upper | |
| Description of screened section | Overlying sandstone roof and Glasgow Upper mine working waste | |
| Depth of top of screened interval (m below top of borehole casing) | 44.81 | |
| Length of screened section (m) | 3.6 | |
| Approximate height of mine working (m) | 1.26 | |
| Type of pump | Grundfos SP 95-4 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 42.31 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.82 | |
| Height of final floor level of manhole chamber (m OD) | 9.38 | |
| Date of test | 14/01/2020 | 15/01/2020 |
| Start time of pumping | 10:15 | 10:05 |
| End time of pumping | 15:15 | 15:05 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Average pumping rates for each step (L/s) | 4.8/10.3/15/19.7/24.9 | 19.9 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 270 | 360 |
| Rest water level (m below top of dip tube) | 0.40 | 0.47 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 2.12 | 1.81 |
| Maximum drawdown during pump test (m) | 1.73 | 1.34 |

### 6.1.2 Manual dip and logger data for GGA01

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 36 and Figure 37 plot the manual and logger data from the SDT and CRT on GGA01.

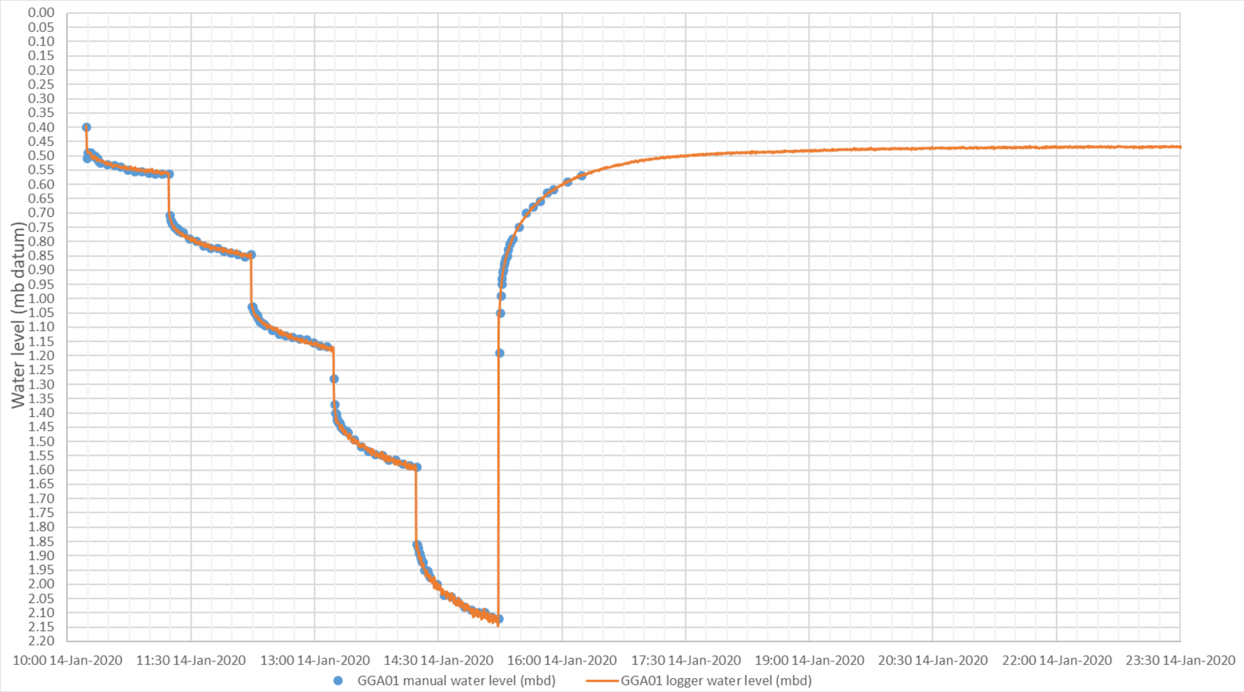


**Figure 36 Borehole water levels in GGA01 during SDT (data logger and manual dips)**

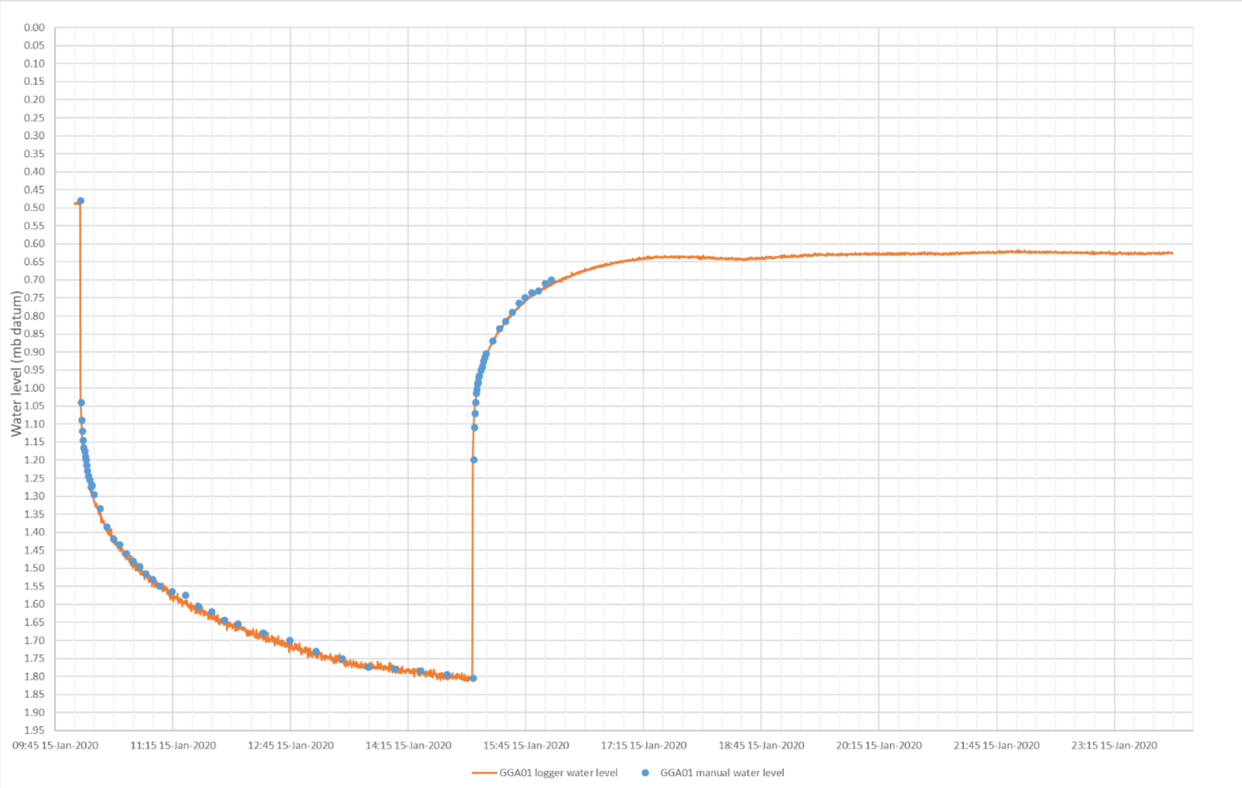


**Figure 37 Borehole water levels in GGA01 during CRT (data logger and manual dips**

### 6.1.3 Observation data during GGA01 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA01 pump tests

Figure 38 and Figure 39. For clarity the superficial boreholes have not been included on these graphs as they showed no obvious water level change during these tests.

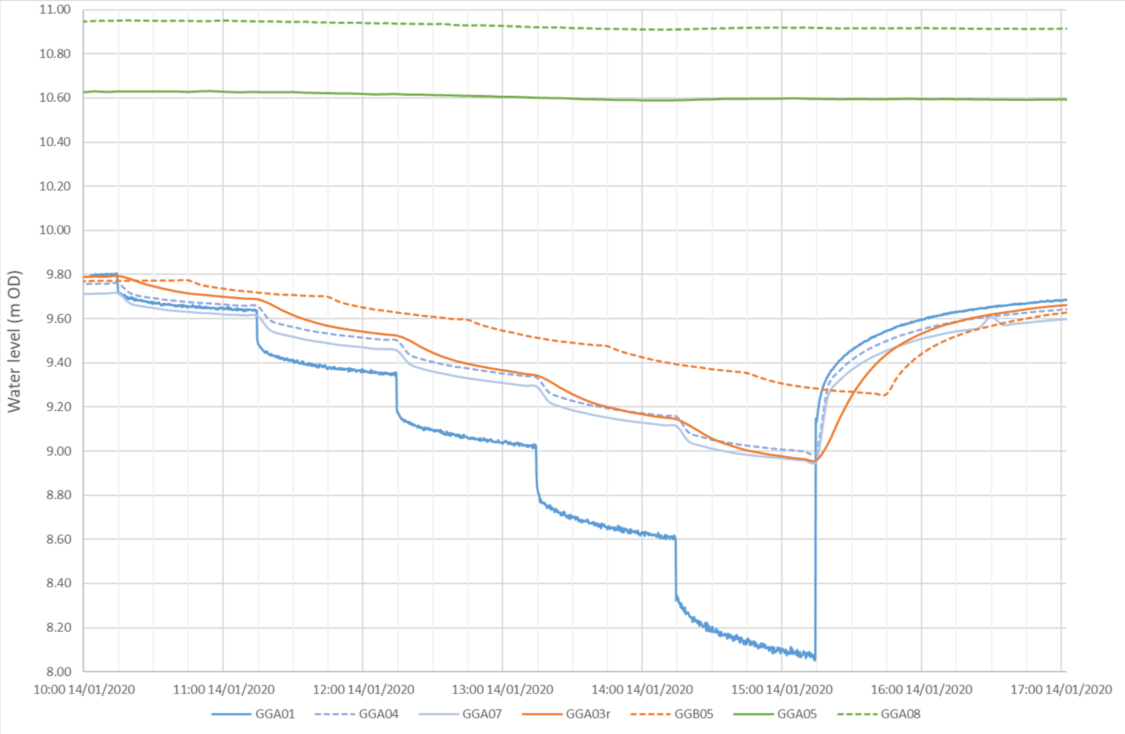


**Figure 38 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA01**

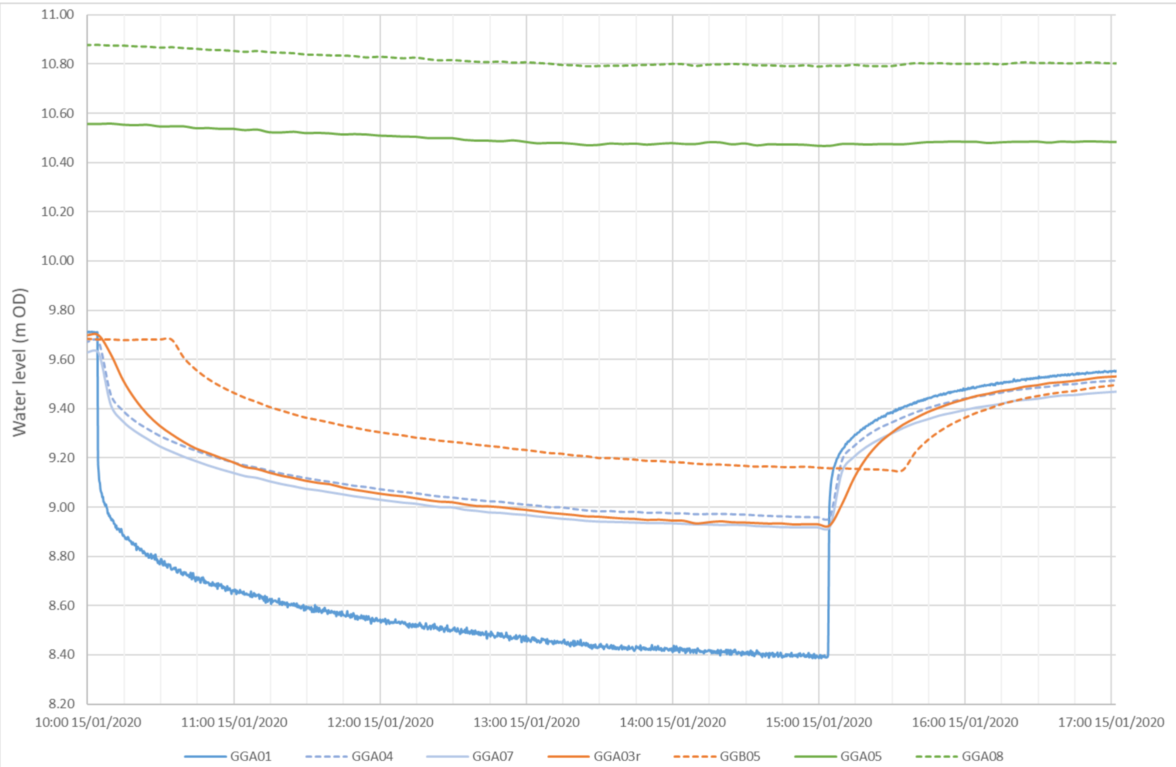


**Figure 39 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA01**

### 6.1.4 Preliminary time-drawdown curves of GGA01

Figure 40 and Figure 41 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT GGA01. See Section 2.5 for more detail on the analyses used. A transmissivity value of 1130 $m^2$/day was derived using the Jacob straight line method for drawdown data and 1020 $m^2$/day using the Theis recovery method for recovery data.

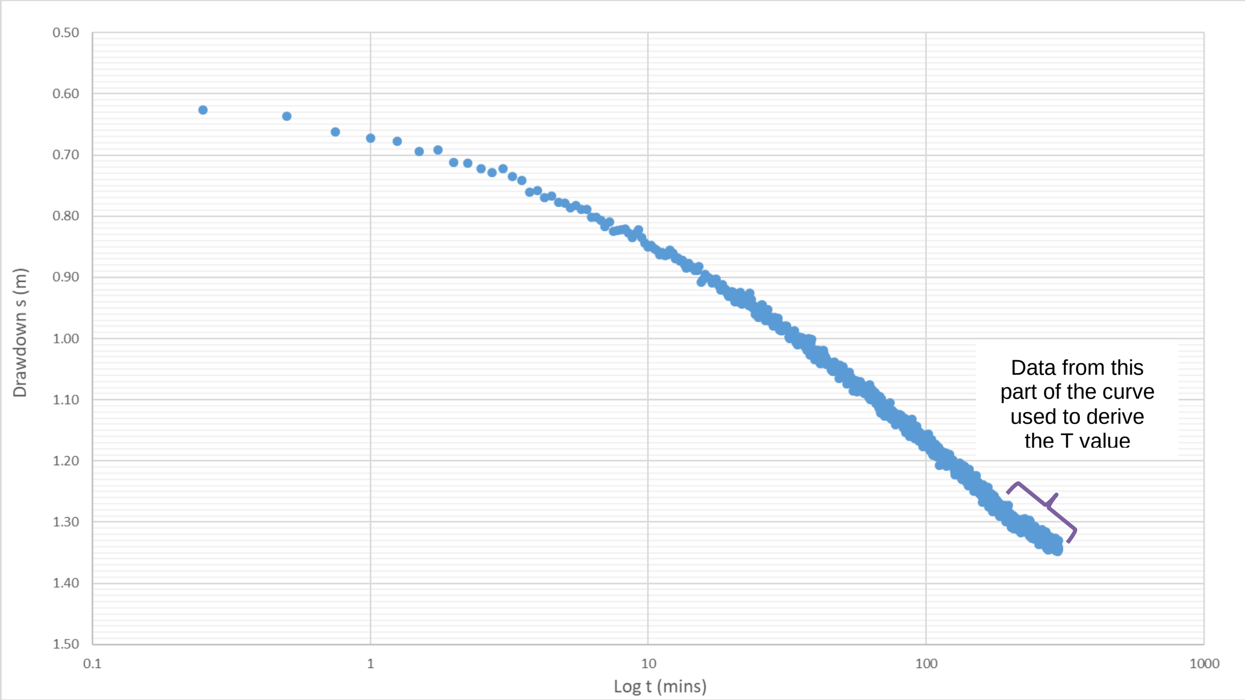


**Figure 40 Time-drawdown (from data logger) for drawdown phase of CRT on GGA01**

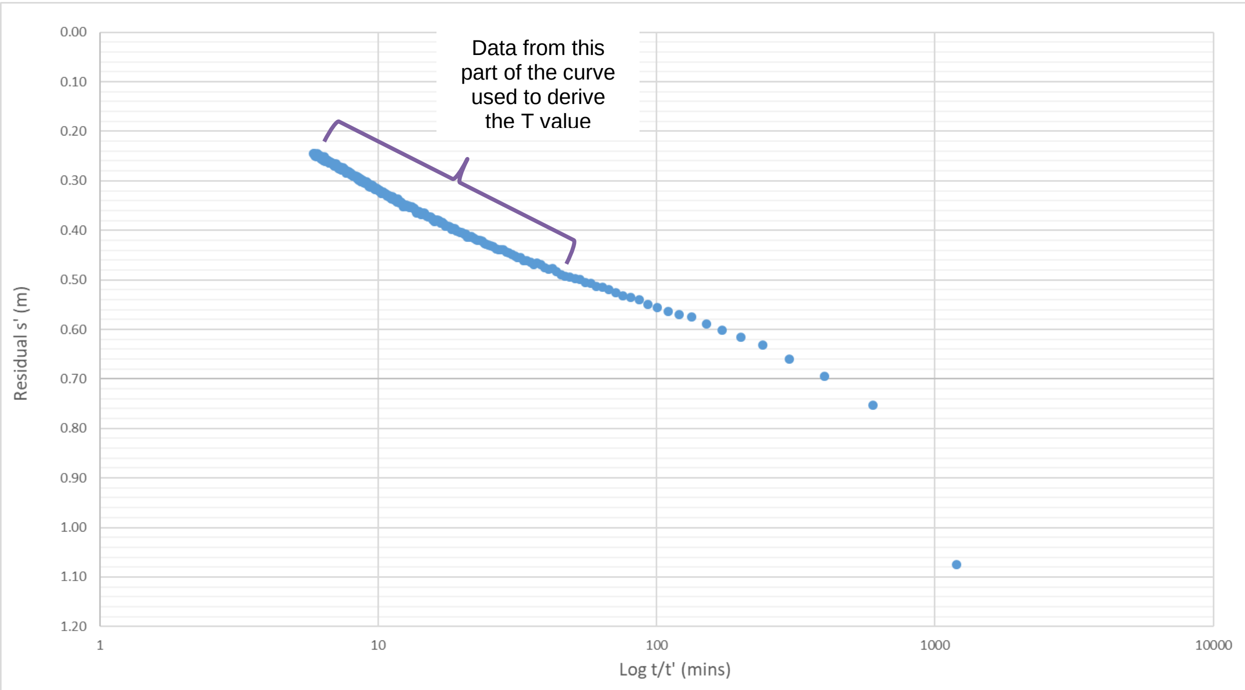


**Figure 41 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA01**

## 6.2 TEST PUMPING: GGA04

### 6.2.1 Overview of GGA04

An overview of the test pumping carried out on GGA04 is in Table 12. Further details on the geology and borehole construction can be found in the GGA04 borehole information pack, which can be downloaded here: https://doi.org/10.5285/83ab3481-45d9-475d-8814-008edc9fb1cb.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA04_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGA04_FINAL.xlsx
- CRT_ GGA04_FINAL.xlsx
- GGA04_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA04 provided by Drilcorp is in file:

- GGA04_Welltesting_Jan-2020_Report_v2.pdf

**Table 12 Overview of test pumping on GGA04**

| | Step drawdown test | Constant rate test |
|---|---|---|
| Target aquifer horizon | Glasgow Upper | |
| Description of screened section | Overlying sandstone roof and Glasgow Upper mine working position, coal and mudstone | |
| Depth of top of screened interval (m below top of borehole casing) | 47.4 | |
| Length of screened section (m) | 3.6 | |
| Approximate thickness of coal/mudstone | 1.14 | |
| Type of pump | Grundfos SP 95-4 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 44.28 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.76 | |
| Height of floor of manhole chamber (m OD) | 11.53 | |
| Date of test | 27/01/2020 | 28/01/2020 |
| Start time of pumping | 09:15 | 09:15 |
| End time of pumping | 14:15 | 14:15 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Pumping rates for each step (L/s) | 4/7.9/11.7/15.5/19.8 | 14.8 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 214 | 270 |
| Rest water level (m below top of dip tube) | 2.73 | 2.74 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 31.51 | 18.24 |
| Maximum drawdown during pump test (m) | 28.78 | 18.24 |

### 6.2.2 Manual dip and logger data for GGA04

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 42 and Figure 43 plot the manual and logger data from the SDT and CRT on GGA04.

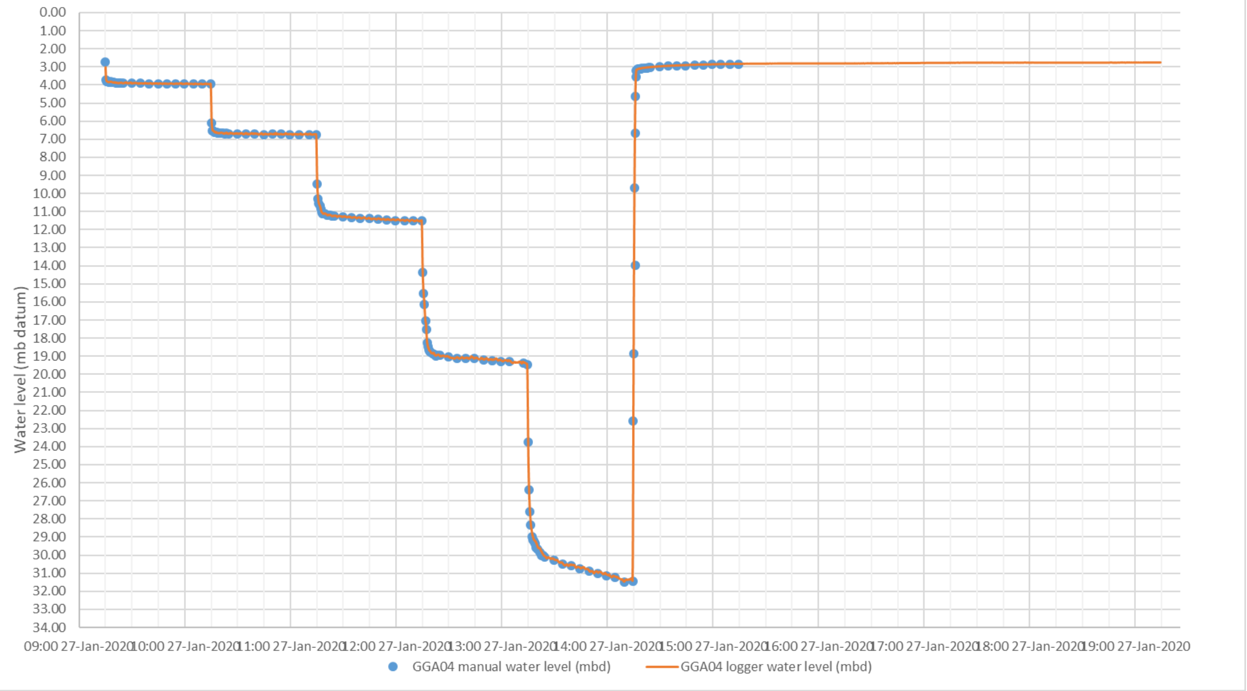


**Figure 42 Borehole water levels in GGA04 during the SDT (data logger and manual dip)**

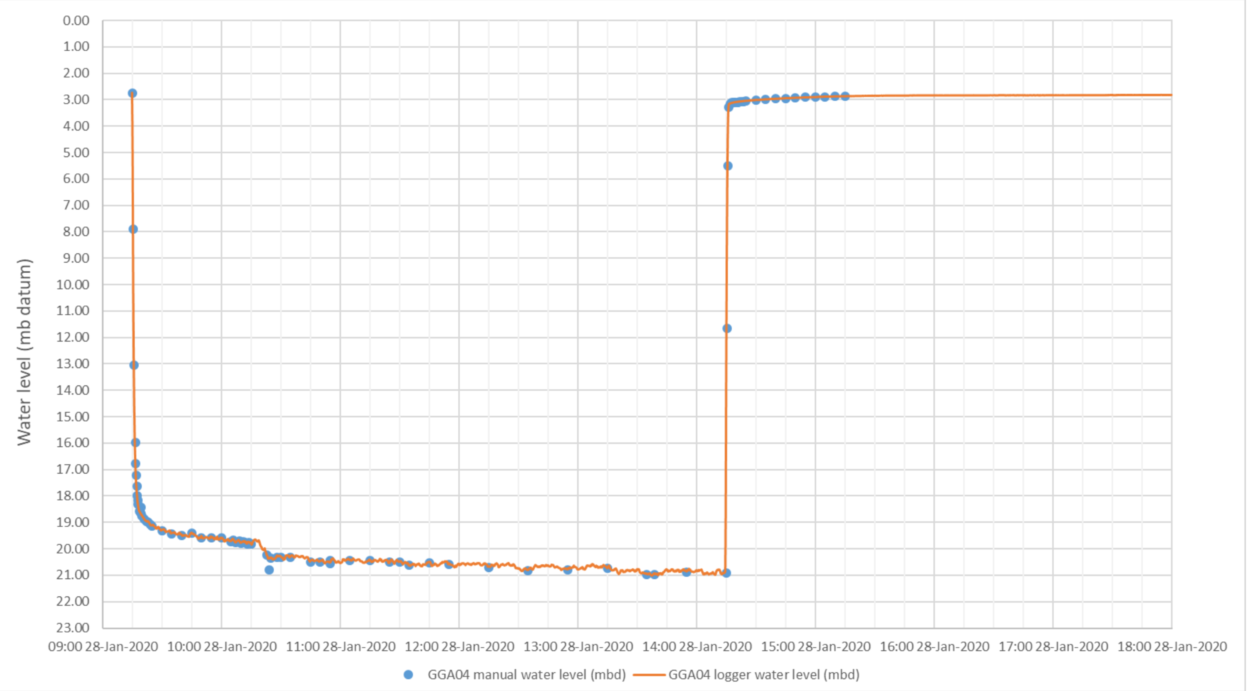


**Figure 43 Borehole water levels in GGA04 during the CRT (data logger and manual dip)**

### 6.2.3 Observation data during GGA04 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA04 pump tests. Figure 44 is the observation data during the SDT and Figure 45 during the CRT of GGA04. For clarity the superficial boreholes have not been included on these graphs as they showed no obvious water level change during these tests.

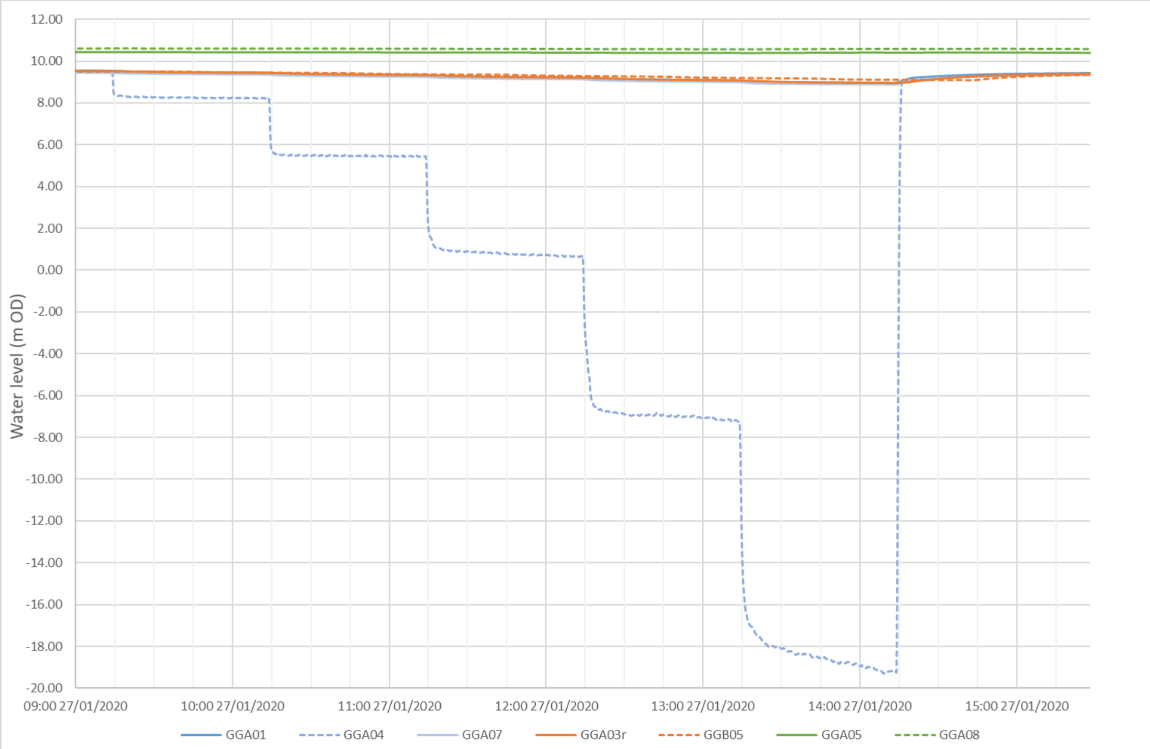


**Figure 44 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA04. Data from GGA01 and GGA07 is included on the graph behind GGA03r and GGB05.**

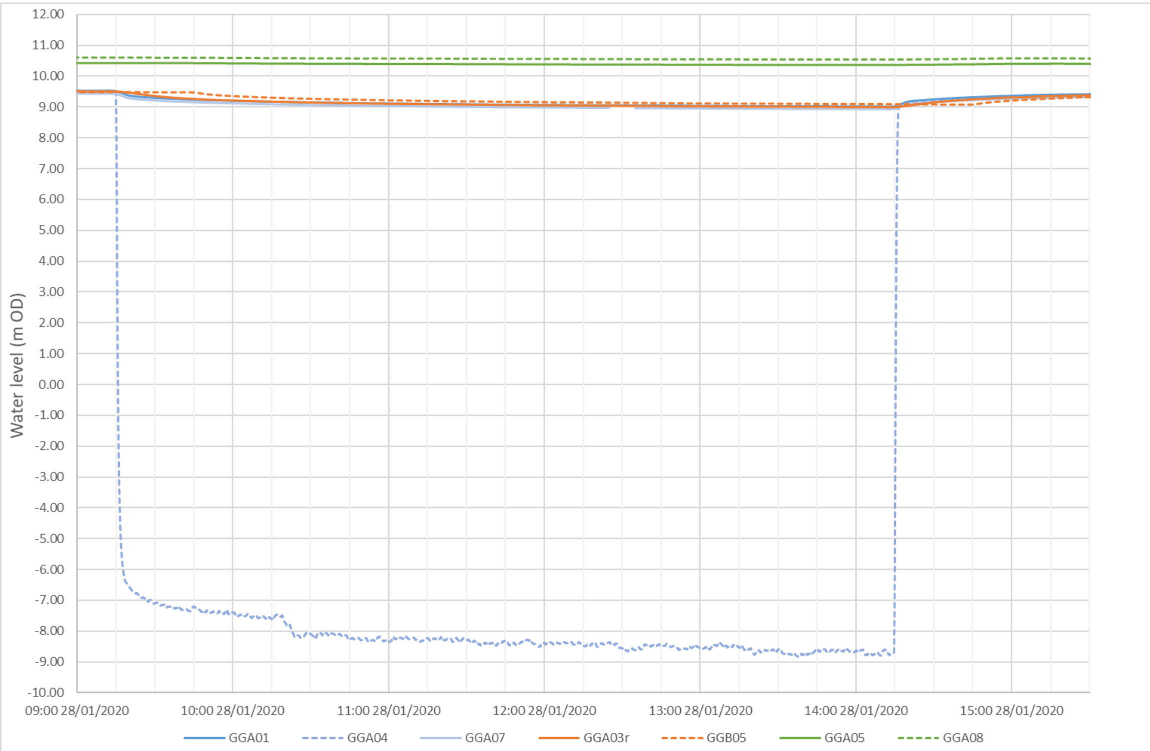


**Figure 45 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA04. Data from GGA01 and GGA07 is included on the graph behind GGA03r and GGB05.**

### 6.2.4 Preliminary time-drawdown curves of GGA04

Figure 46 and Figure 47 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA04, see Section 2.5 for more detail on the analyses used. A transmissivity value of 240 $m^2$/day was derived using the Jacob straight line method for drawdown data and 950 $m^2$/day using the Theis recovery method for recovery data.

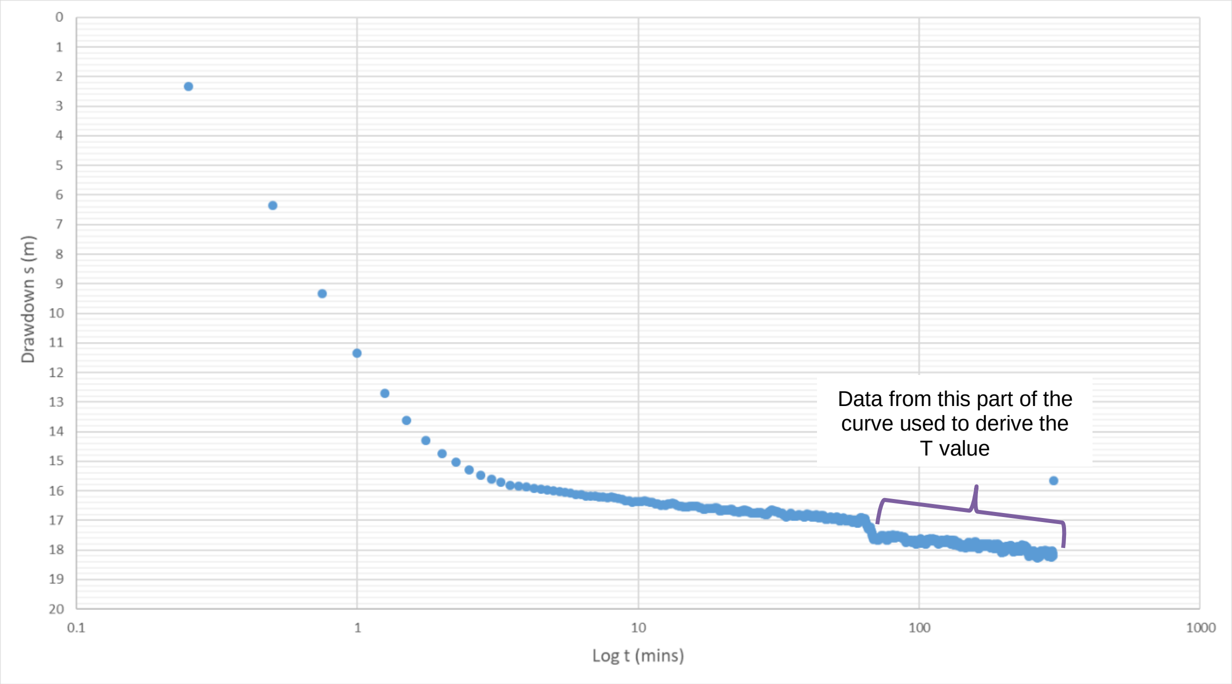


**Figure 46 Time-drawdown (from data logger) for drawdown phase of CRT on GGA04**

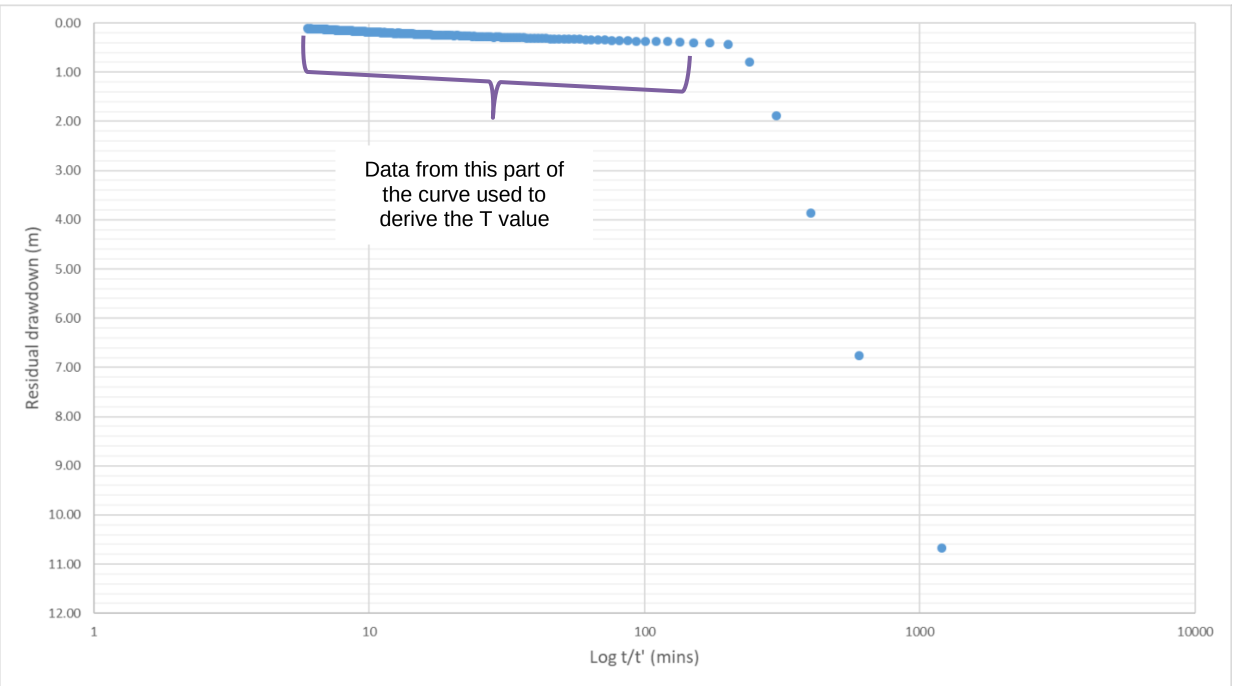


**Figure 47 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA04**

### 6.3 TEST PUMPING: GGA07

#### 6.3.1 Overview of GGA07

An overview of the test pumping carried out on GGA07 is in Table 13. Further details on the geology and borehole construction can be found in the GGA07 borehole information pack, which can be downloaded here: https://doi.org/10.5285/d8d27fb5-3be4-4a54-aef7-8429ec234667.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA07_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGA07_FINAL.xlsx
- CRT_ GGA07_FINAL.xlsx
- GGA07_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA07 provided by Drilcorp is in file:

- GGA07_Welltesting_Feb-2020_Report_v1.pdf

**Table 13 Overview of test pumping on GGA07**

| | **Step drawdown test** | **Constant rate test** |
|---|---|---|
| Target aquifer horizon | Glasgow Upper | |
| Description of screened section | Overlying mudstone and Glasgow Upper mine working, coal pillar and void | |
| Depth of top of screened interval (m below top of borehole casing) | 50.91 | |
| Length of screened section (m) | 2.7 | |
| Approximate height of mine working (m) | 1.7 | |
| Type of pump | Grundfos SP 95-4 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 43.25 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.68 | |
| Height of floor of manhole chamber (m OD) | 10.78 | |
| Date of test | 06/02/2020 | 07/02/2020 |
| Start time of pumping | 08:50 | 08:45 |
| End time of pumping | 13:50 | 13:45 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Pumping rates for each step (L/s) | 5/10.1/15/20/25 | 20 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 270 | 360 |
| Rest water level (m below top of dip tube) | 1.97 | 1.98 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 5.08 | 4.23 |
| Maximum drawdown during pump test (m) | 3.11 | 2.27 |

### 6.3.2 Manual dip and logger data for GGA07

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 48 and Figure 49 plot the manual and logger data from the SDT and CRT on GGA07.

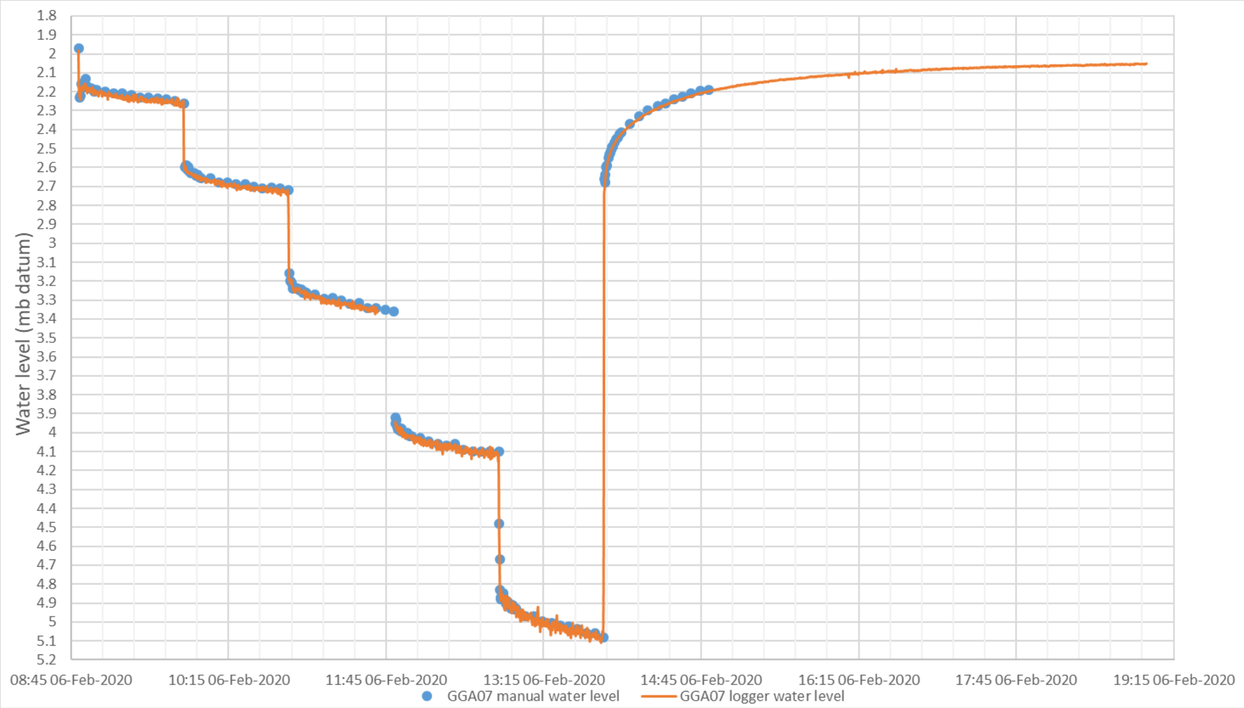


**Figure 48 Borehole water levels in GGA07 during SDT (data logger and manual dip)**

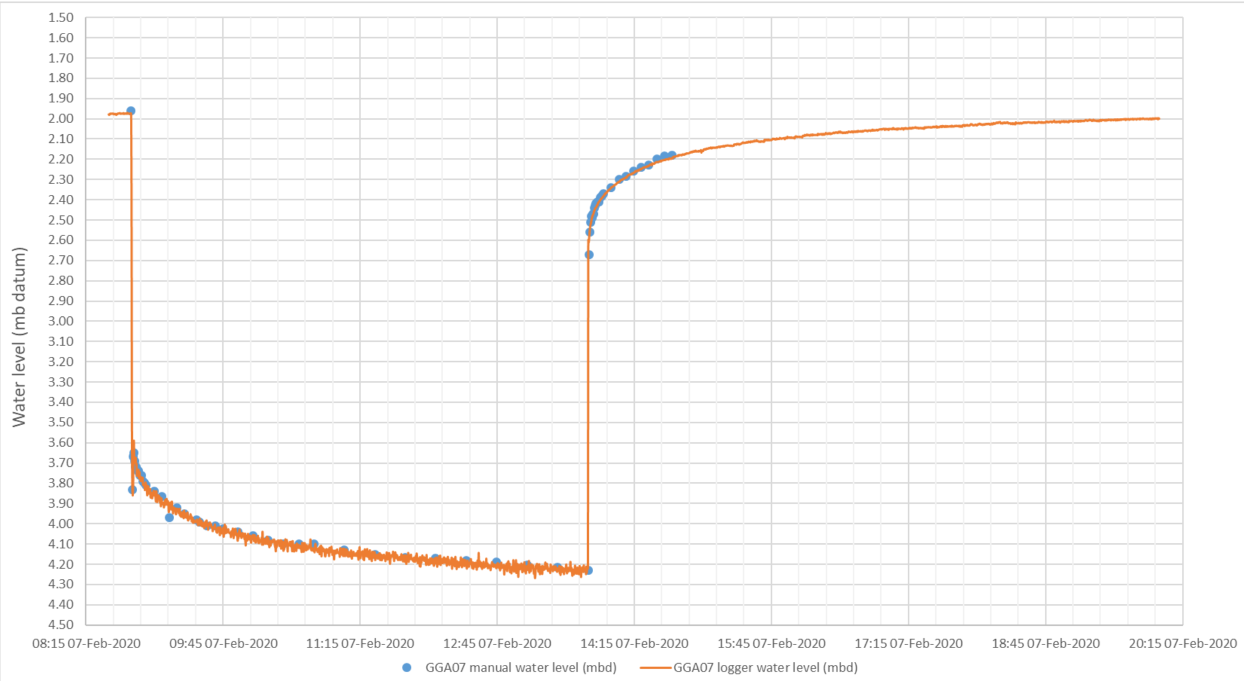


**Figure 49 Borehole water levels in GGA07 during CRT (data logger and manual dip)**

### 6.3.4 Observation data during GGA07 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA07 pump tests Figure 50 is the observation data during the SDT and Figure 51 during the CRT of GGA07. For clarity the superficial boreholes have not been included on these graphs as they showed no obvious water level change during these tests.

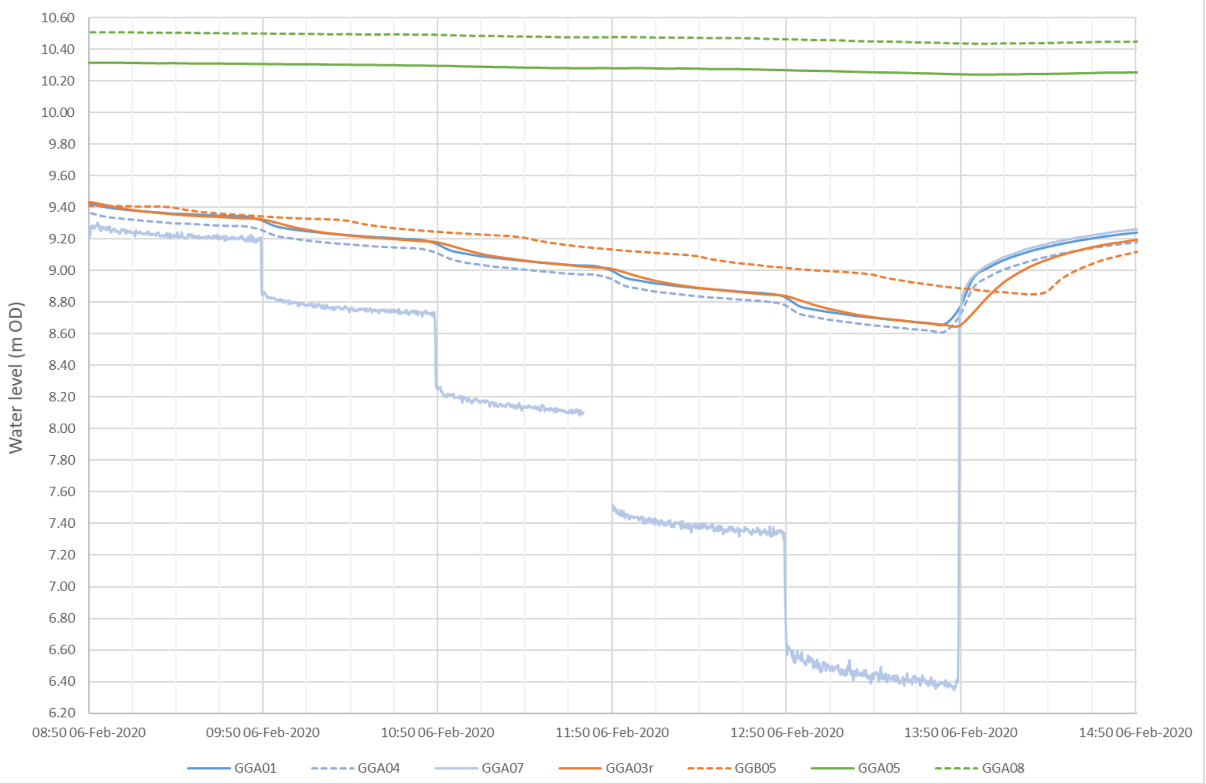


**Figure 50 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA07**

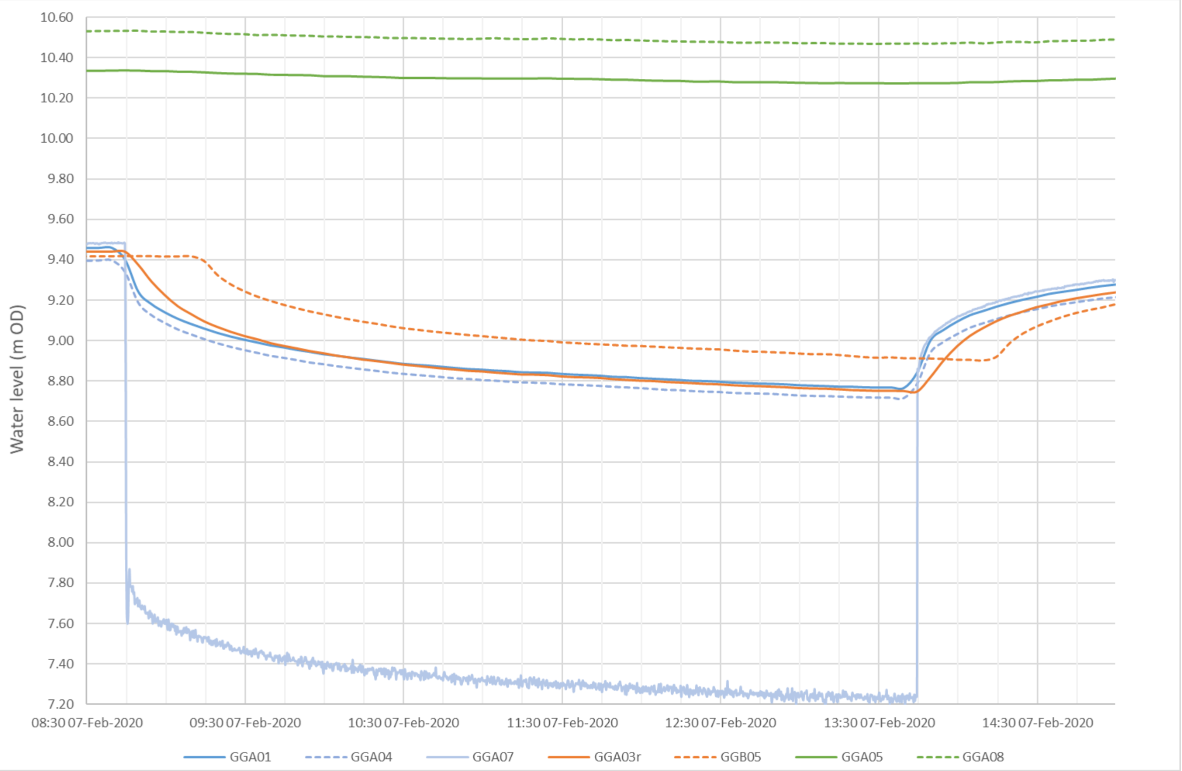


**Figure 51 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA07**

### 6.3.5 Preliminary time-drawdown curves of GGA07

Figure 52 and Figure 53 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA07, see Section 2.5 for more detail on the analyses used. A transmissivity value of 1050 $m^2$/day was derived using the Jacob straight line method for drawdown data and 1020 $m^2$/day using the Theis recovery method for recovery data.

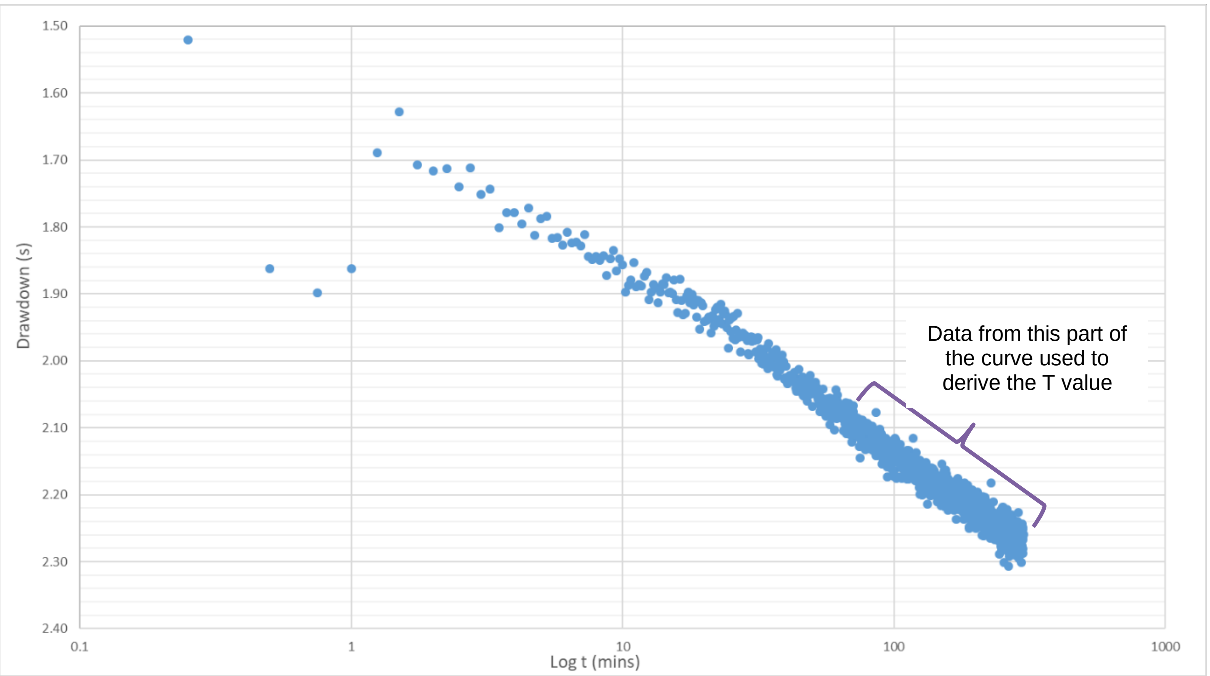


**Figure 52 Time-drawdown (from data logger) for drawdown phase of CRT on GGA07**

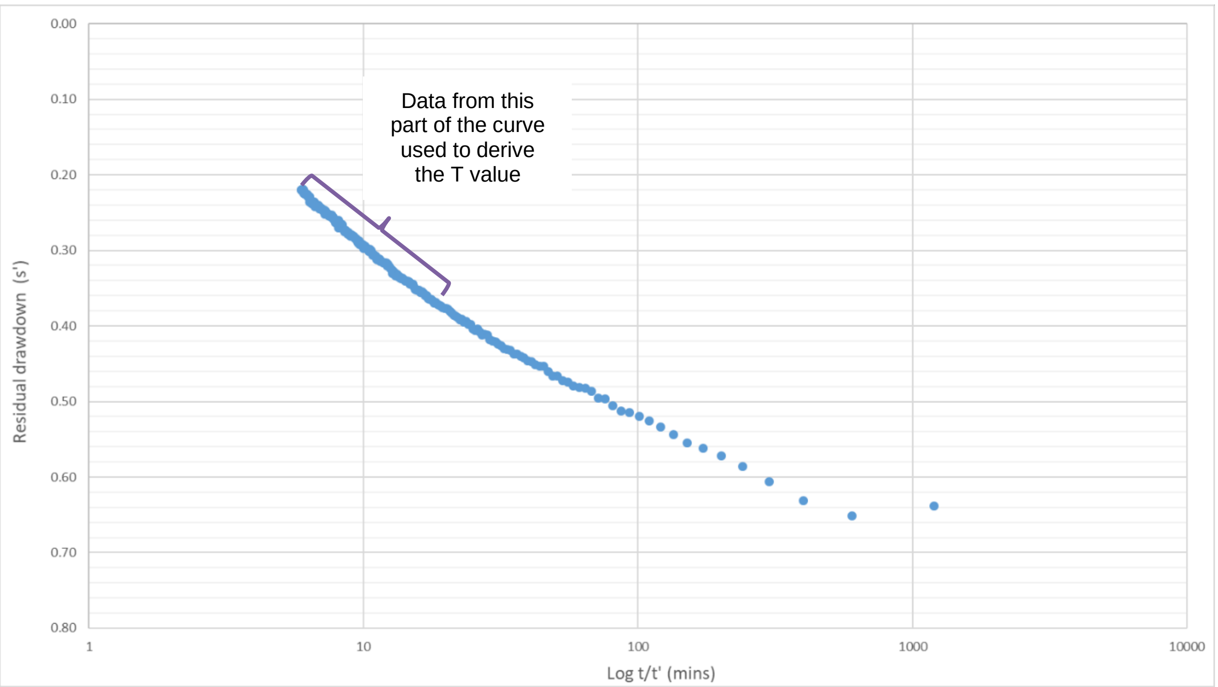


**Figure 53 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA07**

# 7 Glasgow Main mine working boreholes

Presented in Sections 7.1 and 0 are the results of test pumping carried out on the two boreholes installed in the Glasgow Main mine working, GGA05 (located at Site 2) and GGA08 (located at Site 3).

## 7.1 TEST PUMPING: GGA05

### 7.1.1 Overview of GGA05

An overview of the test pumping carried out on GGA05 is in Table 14. Further details on the geology and borehole construction can be found in the GGA05 borehole information pack, which can be downloaded here: https://doi.org/10.5285/714fe9fc-ce77-4479-8053-1c5fd4e86f06.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA05_SDT&CRT_Hydraulic data_v1.xlsx
- SDT_ GGA05_FINAL.xlsx
- CRT_ GGA05_FINAL.xlsx
- GGA05_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA05 provided by Drilcorp is in file:

- GGA05_Welltesting_Jan-2020_Report_v2.pdf

**Table 14 Overview of test pumping on GGA05**

| | Step drawdown test | Constant rate test |
|---|---|---|
| Target aquifer horizon | Glasgow Main | |
| Description of screened section | Overlying sandstone roof and Glasgow Main mine working void, to mudstone floor | |
| Depth of top of screened interval (m below top of borehole casing) | 83.6 | |
| Length of screened section (m) | 2.7 | |
| Approximate height of mine working (m) | 0.7 void and 1.7 disrupted floor zone | |
| Type of pump | Grundfos SP 95-4 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 50.02 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.71 | |
| Height of final floor level of manhole chamber (m OD) | 11.5 | |
| Date of test | 22/01/2020 | 23/01/2020 |
| Start time of pumping | 08:45 | 08:45 |
| End time of pumping | 13:45 | 13:45 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Average pumping rates for each step (L/s) | 5/10/14.9/19.9/25 | 19.8 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 270 | 360 |
| Rest water level (m below top of dip tube) | 1.89 | 1.87 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 2.24 | 2.17 |
| Maximum drawdown during pump test (m) | 0.35 | 0.30 |

### 7.1.2 Manual dip and logger data for GGA05

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 54 and Figure 55 plot the manual and logger data from the SDT and CRT on GGA05.

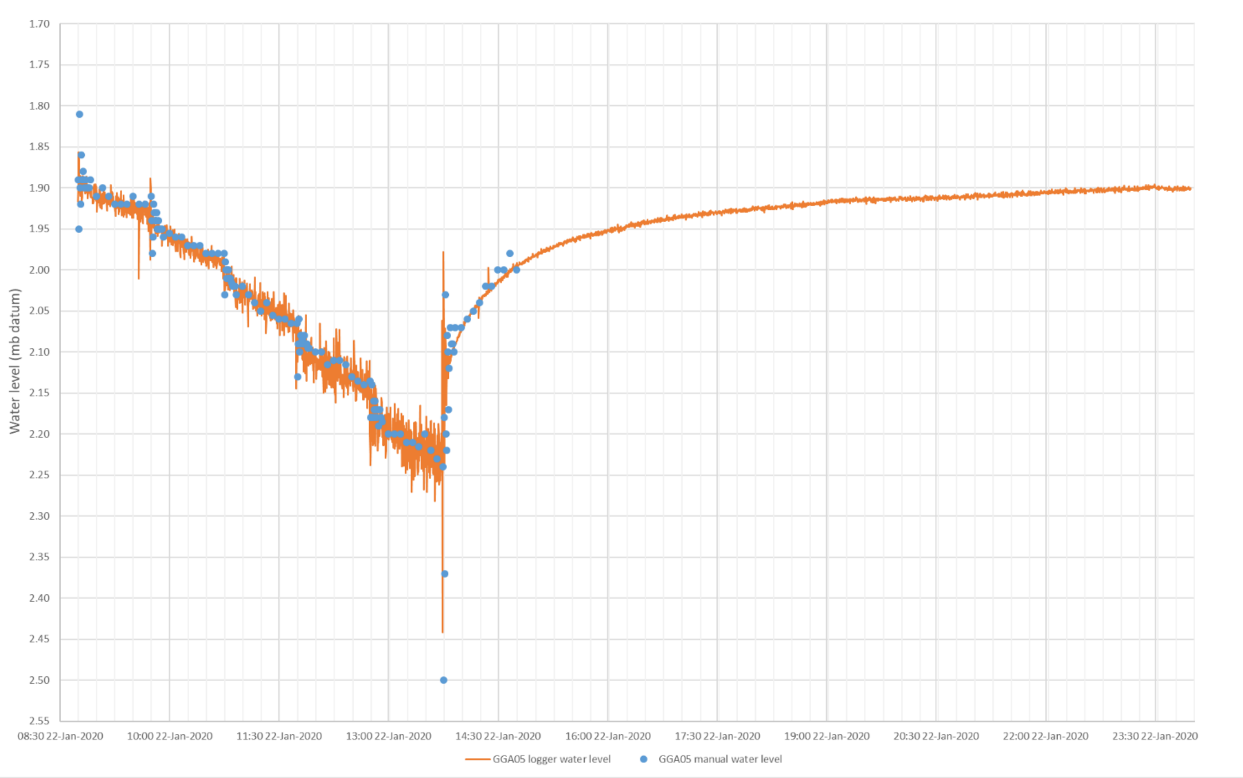


**Figure 54 Borehole water levels in GGA05 during SDT (data logger and manual dip)**

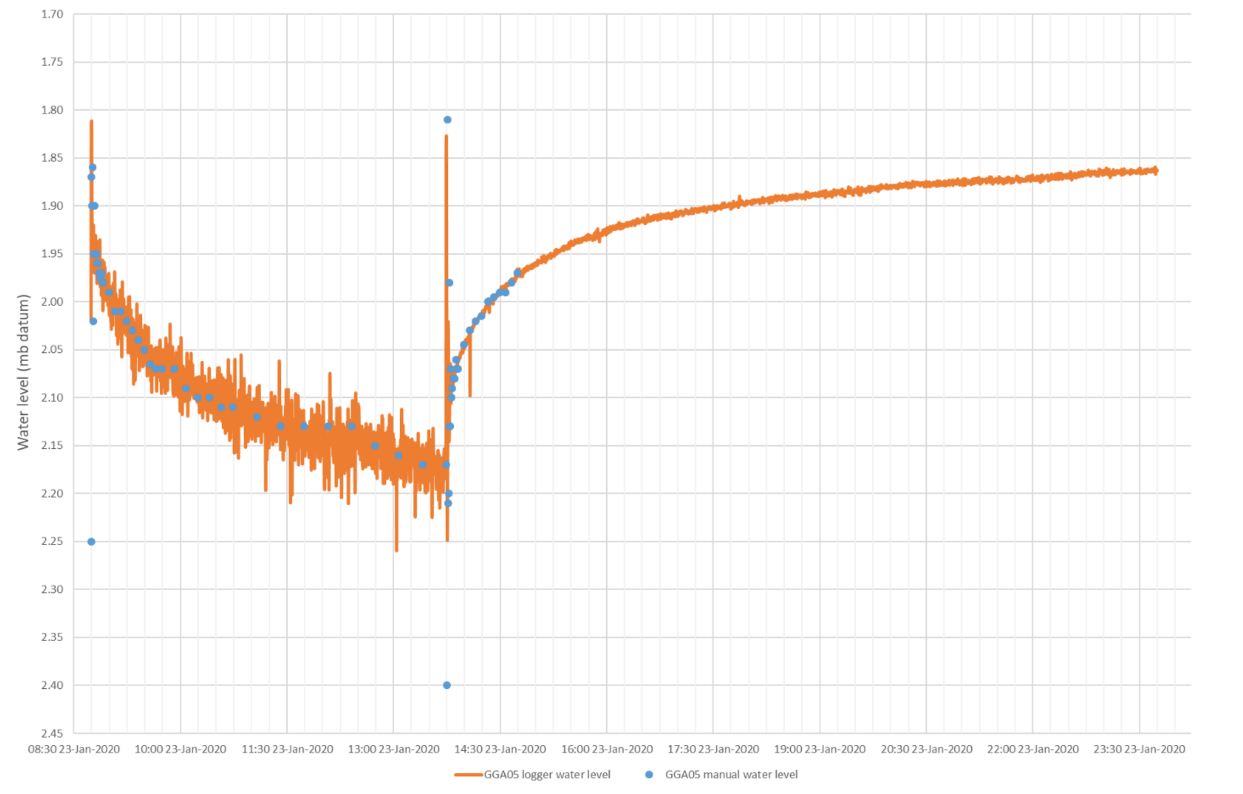


**Figure 55 Borehole water levels in GGA05 during CRT (data logger and manual dip**

### 7.1.3 Observation data during GGA05 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA05 pump tests (Figure 56 and Figure 57). For clarity the superficial boreholes have not been included on these graphs as they showed no obvious water level change during these tests.

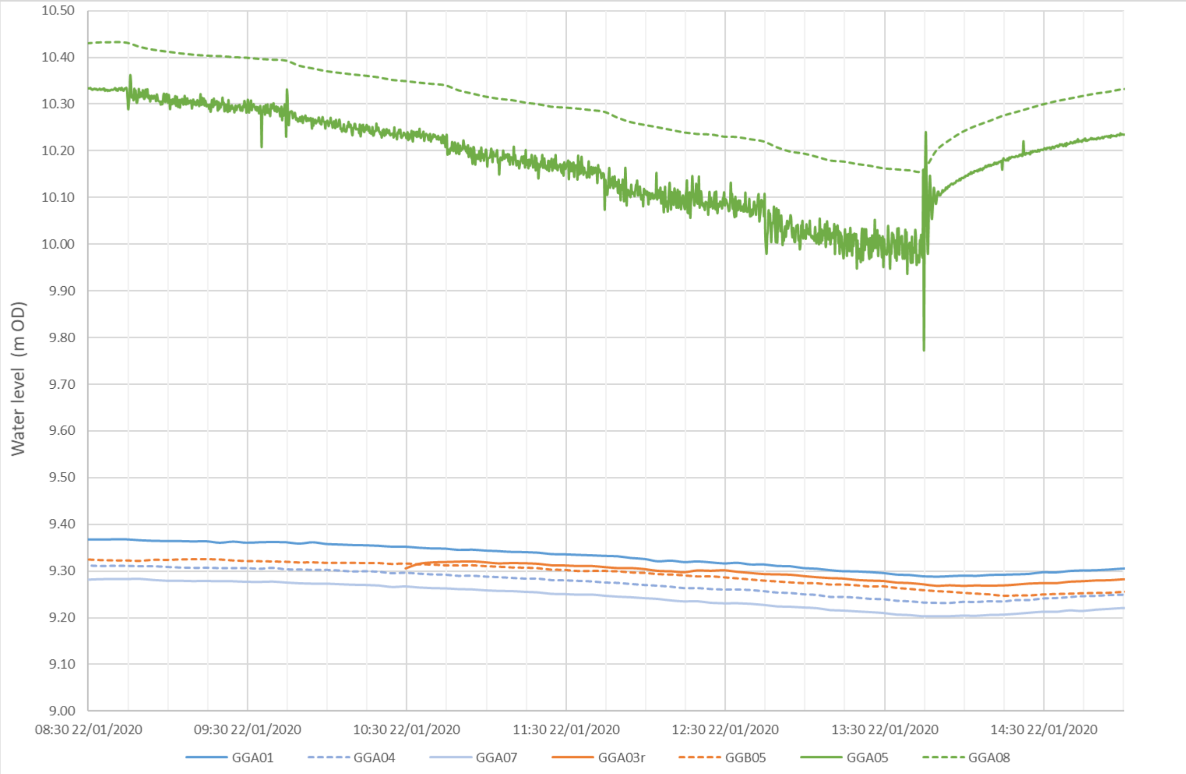


**Figure 56 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA05**


**Figure 57 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA05**

### 7.1.4 Preliminary time-drawdown curves of GGA05

Figure 58 and Figure 59 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA05, see Section 2.5 for more detail on the analyses used. A transmissivity value of 1976 $m^2$/day was derived using both the Jacob straight line method for drawdown data and the Theis recovery method for recovery data.

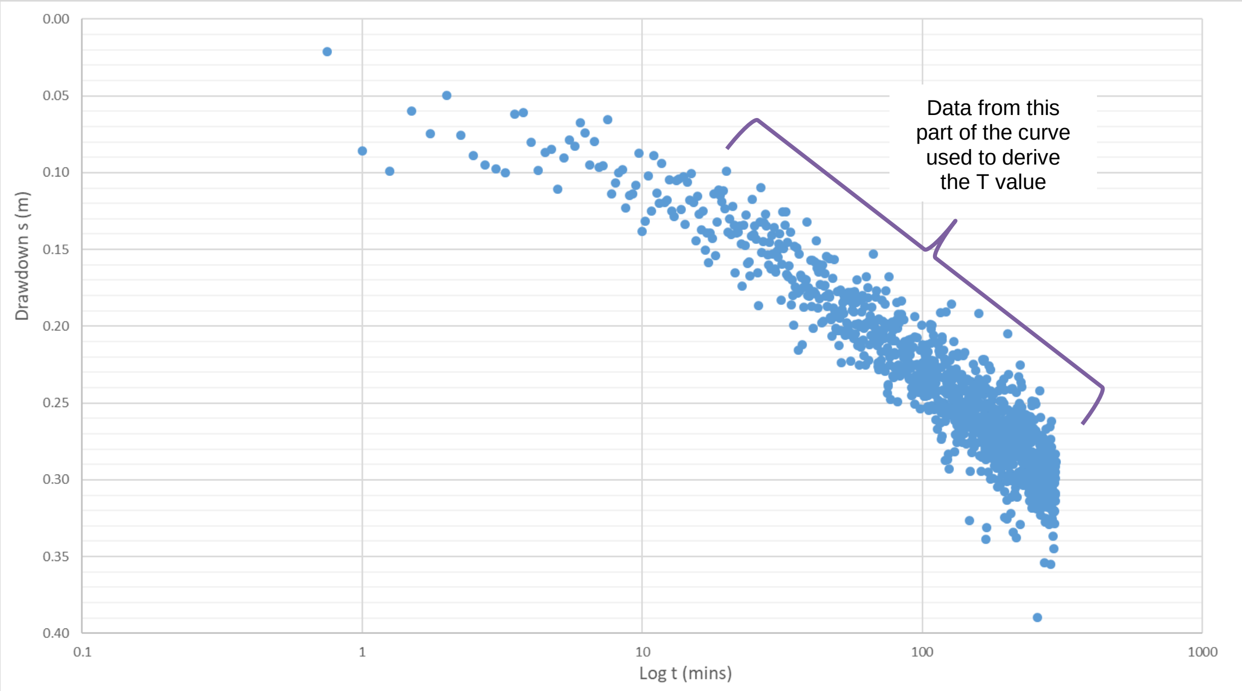


**Figure 58 Time-drawdown (from data logger) for drawdown phase of CRT on GGA05**

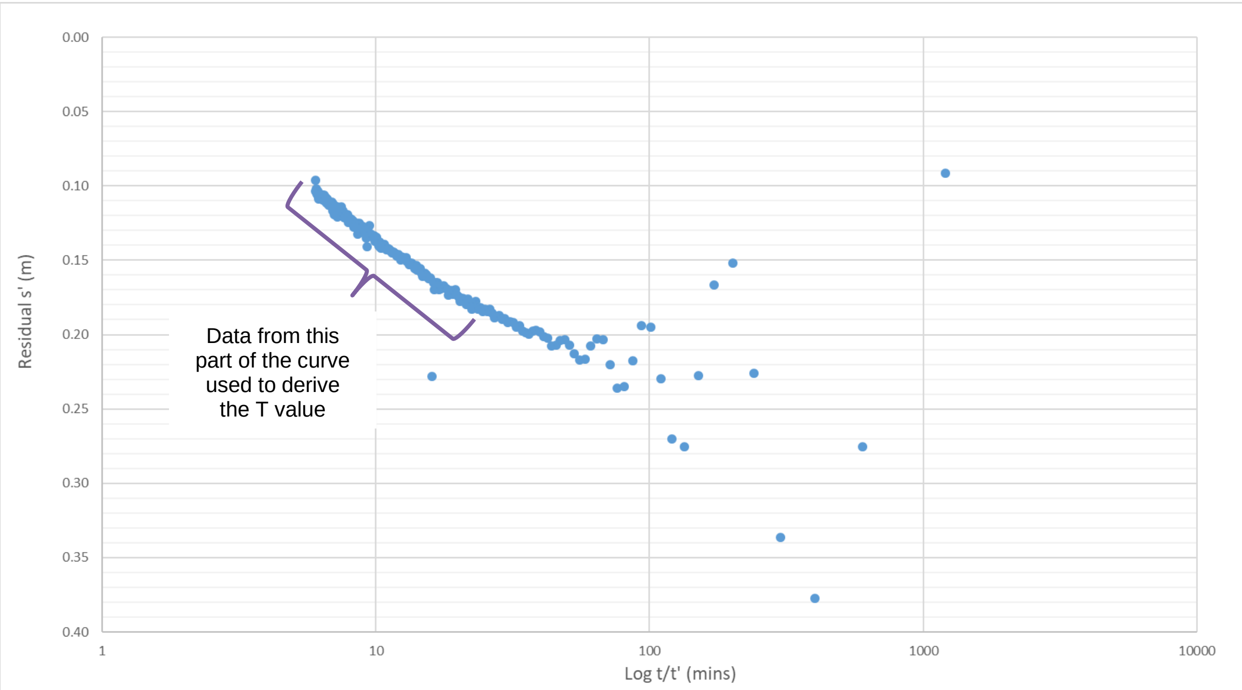


**Figure 59 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA05**

## 7.2 TEST PUMPING: GGA08

### 7.2.1 Overview of GGA08

An overview of the test pumping carried out on GGA08 is in Table 15 Further details on the geology and borehole construction can be found in the GGA08 borehole information pack, which can be downloaded here: https://doi.org/10.5285/b19497aa-75a5-4f51-8089-299f9229b9ca.

Test pumping data (including measurements of borehole water levels and pumping rates throughout the test) are available in the following files:

- GGA08_SDT&CRT_Hydraulicdata_v1.xlsx
- SDT_ GGA08_FINAL.xlsx
- CRT_ GGA08_FINAL.xlsx
- GGA08_CT2X_datalogger_V2.xlsx

A summary of the test pumping carried out on GGA08 provided by Drilcorp is in file:

- GGA08_Welltesting_Feb-2020_Report_v1.pdf

**Table 15 Overview of test pumping on GGA08**

| | **Step drawdown test** | **Constant rate test** |
|---|---|---|
| Target aquifer horizon | Glasgow Main mine working | |
| Description of screened section | Overlying sandstone/siltstone and Glasgow Main mine roadway | |
| Depth of top of screened interval (m below top of borehole casing) | 85.08 | |
| Length of screened section (m) | 2.7 | |
| Approximate height of mine working (m) | 3.0 (0.5 m is covered by installed screen) | |
| Type of pump | Grundfos SP 95-4 submersible pump | |
| Depth of pump intake (m below top of borehole casing) | 43.28 | |
| Datum for water level measurements | Top of dip tube | |
| Height of dip tube above base of borehole manhole chamber (m) | 0.82 | |
| Height of final floor level of manhole chamber (m OD) | 10.768 | |
| Date of test | 03/02/2020 | 04/02/2020 |
| Start time of pumping | 10:05 | 08:45 |
| End time of pumping | 15:05 | 13:45 |
| Number of pumping steps | 5 | 1 |
| Length of pumping steps (hours) | 1 | 5 |
| Total length of pumping (hours) | 5 | 5 |
| Average pumping rates for each step (L/s) | 5/10.1/15.2/20.2/25.2 | 20 |
| Length of manually monitored recovery period (hours) | 1 | 1 |
| Approximate volume of water abstracted ($m^3$) | 270 | 360 |
| Rest water level (m below top of dip tube) | 1.02 | 1.04 |
| Manually dipped water level at end of pumping phase (m below top of dip tube) | 1.39 | 1.39 |
| Maximum drawdown during pump test (m) | 0.37 | 0.35 |

### 7.2.2 Manual dip and logger data for GGA08

During the test pumping manual water level measurements were taken for each drawdown step and for one hour after the pump was switched off. A data logger monitored water levels every 15 seconds throughout the test duration and for a period of time before and after each test. Figure 60 and Figure 61 plot the manual and logger data from the SDT and CRT on GGA08.

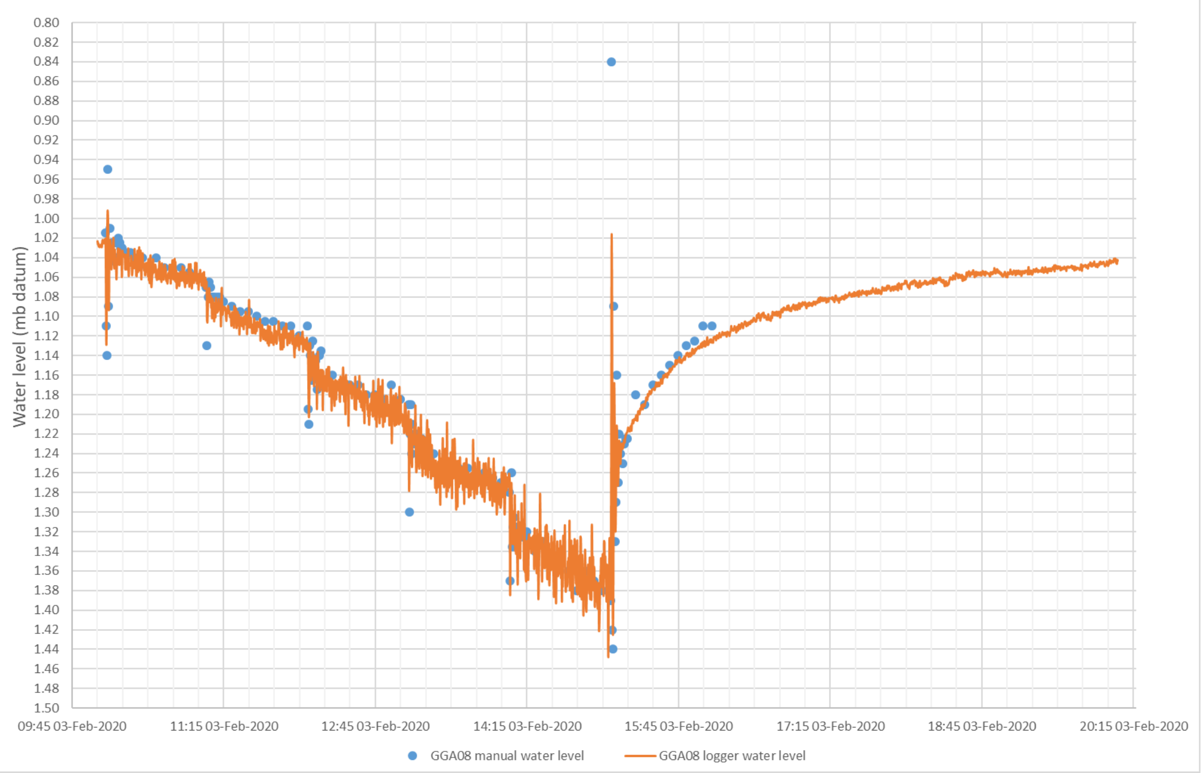


**Figure 60 Borehole water levels in GGA08 during SDT (data logger and manual dip)**

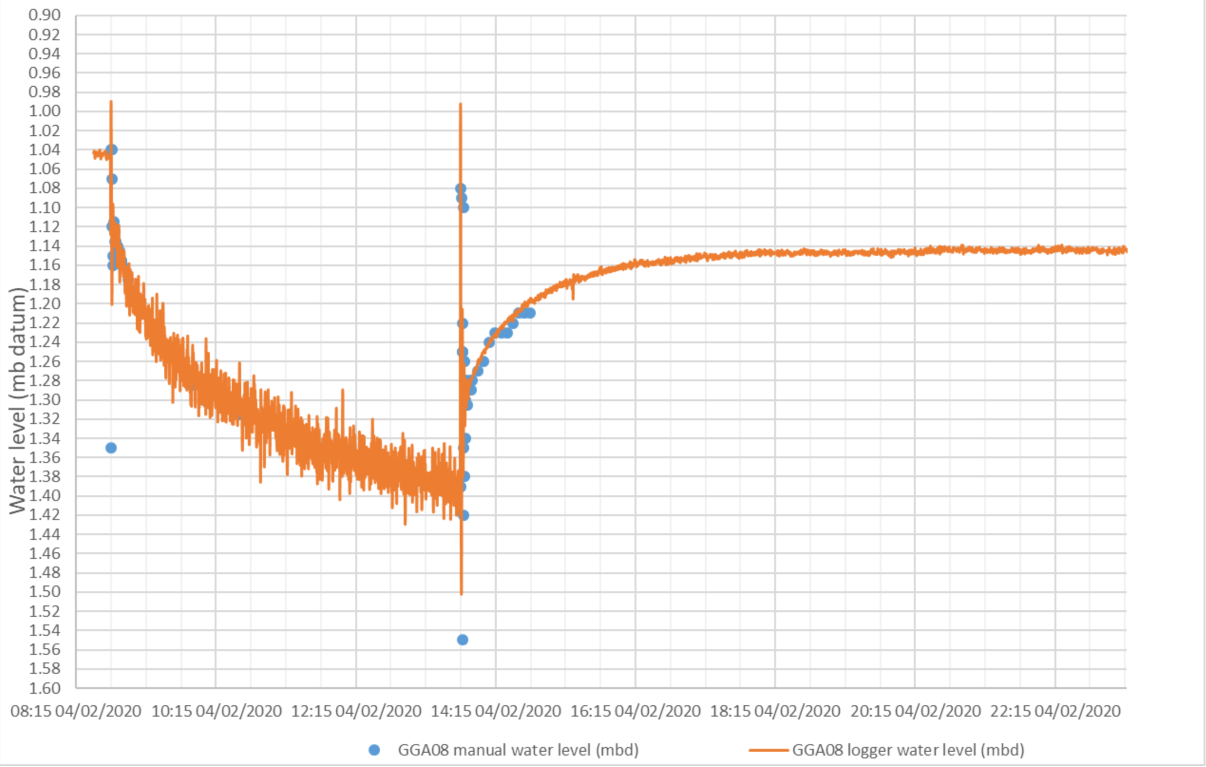


**Figure 61 Borehole water levels in GGA08 during CRT (data logger and manual dip**

### 7.2.3 Observation data during GGA08 test pumping

Data loggers were placed in the nine other observation boreholes to collect observation water level data during the GGA08 pump tests. Figure 62 is the observation data during the SDT on and Figure 63 during the CRT on of GGA08.

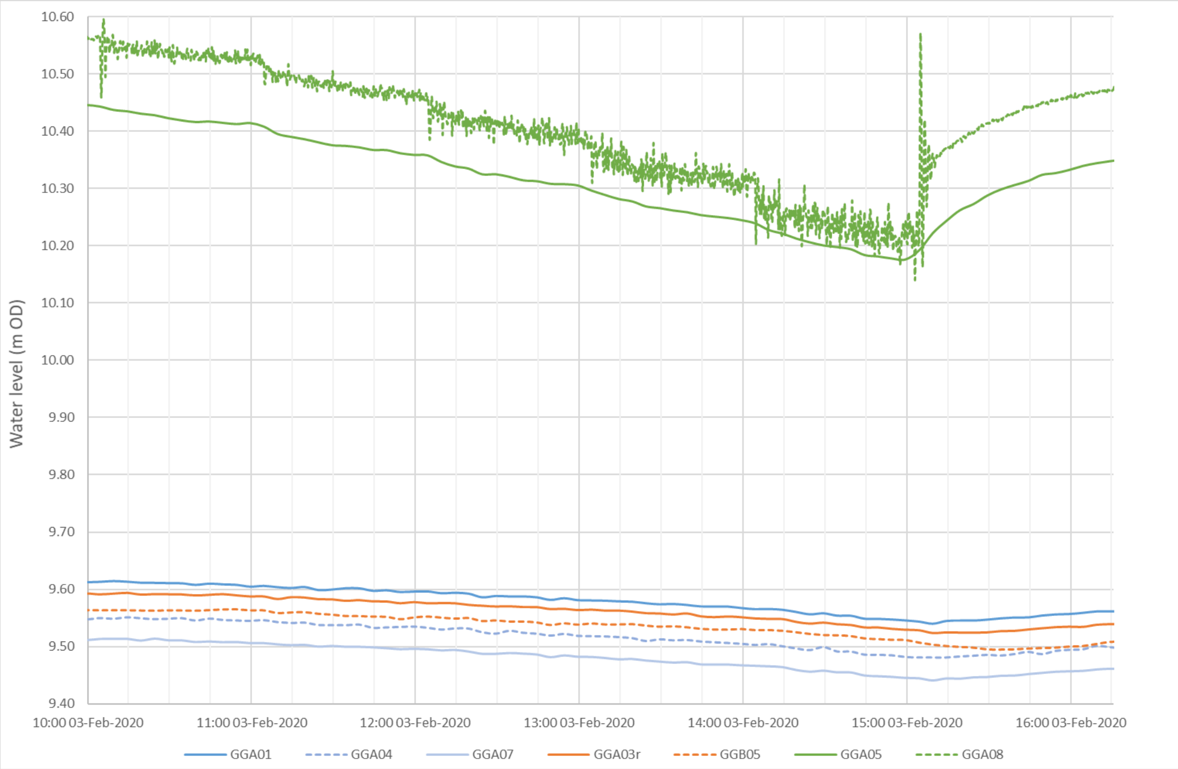


**Figure 62 Borehole water levels (from data logger) in pumping and observation boreholes during the SDT on GGA08**

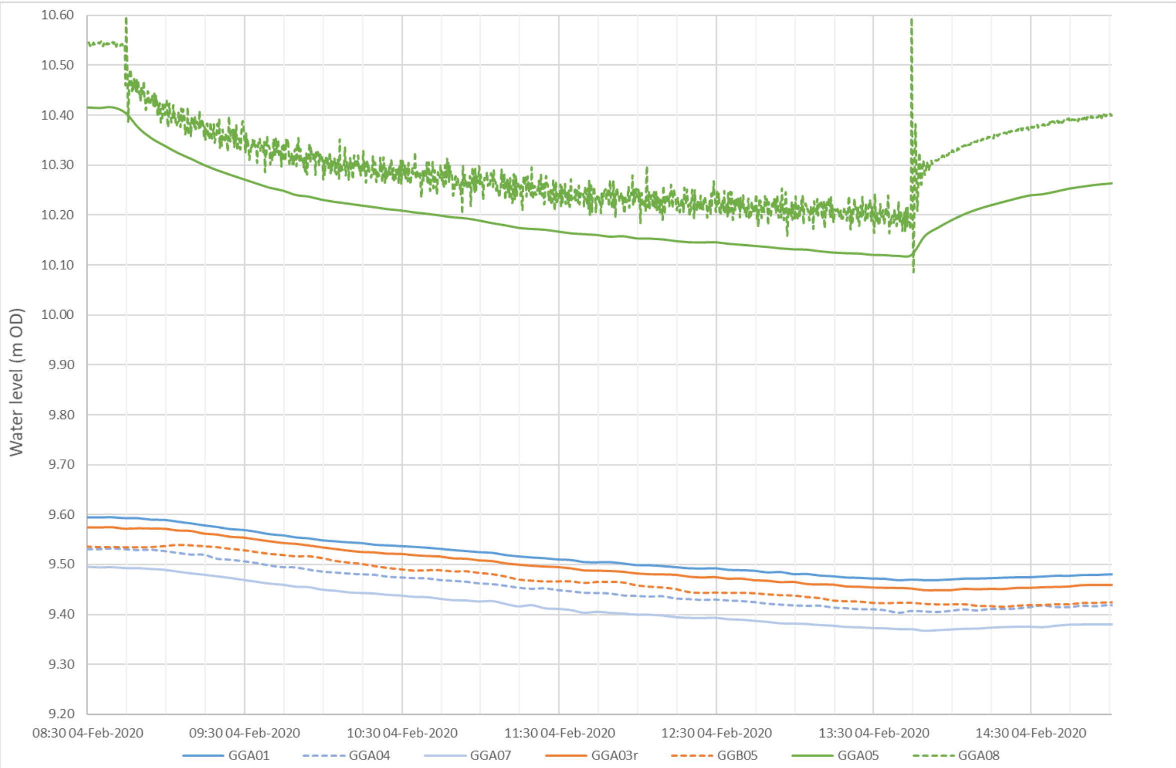


**Figure 63 Borehole water levels (from data logger) in pumping and observation boreholes during the CRT on GGA08**

### 7.2.4 Preliminary time-drawdown curves of GGA08

Figure 64 and Figure 65 plot the derived drawdown and recovery curves used for this interpretation from the data collected from the data logger during the CRT of GGA08, see Section 2.5 for more detail on the analyses used. A transmissivity value of 1750 $m^2$/day was derived using the Jacob straight line method for drawdown data and 2100 $m^2$/day using the Theis recovery method for recovery data.

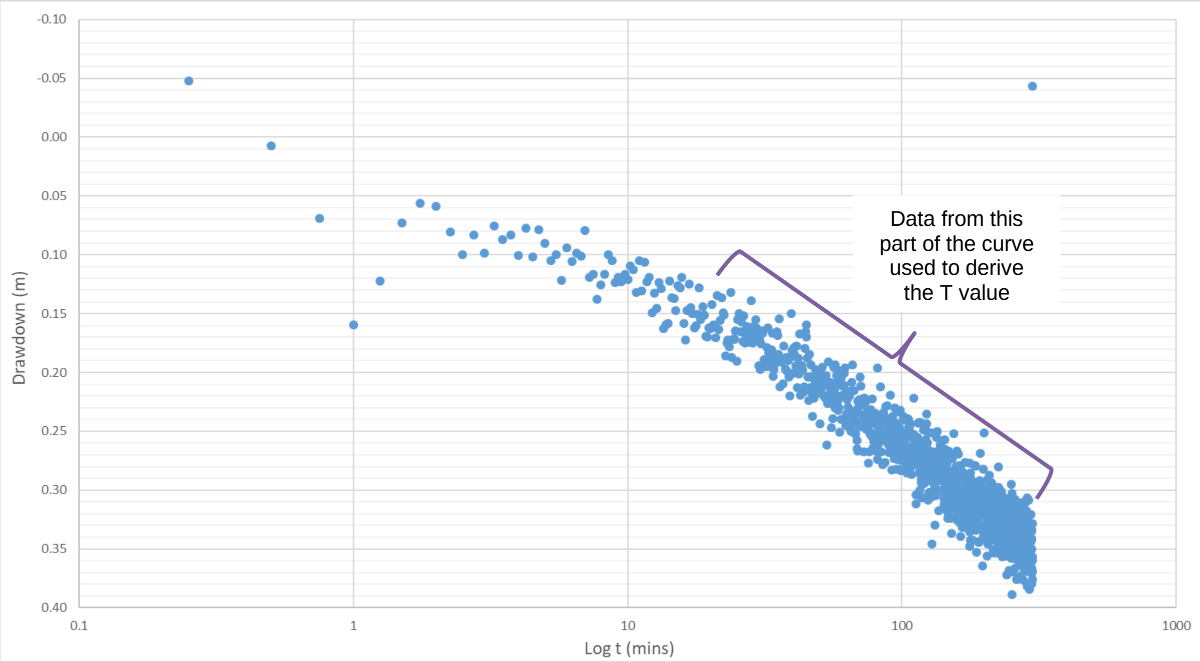


**Figure 64 Time-drawdown (from data logger) for drawdown phase of CRT on GGA08**

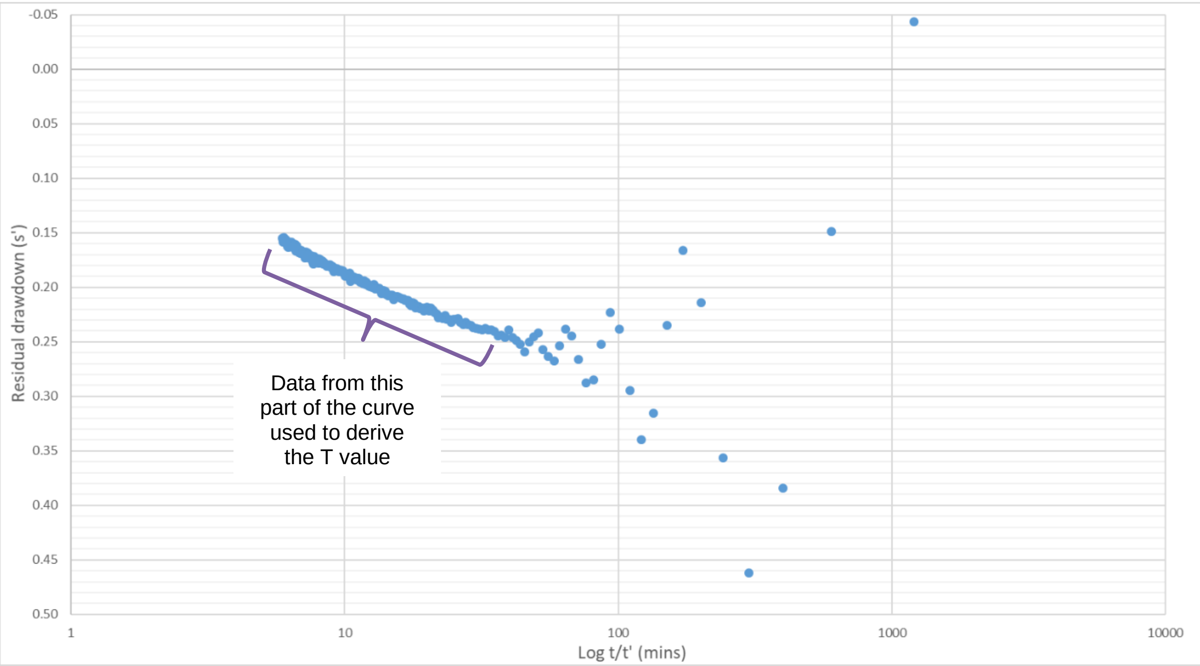


**Figure 65 Residual time-residual drawdown (from data logger) for recovery phase of CRT on GGA08**

# 8 Groundwater temperature and conductivity during test pumping

## 8.1 GROUNDWATER TEMPERATURE IN PUMPING BOREHOLES

Temperatures in the pumped borehole were recorded during the test pumping using the Solinst data logger. Table 16 summarises the temperature data during the SDT and CRT carried out on each borehole. The temperature change over the length of the test pumping at each borehole is shown in Figure 66 to Figure 69. The data logger was placed at least 1 m higher than the pump in the borehole to reduce the influence of the pump temperature on the groundwater temperature readings, however it is possible the pump does have an influence, particularly in the recovery phase where the water is not flowing quickly. Data from when the data logger was removed from the borehole for any reason has been removed from the graphs for clarity.

**Table 16 Summary of temperatures measured during and at the end of each SDT and CRT**

| Lithology | Borehole number | Depth of logger (m below top of dip tube)^ | Depth of top of screened section in borehole (m below top of borehole casing) | Average temperature in 12 hours before SDT (°C) | Temperature at the end of the last step of the SDT (°C) | Average temperature in 12 hours before CRT (°C) | Temperature at the end of the pumping phase of the CRT (°C) |
|---|---|---|---|---|---|---|---|
| **Superficials** | GGA06r | 12.15 | 11.79 | 11.40 | 11.37 | 11.42 | 11.36 |
| **Superficials** | GGA09r | 8.89 | 11.43 | NA | 11.48* | 11.48 | 11.30 |
| **Superficials** | GGB04 | 12.92 | 10.09 | 11.14** | | | |
| **Bedrock** | GGA03r (1st CRT) | 31.23 | 37.00 | 11.80 | 12.52 | 11.79 | 11.90 |
| **Bedrock** | GGA03r (2nd CRT) | 21.39 | 37.00 | NA | NA | NA | 12.56 |
| **Bedrock** | GGB05 | 21.34 | 42.39 | 11.53 | 11.60 | 11.56 | 11.60 |
| **Glasgow Upper mine working** | GGA01 | 41.69 | 44.81 | 11.95 | 11.88 | 11.95 | 11.87 |
| **Glasgow Upper mine working** | GGA04 | 35.85 | 47.40 | 12.06 | 12.37 | 12.07 | 12.32 |
| **Glasgow Upper mine working** | GGA07 | 34.7 | 50.91 | 11.61 | 11.75 | 11.63 | 11.81 |
| **Glasgow Main mine working** | GGA05 | 40.83 | 83.60 | 12.06 | 12.21 | 12.13 | 12.27 |
| **Glasgow Main mine working** | GGA08 | 34.70 | 85.08 | NA | 12.00 | 11.92 | 12.11 |

^See Figure 4 for borehole setup. Generally there was <10 cm difference between the top of the dip tube and top of borehole casing.

*The water level dropped below the level of the data logger during the last step of GGA09r SDT and therefore this temperature relates to the last temperature recorded at the end of the 3rd step.

**During the slug tests carried out on GGB04 water temperature was stable staying around 11.14 °C.

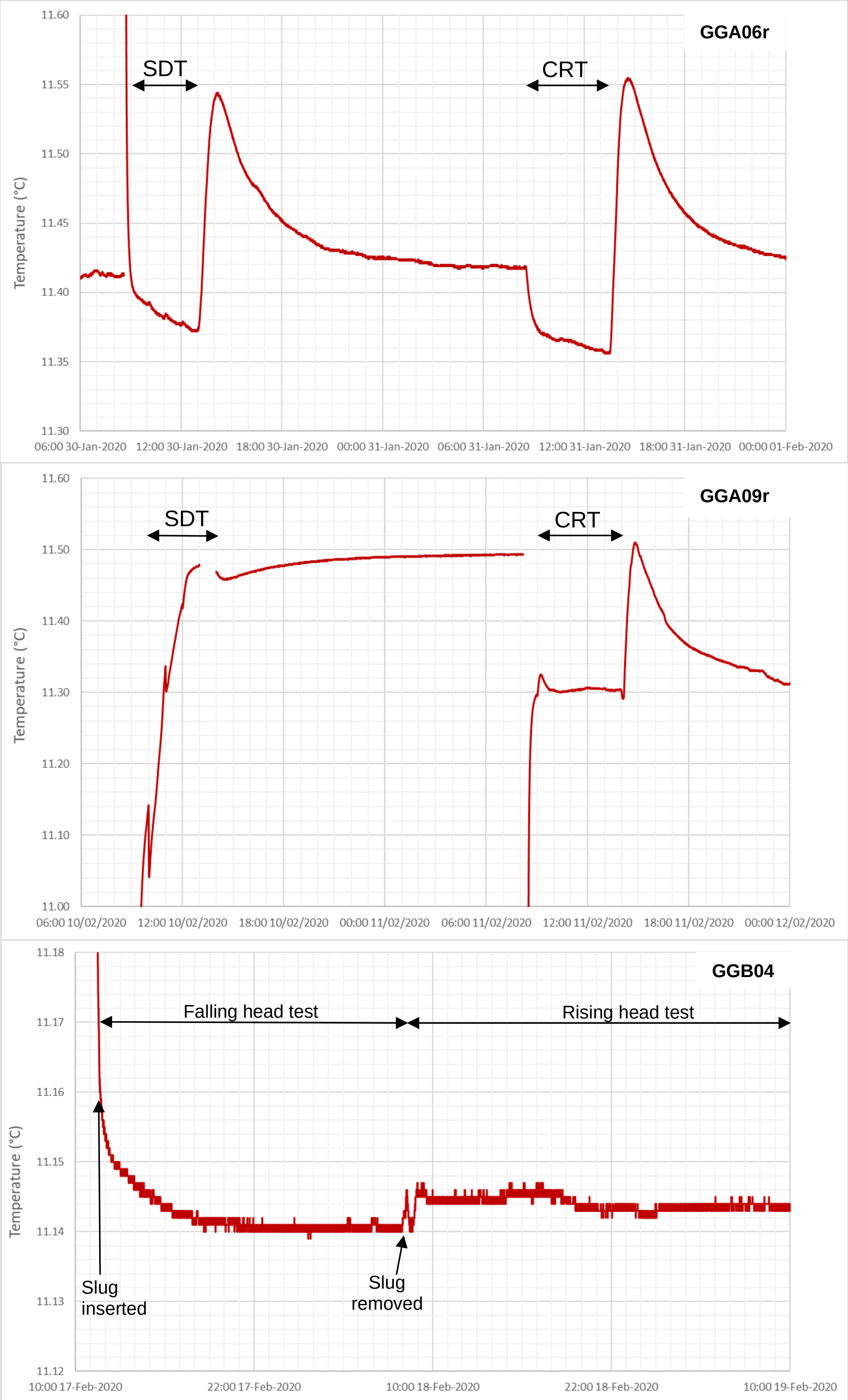


**Figure 66 Temperature profiles from superficial deposit boreholes during test pumping of each borehole**

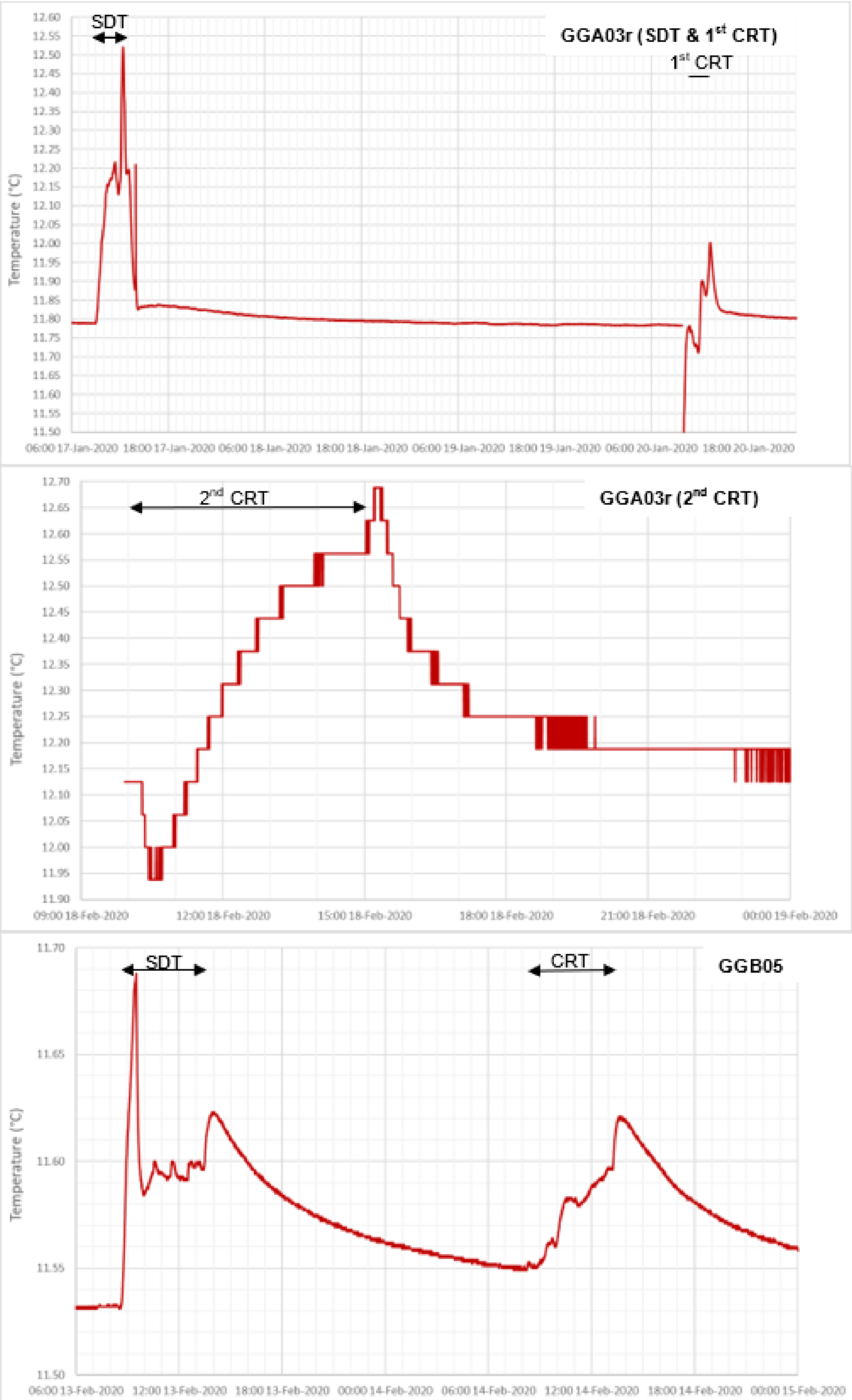


**Figure 67 Temperature profiles from bedrock boreholes during test pumping of each borehole**

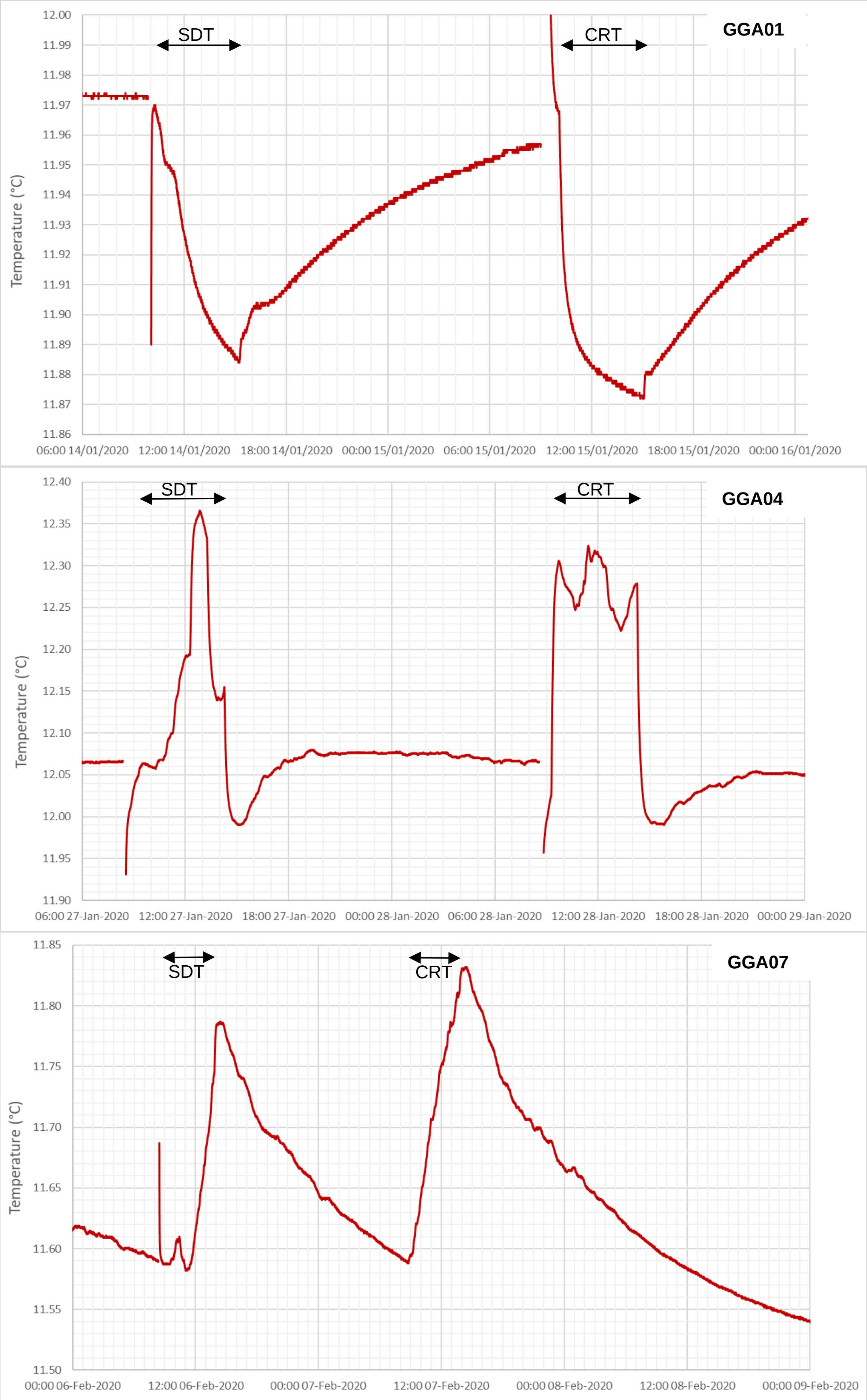


**Figure 68 Temperature profiles from GGA01, GGA04 and GGA07 (Glasgow Upper mine working) boreholes during test pumping of each borehole**

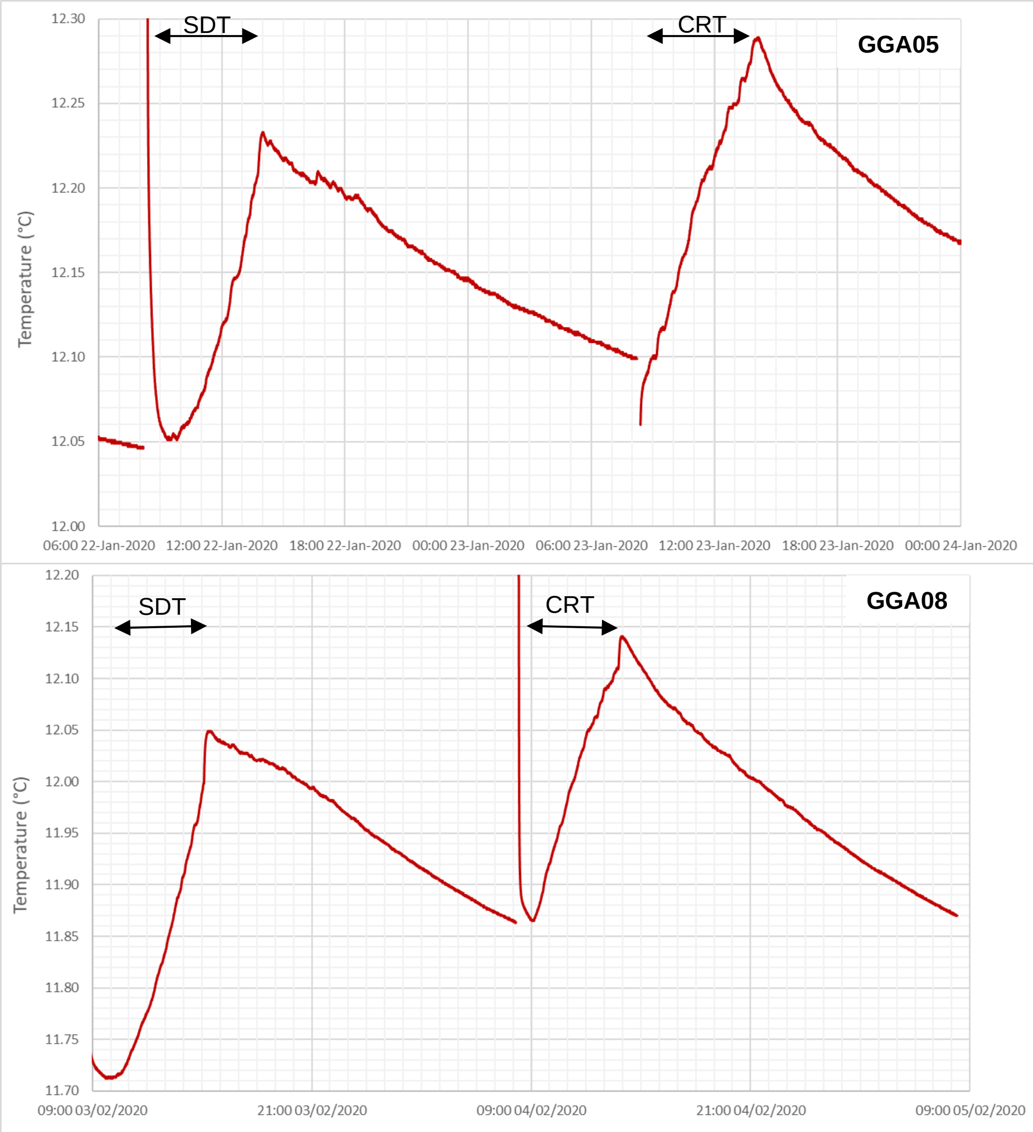


**Figure 69 Temperature profiles from Glasgow Main mine working (GGA05 & GGA08) boreholes during test pumping of each borehole**

## 8.2 GROUNDWATER TEMPERATURE AND CONDUCTIVITY IN OBSERVATION BOREHOLES

A summary of temperature and conductivity data from the CT2X data loggers is presented below. Some values were removed from the data prior to analysis where the values coincided with data loggers being removed from boreholes or similar activities.

Figure 70a shows the range of temperature recorded in each observation borehole recorded at five minute intervals throughout the test pumping and Figure 70b the range of conductivity values. The time period covered is 09/01/2020 – 20/02/2020, although not all data loggers were input on exactly the same date or removed on exactly the same date, see individual Excel® files for exact timings. Overall, temperatures are slightly higher than average Scottish groundwater temperature of 10ºC (MacDonald et al. 2017), and the estimated modern average air temperature at the site of 10.7 ºC (Watson and Westaway 2020) and the mine waters are above the 75th percentile of measurements from water boreholes abstracting from other Carboniferous mined aquifers in Scotland (MacDonald et al. 2017). Highest temperatures are within the Glasgow Main (approx. 12.5 ºC) although GGA04 in the Glasgow Upper mine working also has similar temperatures to the Glasgow Main. Conductivity measurements (SEC) are high across all boreholes, with median values in all bedrock and mine water boreholes in the range 1350 - 1600 µScm$^{-1}$ @25 ºC and for the superficial deposits 1000 – 1400 µScm$^{-1}$ @25 ºC. These are typical values for groundwater within Carboniferous mined areas (MacDonald et al. 2017), although for the superficial deposits, these are considerably higher than would be expected from superficial deposits outside Glasgow (Ó Dochartaigh et al., 2015), they are typical of those measured from site investigation boreholes within Glasgow (Ó Dochartaigh et al. 2018). Further discussion of temperature and conductivity is provided in Section 9.3.

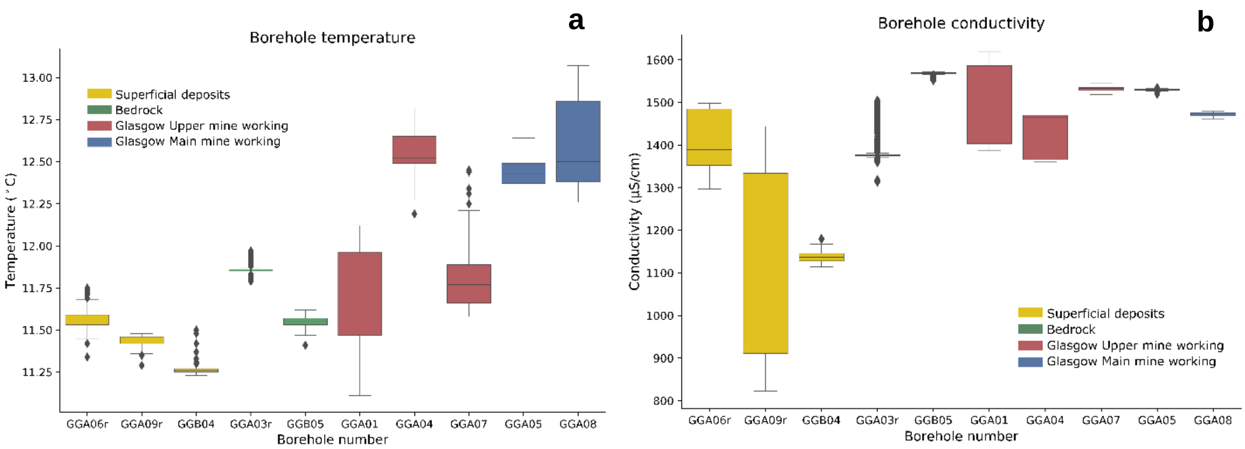


**Figure 70 a) Range of temperature recorded in the observation boreholes over the period of test pumping. b) Range of conductivity recorded in the observation boreholes over the period of test pumping.**

# 9 Discussion

An initial analysis of the test pumping data has been completed to characterise resulting changes in ground water level, temperature and conductivity. Aquifer transmissivity has also been estimated from water level drawdown and recovery data for the pumping wells. Further detailed analysis is required to better characterise and interpret these parameters. A preliminary interpretation of the test pumping findings is presented below for the four main targeted units: superficial deposits, sandstone bedrock; Glasgow upper mine workings; and Glasgow Main mine workings. Table 17 summarises the results from the CRTs as presented in Sections 4 to 7.

## 9.1 WATER LEVEL DRAWDOWN AND RECOVERY

In this section we describe the general response to pumping for each borehole, and in Section 9.2 we discuss the aquifer parameters calculated from the tests. Prior to test pumping all boreholes had been purged and cleaned following completion of casing installation and this information was used to select the pumping rates for each test.

### 9.1.1 GGA06r, GGA09r and GGB04 (Superficial deposits boreholes)

Water level drawdown in GGA06r and GGA09r was initially rapid, but quickly reached a standard logarithmic decline during both the SDT and CRT suggesting high borehole inefficiency probably as a result of the small screen area. In GGB04, the aquifer yield was so low that only a slug test could be performed. Resting water levels are similar for all three superficial deposits, approximately 3 - 5 m OD (Figure 71) or 7 – 9 m below ground level and are approximately 5 m lower than the water levels measured in the bedrock and mine workings. The deeper water levels may reflect the local control of the River Clyde on the superficial deposits aquifer. None of the superficial deposits boreholes respond to pumping from the bedrock and mine working boreholes. Although the pumping tests were too short (five hours) to definitively rule out connectivity, it is likely that clay rich layers within the superficial deposits are acting as a barrier to direct hydraulic connection between the superficial and the underlying bedrock.

### 9.1.2 GGA03r and GGB05 (Bedrock boreholes)

Drawdown and recovery in the sandstone bedrock varied considerably between GGA03r and GGB05. The SDT and first CRT carried out in GGA03r resulted in water level being drawn down close to the level of the pump meaning both tests being aborted early to avoid damaging the pump. The second CRT, carried out at 0.1 L/s did enable the borehole to be tested, with the drawdown by the end of the test approximately 8 m (Figure 25, Table 17). By contrast, test pumping in GGB05, after an initial rapid drawdown due probably to borehole efficiency, exhibited the desired logarithmic decline in all five steps of the SDT and shortly into the CRT (carried out at 4.4 L/s). The proximity of the Glasgow Upper mine working to this part of the bedrock could explain the large variation between these two boreholes. Fractures, either naturally occurring or mining induced, can lead to heterogeneous groundwater level pumping responses over small distances. The longer term RWL variations are similar between the two boreholes, and are approximately 9 – 10 m OD (Figure 71), corresponding to 1 – 2 m below ground level, and indicate a level of connection across the aquifer.

During pumping of GGA03r there was no observable response in any other boreholes, most likely due to the very low rate of pumping. However, the test pumping in GGB05 gave rise to strong responses in the three boreholes in the Glasgow Upper mine workings, illustrating the connection between the Upper mine workings and the overlying sandstone. A small response was also observed in the other sandstone bedrock borehole GGA03r.

### 9.1.3 GGA01, GGA04 and GGA07 (Glasgow Upper mine working boreholes)

The character of the Glasgow Upper mine working is highly variable within this area, as evidenced by the difference in the screened sections of GGA01, GGA04 and GGA07. GGA04 is installed into a possible coal pillar, and was pumped at a lower rate (14.8 L/s) than GGA01 and GGA07 as it could not sustain the higher flow rates tested in those boreholes (20 L/s). GGA01 was installed into likely mine waste within the mine workings and GGA07 within a partial coal pillar and partial void. GGA01 and GGA07 showed text book responses to pumping, with no evidence of borehole inefficiency, suggesting that groundwater could flow easily into the boreholes through the short screened section to sustain the abstraction. Water levels in GGA04 however fell rapidly in response to pumping before exhibiting a logarithmic response, and likewise recovered rapidly. This is consistent with the screened section being in a pillar, restricting flow into the borehole and reducing efficiency. A change in gradient of the water level in GGA04 after one hour pumping is likely due to borehole development through the test. A water level change noted on Figure 43 after one hour of pumping during the CRT of GGA04 potentially suggests that one of the pathways for water entering the borehole through the fractured coal pillar and mudstone became blocked during this test leading to decreased permeability in the surrounding rock.

RWLs in the Glasgow Upper mine workings are similar to those on the bedrock aquifer above, and again respond together: average levels over the testing period were 9 – 10 m OD (Figure 71), corresponding to 1 – 2 m below ground level.

During the test pumping, each of the observation boreholes in the Glasgow Upper and bedrock responded strongly to pumping, again illustrating the strong connectivity across the mine working, and also with the sandstone roof above. There were small responses observed in the Glasgow Main boreholes suggesting some limited connectivity. None of the superficial boreholes responded to pumping.

### 9.1.4 GGA05 and GGA08 (Glasgow Main mine working boreholes)

GGA05 and GGA08 installed into the Glasgow Main mine working are both screened across a void within the Glasgow Main. The test pumping of these two boreholes resulted in a similar response and maximum drawdown of less than 0.5 m. There was no evidence of inefficiency in the boreholes, consistent with the boreholes being screened in a void space, and the screened surface being sufficient to cope with 20 L/s pumping. The water-level response was similar to typical response for a theoretical pumping test. RWLs in the Glasgow Main mine workings were approximately 10 – 11 m OD (Figure 71), approximately one metre shallower than in the Glasgow Upper mine workings. RWLs variation over the several months of the test pumping were similar between the two boreholes.

The other borehole within the Glasgow Main mine workings responded strongly to the test pumping. Small responses were also noted from each of the Glasgow Upper and bedrock boreholes, indicating a hydraulic connection between the two mine workings.

A further phenomenon that occurred during the tests carried out on the Glasgow Main boreholes, was the constantly fluctuating water level monitored before, during and after the testing of 2 – 5 cm. Also notable was the large oscillations in water level that occurred once the pump was turned off. The most likely explanation is the widespread void space within the mine workings, enabling rapid flow and high frequency variability similar to that found in karstic networks.

**Table 17 Summary of water level responses and transmissivity results for all test pumped boreholes.**

| Screened unit | Site | Borehole | Length of CRT (hours) | CRT pumping rate (L/s) | Observation BHs responded* | Transmissivity of drawdown data ($m^2$/day) | Transmissivity of recovery data ($m^2$/day) | Temperature at the end of the CRT |
|---|---|---|---|---|---|---|---|---|
| Superficials | 2 | GGA06r | 5 | 0.5 | No obvious response | 79 | 225 | 11.36 |
| Superficials | 3 | GGA09r | 5 | 0.5 | No obvious response | 225 | 225 | 11.30 |
| Superficials | 5 | GGB04 | 47.3 (falling/rising head test) | NA | No obvious response during slug test | 0.04 (falling head test) | 0.018 (rising head test) | 11.14 (end of rising head test) |
| Bedrock | 1 | GGA03r (1st CRT) | 2 | ~0.2 | No obvious response | NA | NA | 11.90 |
| Bedrock | 1 | GGA03r (2nd CRT) | 5 | 0.1 | No obvious response | 2.6 | Not possible to calculate a value | 12.56 |
| Bedrock | 5 | GGB05 | 5 | 4.4 | **GGA01**, GGA03r, **GGA04, GGA07** | 990 | 580 | 11.60 |
| Glasgow Upper mine working | 1 | GGA01 | 5 | 20 | **GGA03r**, **GGA04**, GGA05, **GGA07**. GGA08 **GGB05** | 1130 | 1020 | 11.87 |
| Glasgow Upper mine working | 2 | GGA04 | 5 | 15 | **GGA01**, **GGA03r**, GGA05, **GGA07**, GGA08, **GGB05** | 240 | 950 | 12.32 |
| Glasgow Upper mine working | 3 | GGA07 | 5 | 20 | **GGA01**, **GGA03r**, **GGA04**, GGA05, GGA08, **GGB05** | 1050 | 1020 | 11.81 |
| Glasgow Main mine working | 2 | GGA05 | 5 | 20 | GGA01, GGA03r, GGA04, GGA07, **GGA08**, GGB05 | 1976 | 1976 | 12.27 |
| Glasgow Main mine working | 3 | GGA08 | 5 | 20 | GGA01, GGA03r, GGA04, **GGA05,** GGA07, GGB05 | 1750 | 2100 | 12.11 |

*Boreholes showing the biggest responses are highlighted in **bold**

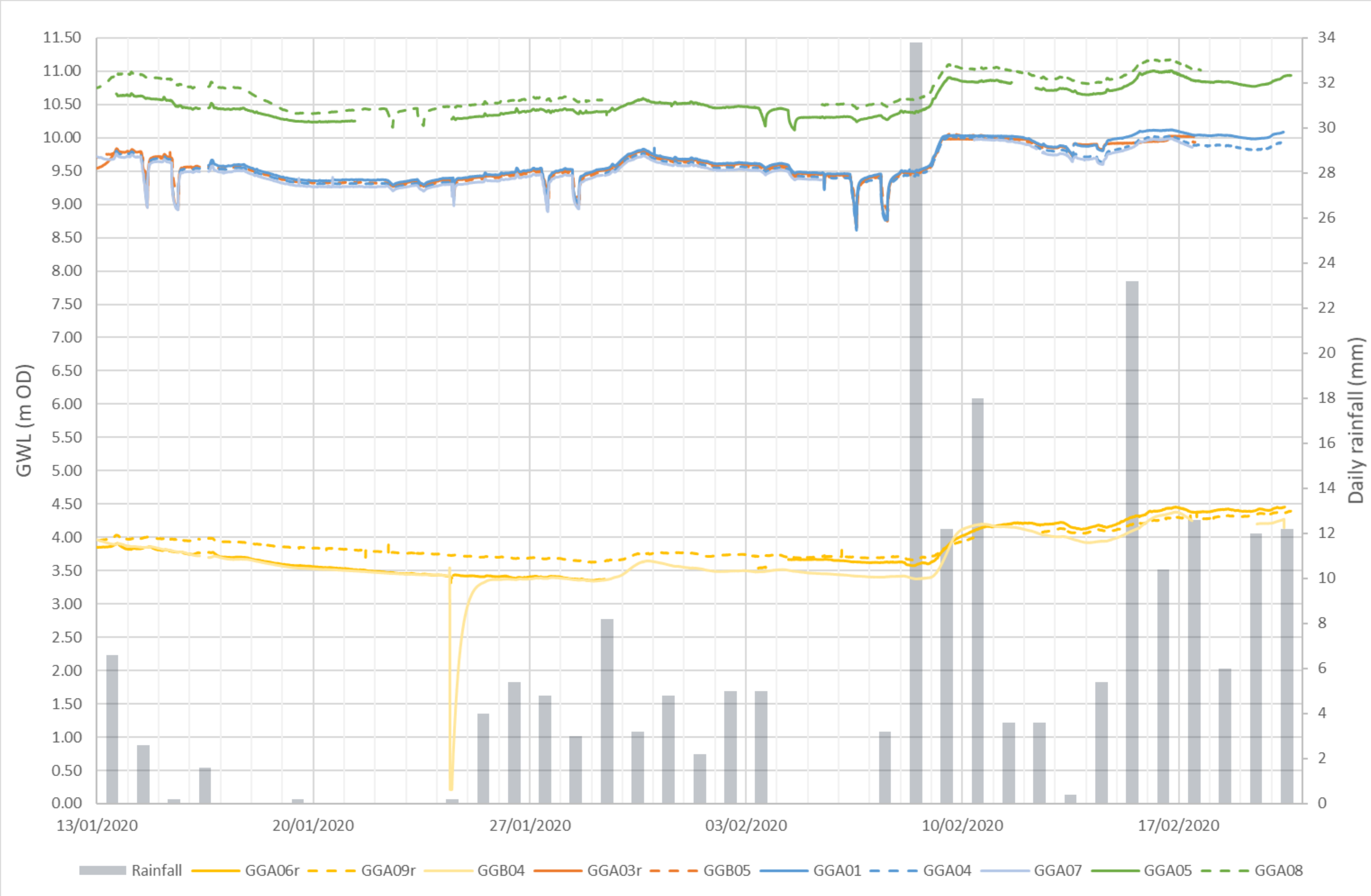


**Figure 71 Overview of water level heights in all 10 test pumped boreholes over the duration of the test pumping period. The bedrock boreholes, denoted in orange on the graph, are shown behind the Glasgow Upper boreholes in blue. Rainfall data from SEPA.**

## 9.2 TRANSMISSIVITY

Following the test pumping, initial estimates of transmissivity were derived using the Jacobs straight line method for drawdown and the Theis recovery method outlined in Section 2.5. The curves from this analysis and the data used to calculate transmissivity values are outlined in each individual borehole section and Table 17 summarises the calculated transmissivity values. It was outwith the scope of this work to interpret the observation borehole data, and the results are based on the pumped borehole, therefore more weight is given to the recovery data from each test. As stated in Section 2.5 not all assumptions were wholly met for analysis using the Jacob's Method or Theis recovery. However, research and modelling has shown that transmissivity estimated using these methods in more heterogeneous aquifers can still give realistic results (Sanchez-Vila et al. 1999). The results therefore can be considered as an initial estimate of the transmissivity of the different units.

The superficial deposits in GGA06r and GGA09r are highly variable reflecting the diversity of superficial material. Values range from 0.04 and 225 $m^2$/day over the three boreholes, reflecting the heterogeneous nature of the superficial deposits. Both GGA06r and GGA09r give estimates of transmissivity of 225 $m^2$/d. These values are at the higher end of transmissivity and hydraulic conductivity measurements for the superficial deposits of the Glasgow area (Williams, et al. 2017), but within the range found across Scotland (Graham et al. 2009).

The two bedrock pumping tests also gave very different results: 2.6 and 580 $m^2$/d. Transmissivity of greater than 500 $m^2$/d is rare in Carboniferous sandstones (Graham et al. 2009, Ó Dochartaigh et al. 2015) and is invariably associated with extensive fracturing. The lower transmissivity value of 2.6 $m^2$/d is in accordance with the 2 m borehole screen interval being across poorly fractured sandstone (with hydraulic conductivity of 1 m/d). The high transmissivity value of 580 $m^2$/d likely reflects an extensively fractured sandstone, with the fracturing possibly induced by mining below.

The three boreholes in the Glasgow Upper mine workings gave a consistent transmissivity estimate of 950 – 1020 $m^2$/d. This consistency is interesting given that the immediate surroundings of the three boreholes were different: coal pillar, void, and mine waste. This is likely because the five hour test enabled the cone of depression to extend sufficiently to take in a larger volume of the mine workings, integrating the response. There are very few other pumping tests in previously mined Carboniferous rocks in Scotland and none that have given a transmissivity greater than 1000 $m^2$/d (Graham et al. 2009; Ó Dochartaigh et al. 2015).

The two boreholes intersecting the Glasgow Main mine workings gave transmissivity estimates of 2000 – 2100 $m^2$/d. This high transmissivity may reflect the open voids that remain in the Glasgow Main workings, compared to the more heterogeneous nature of the Glasgow Upper workings. There was no evidence from the five hour pumping test of the cone of depression reaching a boundary – either the edge of the workings, or reaching an additional source of water, such as the river.

## 9.3 GROUNDWATER TEMPERATURE AND CONDUCTIVITY

Temperature measurements from the observation boreholes monitored throughout the testing period show that the groundwater in the deeper Glasgow Main mine workings are warmer than the shallower workings, bedrock or superficial deposits with a values generally 12.4 – 12.8 ºC. These values are slightly higher than generally found in water boreholes from mined Carboniferous strata (MacDonald et al. 2017) and slightly higher than that measured in the temperature log from GGC01 at similar depth (Starcher et al. 2019). Temperatures in the superficial deposits (11.1 – 11.5 ºC) are also higher than expected given the estimated average annual ground temperature of 10.7 ºC. Temperatures in the Glasgow Upper mine workings and the overlying bedrock are broadly similar, 11.5 – 12 ºC, apart from GGA04 where the temperature is more similar to the deeper Glasgow Main boreholes. Future data releases of data logger data including temperature of the boreholes post construction will be available.

During the test pumping, water temperatures in the pumping borehole varied by up to 0.5 ºC, although variation was typically less than 0.3 ºC. The temperature loggers were above both the screened section and the pump and were therefore measuring the temperature of water in the static water column above the pump. The temperature variability during the tests were therefore more likely to be reflecting the warming and cooling of the pump, with different responses attributable to the exact position of the logger, the size of the pump and the volume of the water column. More accurate temperatures may be available from the flow through cell during the test pumping, and reported in the UKGEOS Test Pumping Geochemistry report to be released later in 2021. For the superficial deposits, temperatures of 11.3 – 11.4 ºC were recorded towards the end of the CRT, but after the cessation of pumping temperatures rose and fell gradually, most likely in response to the pump being switched off. For the two bedrock pumping tests, GGA03r was affected by the low pumping rate but GGB05 gave a consistent temperature of 11.5-11.6 ºC. For each of the boreholes in the mine workings, except for GGA01, the temperature tended to rise slightly during the test, (by approximately 0.2 ºC) then fall after the pumping stopped. Two Glasgow Upper boreholes, GGA01 and GGA07, gave temperatures of 11.8 – 11.9 ºC by the end of the test, and the two Glasgow Main boreholes, GGA05 and GGA08, 12.1 - 12.3 ºC. One of the Glasgow Upper boreholes GGA04 breaks this trend, giving a temperature of 12.3 ºC by the end of the test – similar to the Glasgow Main boreholes. This borehole also showed similar elevated temperatures from the observation well data during the test period and could suggest a possible link to the Glasgow Main mine workings.

As discussed in Section 8.2, the conductivity measurements from the mine workings and bedrock boreholes lie in the range 1350 - 1600 $\mu Scm^{-1}$ @25 ºC and are typical of measurements from water boreholes within the mined Carboniferous rocks (MacDonald et al. 2017). The Glasgow Main measurements are consistent and generally higher, but measurements from the Glasgow Upper workings tend to be variable, possibly reflecting some mixing of the waters. The conductivity measured in the superficial deposits are variable, and high (1000 – 1400 $\mu Scm^{-1}$ @25 ºC) although within the range of those found in Glasgow (Ó Dochartaigh et al. 2018). The conductivity of groundwater in superficial deposits in Glasgow tends to by higher than that measured elsewhere in Glasgow, and may reflect the made ground, urban setting, or past influence from the sea, although leakage from mine workings cannot be ruled out.

# 10 Conclusions

This report summarises data collected during test pumping of 10 boreholes at the UK Geoenergy Observatory at Cuningar Loop in Glasgow during January and February 2020. The main objectives of the pumping tests were to obtain data regarding: the physical aquifer properties, in particular transmissivity, of the different hydrogeological zones at the site; to investigate borehole efficiency; and to gather data on the connectivity between different hydrogeological zones.

1. Successful step tests and five hour constant rate tests were carried out in all boreholes except GGB04 in the superficial deposits where a slug test was carried out instead due to the low yield. Time series data of water levels, temperature and conductivity were collected in the pumping and observation boreholes. Appendix B lists the associated digital files of test pumping data available with this data release. The constant rate tests were analysed using Jacob's approximation and Theis recovery methods to give a preliminary interpretation of the transmissivity. The drawdown curves were visually inspected to help identify borehole inefficiency and significant responses from observation boreholes to pumping.
2. The transmissivity of the superficial deposits at the site are highly variable (0.04 and 225 $m^2$/day), reflecting the diversity of superficial material, but within the range measured across Glasgow (Williams, et al., 2017). The two bedrock test pumping responses also give very different results: 2.6 and 580 $m^2$/d which reflects the fracturing within the sandstones. The lower value may reflect the generally hydraulic conductivity of poorly fractured sandstone (1 m/d) and the high transmissivity of 580 $m^2$/d reflects extensive fracturing possibly induced by the mining below. The three boreholes in the Glasgow Upper mine workings give a consistent transmissivity estimate of 950 – 1020 $m^2$/d despite the difference in the immediate surroundings of the 3 boreholes (coal pillar, void, and mine waste). This is likely because the five hour test enabled the cone of depression to extend sufficiently to take in a larger volume of the mine workings, integrating the response. The two boreholes intersecting the Glasgow Main mine workings give transmissivity estimates of 2000 – 2100 $m^2$/d. This high transmissivity may reflect the open voids that remain in the Glasgow Main mine workings, compared to the more heterogeneous nature of the Glasgow Upper mine workings.
3. There is clear connectivity between the bedrock boreholes and the Glasgow Upper mine workings during pumping, with strong responses between boreholes from most pumping tests. There is also strong connectivity within the individual mine workings. There is also evidence of some connectivity between the Glasgow Main mine workings and the Glasgow Upper mine workings with noticeable responses from observation boreholes in each working from pumping tests in the other working.
4. There is an upward vertical hydraulic gradient at the site, with rest water levels approximately 10 – 11 m OD in the Glasgow Main workings; 9 – 10 m OD in the Glasgow Upper mine workings and bedrock boreholes, and 3 – 4.5 m OD in the superficial deposits.
5. Temperature measurements from the observation boreholes monitored throughout the testing period show that the groundwater in the deeper Glasgow Main mine workings are warmer than the shallower workings, bedrock or superficial deposits with a value generally 12.4 – 12.8 ºC. Temperatures in the Glasgow Upper mine workings and the overlying bedrock are broadly similar, 11.5 – 12 ºC, apart from GGA04 where the temperature is more similar to the deeper Glasgow Main boreholes. During the test pumping, water temperatures in the pumping borehole varied by up to 0.5 ºC, and was possibly influenced by the position of the pump. Two Glasgow Upper boreholes,

GGA01 and GGA07, gave temperatures of 11.8 – 11.9 ºC by the end of the test, and the two Glasgow Main boreholes, GGA05 and GGA08, and the Glasgow Upper borehole GGA04, 12.1 - 12.3 ºC the end of the test.

6. The conductivity measurements from the mine workings and bedrock boreholes lie in the range 1350 - 1600 $\mu Scm^{-1}$ @25 ºC and are typical of measurements from water boreholes within the mined Carboniferous rocks (MacDonald et al. 2017). The conductivity measured in the superficial deposits are high and variable, 1000 – 1400 $\mu Scm^{-1}$ @25 ºC, although within the range of those found in Glasgow (Ó Dochartaigh et al. 2018).

The data provided in this report provide an opportunity for further analysis of the pumping tests to refine the preliminary interpretations provided here.

# Appendix A Field forms used during test pumping

## Step drawdown: pumping/recovery test (delete as appropriate)

**Site:** **Borehole:**

**Test start date:** **Pump start time:** **Rest water level (m):**

**Pump end time:** **Average pumping rate (l/s):**

**Initial flow meter reading:** **Step number:**

**End flow meter reading:**

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 0 | | |
| 0.5 | | |
| 1 | | |
| 1.5 | | |
| 2 | | |
| 2.5 | | |
| 3 | | |
| 3.5 | | |
| 4 | | |
| 4.5 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |
| 15 | | |
| 20 | | |
| 25 | | |
| 30 | | |
| 35 | | |
| 40 | | |
| 45 | | |
| 50 | | |
| 55 | | |
| 60 | | |
| | | |
| | | |
| | | |

## Step drawdown: pumping/recovery test (delete as appropriate)

**Site:** **Borehole:**

**Test start date:** **Pump start time:** **Rest water level (m):**

**Pump end time:** **Average pumping rate (l/s):**

**Initial flow meter reading:** **Step number:**

**End flow meter reading:**

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 60 | | |
| 60.5 | | |
| 61 | | |
| 61.5 | | |
| 62 | | |
| 62.5 | | |
| 63 | | |
| 63.5 | | |
| 64 | | |
| 64.5 | | |
| 65 | | |
| 66 | | |
| 67 | | |
| 68 | | |
| 69 | | |
| 70 | | |
| 75 | | |
| 80 | | |
| 85 | | |
| 90 | | |
| 95 | | |
| 100 | | |
| 105 | | |
| 110 | | |
| 115 | | |
| 120 | | |
| | | |
| | | |
| | | |

## Step drawdown: pumping/recovery test (delete as appropriate)

**Site:** **Borehole:**

**Test start date:** **Pump start time:** **Rest water level (m):**

**Pump end time:** **Average pumping rate (l/s):**

**Initial flow meter reading:** **Step number:**

**End flow meter reading:**

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 120 | | |
| 120.5 | | |
| 121 | | |
| 121.5 | | |
| 122 | | |
| 122.5 | | |
| 123 | | |
| 123.5 | | |
| 124 | | |
| 124.5 | | |
| 125 | | |
| 126 | | |
| 127 | | |
| 128 | | |
| 129 | | |
| 130 | | |
| 135 | | |
| 140 | | |
| 145 | | |
| 150 | | |
| 155 | | |
| 160 | | |
| 165 | | |
| 170 | | |
| 175 | | |
| 180 | | |
| | | |
| | | |
| | | |

## Step drawdown: pumping/recovery test (delete as appropriate)

**Site:** **Borehole:**

**Test start date:** **Pump start time:** **Rest water level (m):**

**Pump end time:** **Average pumping rate (l/s):**

**Initial flow meter reading:** **Step number:**

**End flow meter reading:**

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 180 | | |
| 180.5 | | |
| 181 | | |
| 181.5 | | |
| 182 | | |
| 182.5 | | |
| 183 | | |
| 183.5 | | |
| 184 | | |
| 184.5 | | |
| 185 | | |
| 186 | | |
| 187 | | |
| 188 | | |
| 189 | | |
| 190 | | |
| 195 | | |
| 200 | | |
| 205 | | |
| 210 | | |
| 215 | | |
| 220 | | |
| 225 | | |
| 230 | | |
| 235 | | |
| 240 | | |
| | | |
| | | |
| | | |

## Step drawdown: pumping/recovery test (delete as appropriate)

Site: Borehole:

Test start date: Pump start time: Rest water level (m):

Pump end time: Average pumping rate (l/s):

Initial flow meter reading: Step number:

End flow meter reading:

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 240 | | |
| 240.5 | | |
| 241 | | |
| 241.5 | | |
| 242 | | |
| 242.5 | | |
| 243 | | |
| 243.5 | | |
| 244 | | |
| 244.5 | | |
| 245 | | |
| 246 | | |
| 247 | | |
| 248 | | |
| 249 | | |
| 250 | | |
| 255 | | |
| 260 | | |
| 265 | | |
| 270 | | |
| 275 | | |
| 280 | | |
| 285 | | |
| 290 | | |
| 295 | | |
| 300 | | |
| | | |
| | | |
| | | |

## Step drawdown: pumping/recovery test (delete as appropriate)

Site: Borehole:

Test start date: Pump start time: Rest water level (m):

Pump end time: Average pumping rate (l/s):

Initial flow meter reading: Step number:

End flow meter reading:

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 300 | | |
| 300.5 | | |
| 301 | | |
| 301.5 | | |
| 302 | | |
| 302.5 | | |
| 303 | | |
| 303.5 | | |
| 304 | | |
| 304.5 | | |
| 305 | | |
| 306 | | |
| 307 | | |
| 308 | | |
| 309 | | |
| 310 | | |
| 315 | | |
| 320 | | |
| 325 | | |
| 330 | | |
| 335 | | |
| 340 | | |
| 345 | | |
| 350 | | |
| 355 | | |
| 360 | | |
| | | |
| | | |
| | | |

## Constant rate: pumping/recovery test (delete as appropriate)

Site: Borehole:

Test start date: Pump start time: Rest water level (m):

Pump end time: Average pumping rate (l/s):

Initial flow meter reading: Step number:

End flow meter reading: Water level the day after:

Time water level taken the day after:

| Time (mins) | Water Level (m) | Notes |
|---|---|---|
| 0 | | |
| 0.5 | | |
| 1 | | |
| 1.5 | | |
| 2 | | |
| 2.5 | | |
| 3 | | |
| 3.5 | | |
| 4 | | |
| 4.5 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |
| 15 | | |
| 20 | | |
| 25 | | |
| 30 | | |
| 35 | | |
| 40 | | |
| 45 | | |
| 50 | | |
| 55 | | |
| 60 (1hr) | | |
| 70 | | |
| 80 | | |
| 90 (1.5) | | |
| 100 | | |
| 110 | | |
| 120 (2) | | |
| 140 | | |
| 160 | | |
| 180 (3) | | |
| 200 | | |
| 220 | | |
| 240 (4) | | |
| 260 | | |
| 280 | | |
| 300 (5) | | |

# Appendix B List of data files

**Table 18 List of digital files provided by BGS covering the data collected during the test pumping of each borehole and included in this data release**

| Borehole Number | BGS derived files | File description |
|---|---|---|
| GGA01 | *SDT_ GGA01_FINAL.xlsx*<br>*CRT_ GGA01_FINAL.xlsx* | - Spreadsheet of step-drawdown test data including: manually dipped water levels and converted Solinst datalogger water levels<br>- Spreadsheet of constant rate test data including: manually dipped water levels and converted Solinst datalogger water levels |
| GGA03r | *SDT_ GGA03r_FINAL.xlsx*<br>*CRT_ GGA03r_FINAL.xlsx* | |
| GGA04 | *SDT_ GGA04_FINAL.xlsx*<br>*CRT_ GGA04_FINAL.xlsx* | |
| GGA05 | *SDT_ GGA05_FINAL.xlsx*<br>*CRT_ GGA05_FINAL.xlsx* | |
| GGA06r | *SDT_ GGA06r_FINAL*<br>*CRT_ GGA06r_FINAL* | |
| GGA07 | *SDT_ GGA07_FINAL.xlsx*<br>*CRT_ GGA07_FINAL.xlsx* | |
| GGA08 | *SDT_ GGA08_FINAL.xlsx*<br>*CRT_ GGA08_FINAL.xlsx* | |
| GGA09r | *SDT_ GGA09r_FINAL.xlsx*<br>*CRT_ GGA09r_FINAL.xlsx* | |
| GGB04 | *FallingHead_Test_ GGB04_FINAL.xlsx*<br>*RisingHead_Test_ GGB04_FINAL.xlsx* | |
| GGB05 | *SDT_ GGB05_FINAL.xlsx*<br>*CRT_ GGB05_FINAL.xlsx* | |

**Table 19 List of digital files provided by Drilcorp covering the data collected during the test pumping of each borehole and included in this data release**

| Borehole Number | Files provided by Drilcorp | File description |
|---|---|---|
| GGA01 | *GGA01_SDT&CRT_Hydraulicdata.xlsx*<br>*GGA01_Welltesting_Jan-2020_Report_v5.pdf* | - Drilcorp test pumping data – Description of steps carried out on both step drawdown and constant rate test.<br>- Barometric pressure data.<br>- Records from flow meter (pumping rate), dip meter (manually dipped water levels) including height of dip tube above base of manhole chamber during test pumping and Solinst logger datalogger data, including installation depth of data logger.<br>- Drilcorp well testing report – written record of borehole set up during test pumping, including summary of hydraulic background monitoring, step-rate pumping test and constant-rate pumping test |
| GGA03r | *GGA03r_SDT&CRT_Hydraulicdata_v1.xlsx*<br>*GGA03r_CRT_Feb20_Hydraulicdata_v1.xlsx*<br>*GGA03r_Welltesting_Jan-2020&Feb-2020_Report_v1.pdf* | |
| GGA04 | *GGA04_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGA04_Welltesting_Jan-2020_Report_v2.pdf* | |
| GGA05 | *GGA05_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGA05_Welltesting_Jan-2020_Report_v2.pdf* | |
| GGA06r | *GGA06r_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGA06r_Welltesting_Jan-2020_Report_v2.pdf* | |
| GGA07 | *GGA07_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGA07_Welltesting_Feb-2020_Report_v1.pdf* | |
| GGA08 | *GGA08_SDT&CRT_Hydraulicdata_v1.xlsx*<br>*GGA08_Welltesting_Feb-2020_Report_v1.pdf* | |
| GGA09r | *GGA09r_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGA09r_Welltesting_Feb-2020_Report_v1.pdf* | |
| GGB04 | *GGB04_falling&risingtest_Hydraulic data_v1.xlsx*<br>*GGB04_Welltesting_Feb-2020_Report_v1.pdf* | |
| GGB05 | *GGB05_SDT&CRT_Hydraulic data_v1.xlsx*<br>*GGB05_Welltesting_Feb-2020_Report_v1.pdf* | |

Users should be aware that all data for the observation boreholes from the CT2X data loggers listed in Table 20 below has been provided in full. Therefore, if graphing this data there will be spikes in the data when the data logger was removed from the borehole and replaced by the Solinst data logger for the duration of the test pumping at that borehole. The diary in Table 23, Appendix C, provides detail to understand when the CT2X data logger was removed from the borehole. It should be referred to when using this data.

**Table 20 List of digital files provided by BGS covering the data collected from the CT2X datalogger in the observation boreholes and the PT2X barometer and included in this data release**

| Borehole Number | BGS derived files | File description |
|---|---|---|
| Observation borehole | *GGA01_CT2X_datalogger_V2.xlsx*<br>*GGA03r_CT2X_ datalogger_V2.xlsx*<br>*GGA04_CT2X_ datalogger_V2.xlsx*<br>*GGA05_CT2X_logger.xlsx*<br>*GGA06r_CT2X_ datalogger_V2.xlsx*<br>*GGA07_CT2X_ datalogger_V2.xlsx*<br>*GGA08_CT2X_ datalogger_V2.xlsx*<br>*GGA09r_CT2X_ datalogger_V2.xlsx*<br>*GGB04_CT2X_ datalogger_V2.xlsx*<br>*GGB05_CT2X_ datalogger_V2.xlsx* | - Spreadsheet of raw CT2X data logger data including: temperature, conductivity, pressure, salinity and TDS raw data. Depth to water converted data. All datums and measurements of depth of data logger necessary to convert pressure data into water level m below datum or water level height.<br>- Also includes manually dipped water levels taken periodically throughout the test pumping period for calibration of data logger water levels. |
| Barometer | *UKGEOS_PT2X_Barometer.xlsx* | - Spreadsheet of barometric pressure data collected by the PT2X barometer |

# Appendix C Using the test pumping data from the Glasgow Observatory

The Glasgow Observatory was an active construction site throughout the test pumping, meaning the borehole compounds were being completed. The consequence of this ongoing construction resulted in the following datums changing, often multiple times, over the course of the test pumping period:

- Borehole casing height: This was changed throughout the testing as the borehole casing was gradually cut down to its final height. Changes were on the m to cm scale. *Not all changes are documented.*
- Data logger depth: This sometimes changed through the test pumping period, generally in conjunction with changes to the casing height. Changes were on m to cm scale. *Most changes are documented.*
- Manhole chamber floor: Concrete was added to the base of the manhole chamber at various times until it reached the final height. Changes were on cm scale. *None of these changes were documented.*

As well as the three datums above a fourth datum, the top of dip tube, was used for manual water measurements during the borehole tests.

- Top of dip tube: The manual water level measurements for each test were measured from the top of the inserted dip tube (Section 2.2.2)

Whilst extensive checking of the data has occurred and all datum changes that were recorded during the construction work, or changes that could be derived from the data have been provided, there may be some discrepancies in water level heights, meaning that absolute groundwater levels may only be accurate to within 10 – 30 cm. The relative data for each test, measured by the Solinst data logger, however, should be accurate within approximately 5 cm (Solinst 2020). The relative data for each observation borehole, measured by the CT2X data logger, should be accurate within approximately 1 cm (Seametrics 2019).

The *final heights* of the top of borehole casing and base of the manhole chamber are provided below in Table 21. These will differ from the height of the top of borehole casing and base of the manhole chamber at the time of test pumping.

**Table 21 Final heights of each borehole**

| Borehole | Final height top borehole casing (m OD) *01/04/2020* | Final height of floor of manhole chamber (m OD) *01/04/2020* |
|---|---|---|
| GGA01 | 9.99 | 9.38 |
| GGA03r | 10.04 | 9.43 |
| GGA04 | 12.11 | 11.53 |
| GGA05 | 12.12 | 11.50 |
| GGA06r | 12.10 | 11.53 |
| GGA07 | 11.34 | 10.78 |
| GGA08 | 11.37 | 10.77 |
| GGA09r | 11.44 | 10.78 |
| GGB04 | 11.86 | 11.20 |
| GGB05 | 11.74 | 11.16 |

### HOW DOES THIS AFFECT THE TEST PUMPING DATA?

Water level data measured during the tests (the manual water levels and the data logger data from the Solinst data logger) have been displayed in this report as meters below datum, the datum (as explained in Section 2.2.2) is the top of dip tube.

Water level data measured by the Aquistar CT2X data logger in the observation boreholes have been displayed in this report as meters relative to Ordnance Datum (OD) and therefore the water pressure data measured by the data logger has been converted into water level height in m OD.

Table 22 below summarises which data, in which spreadsheet, included in this data pack are affected by the changing datums. Furthermore Table 23 provides a diary of known changes that occurred throughout the test pumping period and outlines in detail which datum applies to which part of the dataset of each borehole. Where there are gaps or time periods that are not covered by the diary in Table 23, this represents times that the data logger in the observation borehole was removed from the borehole, therefore data from these periods is not representative of groundwater level within the observation borehole.

**Table 22 Effects of changing datums on data provided as part of this data pack**

| **Data file**<br>Excel® workbook,<br>*Worksheet within workbook* | **Datum used to calculate water levels** | **Data type** | **How is it affected?** |
|---|---|---|---|
| GG###_SDT&CRT_Hydraulicdata.xlsx<br>*GG###* | Manhole chamber floor.<br>*Denoted as Final Floor Level (FFL)* | Dipmeter – *Water level (m below FFL)* | If converting this data into water level height using the final height level provided for the base of the manhole chamber, the converted values will not represent absolute water levels during this time as concrete was added to the manhole chamber base, changing the level between the time of test pumping and the time of the final height measurement provided. |
| | | Water-level datalogger and barometric datalogger – *Water level (m below FFL)* | If combining this data with the observation borehole data from the Aquistar CT2X data logger for each borehole, there will be a noticeable difference in water level between the two that is not accounted for by rainfall events. This is because we only have final floor heights of the manhole chamber base and no record of any changes of how this differs to the height at the time of the test pumping. |
| SDT_GG###_FINAL,<br>*Manual_dip_data* | Top of dip tube | Water level (mbd) | This was measured from the *top of the dip tube* inserted during test pumping of this borehole. The height of the dip tube was measured above the base of the manhole chamber. If converting this data into water level height using the final height level provided for the base of the manhole chamber, the converted values will not represent absolute water levels during this time as concrete was added to the base, changing the level between the time of test pumping and the time of the final height measurement provided. |
| SDT_GG###_FINAL,<br>*Solinst_datalogger_data* | | | |
| CRT_GG###_FINAL,<br>*Manual_dip_data* | | | |
| CRT_GG###_FINAL,<br>*Solinst_datalogger_data* | | | |
| GG###_CT2X_logger,<br>*GG###_CT2X_datalogger* | | GG### depth to water (mbd) | Depth to water is calculated from the *top of the borehole casing*. The calculated depth to water values from the data logger are calibrated against manually dipped water levels. This information is provided in the spreadsheet. The depth of the logger values for the depth to water represent the approximate depth of the logger within the borehole. These have been calculated from comparing |

| **Data file** Excel® workbook, *Worksheet within workbook* | **Datum used to calculate water levels** | **Data type** | **How is it affected?** |
|---|---|---|---|
| | | | the logger data with the manual dips and from any field notes that registered the depth of the data logger. Large changes on the m scale were almost always noted. However, smaller changes to the data logger depth were not always captured and have been estimated from comparison of data with the manually dipped water levels.<br><br>As well as the data logger depth changing, the casing height of all boreholes was cut down, often multiple times, throughout the test pumping period. Where records show how much casing was removed at a specific time this has been included in this spreadsheet and the data adjusted accordingly. However, not all these changes were captured.<br><br>If converting the depth to water data into water level height please refer to Table 23 below to ensure the correct casing height is used for the correct data. |

**Table 23 Summary of dates where borehole casing or data logger length was changed**

| Borehole | Date | Action | Depth of data logger (m)<br>*Required for calculating depth to water in m below top of borehole casing* | Borehole casing height (m OD)<br>*Required for calculating the height of the water level* | Pressure (mBars) data datum applies to<br>*(measured by the CT2X data logger)* |
|---|---|---|---|---|---|
| GGA01 | 15/01/2020 | Casing height measured. | - | 10.03 | 16/01/2020 09:00 – 13/02/20 14:05 |
| | 16/01/2020 | Logger installed. | 10.20 | - | All data for this borehole. |
| | 13/02/2020 | Casing cut down, logger moved down to accommodate this. No record of amount of change. | - | NR* | None. |
| | 01/04/2020 | Final borehole casing height. | - | 9.99 | 13/02/2020 14:15 – 20/02/2020 09:15 |
| GGA03r | 09/01/2020 | Logger installed. | 29.45 | - | 09/01/2020 16:30 – 13/01/2020 13:25 |
| | 13/01/2020 | Logger wire cut down. | 23.81 | - | 13/01/2020 13:45 – 20/02/2020 15:50 |
| | 15/01/2020 | Casing height measured. | - | 10.06 | 09/01/2020 16:30 – 13/01/2020 13:25 |
| | 13/02/2020 | Casing cut down, logger moved down to accommodate this. | NR | NR | None. |
| | 01/04/2020 | Final borehole casing height. | - | 10.04 | 13/01/2020 13:45 – 20/02/2020 15:50 |
| GGA04 | 13/01/2020 | Logger installed. | 25.23 | 12.29 | 13/01/2020 14:30 – 11/02/2020 14:25 |
| | 11/02/2020 | Casing cut down. | 25.05 | NR | 12/02/2020 08:35 – 20/02/2020 15:40 |
| | 01/04/2020 | Final borehole casing height. | - | 12.11 | All data for this borehole. |
| GGA05 | 13/01/2020 | Logger installed. | 25.03 | 12.27 | 13/01/2020 15:00 - 11/02/20 14:15 |

| Borehole | Date | Action | Depth of data logger (m) *Required for calculating depth to water in m below top of borehole casing* | Borehole casing height (m OD) *Required for calculating the height of the water level* | Pressure (mBars) data datum applies to *(measured by the CT2X data logger)* |
|---|---|---|---|---|---|
| | 11/02/2020 | Casing cut down. | 24.88 | NR | 12/02/2020 08:55 – 20/02/2020 15:55 |
| | 01/04/2020 | Final borehole casing height. | - | 12.12 | All data for this borehole. |
| **GGA06r** | 09/01/2020 | Logger installed. | 11.39 | - | All data for this borehole. |
| | 03/02/2020 | Casing cut down. | NR | NR | None. |
| | 01/04/2020 | Final borehole casing height. | - | 12.10 | All data for this borehole. |
| **GGA07** | 10/01/2020 | Logger installed. | 30.52 | - | 10/01/2020 09:00 – 22/01/2020 08:10 |
| | 22/01/2020 | Logger wire cut down by approximately 10 m. | 20.15 | - | 22/01/2020 08:25 – 29/01/2020 08:30 |
| | 29/01/2020 | Derived from height of borehole casing above base of manhole chamber taken on 29/01/2020 (1.68 m) before casing was cut down. Height of manhole chamber taken as final height provided on 01/04/2020. Approximate casing height is adjusted to smooth data and account for slight difference in final base of manhole chamber height and height when measurement was taken. *Approximate casing height.* | | 12.23** | 10/01/2020 09:00 – 29/01/2020 08:30 |

| Borehole | Date | Action | Depth of data logger (m) *Required for calculating depth to water in m below top of borehole casing* | Borehole casing height (m OD) *Required for calculating the height of the water level* | Pressure (mBars) data datum applies to *(measured by the CT2X data logger)* |
|---|---|---|---|---|---|
| | 29/01/2020 | Logger wire cut down by 1 m. | 19.21 | - | 29/01/2020 10:30 – 05/02/2020 10:35 |
| | 29/01/2020 | Casing was cut down. *Approximate casing height.* | - | 11.36** | 29/01/2020 10:30 – 12/02/2020 09:35 |
| | 10/02/2020 | No record of logger wire being cut down, but DTW changes by ~3 m to align with groundwater level. | 15.92 | - | 10/02/2020 09:10 – 12/02/2020 09:35 |
| | 12/02/2020 | Logger wire is lengthened by 3 m, but no record of this. | 19.17 | - | 12/02/2020 14:10 – 20/02/2020 16:00 |
| | 13/02/2020 | Casing cut down. | NR | NR | |
| | 01/04/2020 | Final borehole casing height. | - | 11.34 | 12/02/2020 14:10 - 20/02/2020 16:00 |
| **GGA08** | 10/01/2020 | Logger installed. | 30.30 | - | 10/01/2020 09:00 – 22/01/2020 08:20 |
| | 22/01/2020 | Logger wire cut down by approximately 11 m. | 19.21 | - | 22/01/2020 08:30 – 29/01/2020 08:10 |
| | 29/01/2020 | Casing cut down, height of casing *before* it was cut down, calculated from measurement taken of borehole casing above concrete manhole chamber. *Approximate casing height.* | - | 12.28** | 10/01/2020 09:00 - 29/01/2020 08:10 |
| | 29/01/2020 | Casing cut down, height of casing *after* it was cut | - | 11.52** | 05/02/2020 11:00 - 13/02/2020 09:30 |

| Borehole | Date | Action | Depth of data logger (m) *Required for calculating depth to water in m below top of borehole casing* | Borehole casing height (m OD) *Required for calculating the height of the water level* | Pressure (mBars) data datum applies to *(measured by the CT2X data logger)* |
|---|---|---|---|---|---|
| | | down, calculated from measurement taken of borehole casing above concrete manhole chamber. *Approximate casing height.* | | | |
| | 29/01/2020 | Logger wire cut down by approximately 1 m. | 18.23 | - | 05/02/2020 11:00 – 13/02/2020 09:30 |
| | 13/02/2020 | Casing was cut down. Logger wire shortened. *Approximate logger wire and casing height.* | 18.02** | 11.42** | 13/02/2020 09:40 – 20/02/2020 15:55 |
| | 01/04/2020 | Final borehole casing height. | - | 11.37 | |
| GGA09r | 10/01/2020 | Logger installed. | 11.64 | - | 10/01/2020 10:00 – 29/01/2020 08:15 |
| | 29/01/2020 | Casing cut down, height of casing *before* it was cut down, calculated from measurement taken of borehole casing above concrete manhole chamber. *Approximate casing height.* | - | 12.34** | 10/01/2020 10:00 – 29/01/2020 08:15 |
| | 29/01/2020 | Casing cut down, height of casing *after* it was cut down, calculated from measurement taken of borehole casing above concrete manhole | - | 11.53** | 29/01/2020 10:40 – 13/02/2020 09:40 |

| Borehole | Date | Action | Depth of data logger (m) *Required for calculating depth to water in m below top of borehole casing* | Borehole casing height (m OD) *Required for calculating the height of the water level* | Pressure (mBars) data datum applies to *(measured by the CT2X data logger)* |
|---|---|---|---|---|---|
| | | chamber. *Approximate casing height.* | | | |
| | 29/01/2020 | Logger wire cut down by 1 m. | 10.64 | - | 29/01/2020 10:40 – 20/02/2020 15:50 |
| | 13/02/2020 | Casing cut down. | - | NR | None. |
| | 01/04/2020 | Final borehole casing height. | - | 11.44 | 13/02/2020 09:55 - 20/02/2020 15:50 |
| **GGB04** | 09/01/2020 | Logger installed. | 11.65 | - | All data for this borehole. |
| | 01/04/2020 | Final borehole casing height. | - | 11.86 | All data for this borehole. |
| **GGB05** | 09/01/2020 | Logger installed. | 30.76 | - | 09/01/2020 15:00 – 13/01/2020 15:35 |
| | 13/01/2020 | Logger wire cut down by approximately 5 m. | 25.77 | - | 13/01/2020 15:50 – 12/02/2020 13:55 |
| | 17/02/2020 | Logger wire shortened. *Approximate logger wire depth.* | 25.60** | - | 17/02/2020 10:50 – 20/02/2020 10:20 |
| | 01/04/2020 | Final borehole casing height. | - | 11.74 | 09/01/2020 15:00 - 20/02/2020 10:20 |

*NR= No record of how much the borehole casing or logger wire changed

**Approximate height derived from measurements of borehole casing above the base of the manhole chamber or from change in water level height over a short span of time

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