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REPORT

De-risking green energy from mine waters by developing a robust hydrogeological conceptual model of the UK Geoenergy Observatory in Glasgow

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Abstract

Mine-water geothermal resources have potential to provide low-carbon heating and cooling in many areas; however, this potential has not been fully realised due to technical, economic and policy challenges. The UK Geoenergy Observatory (UKGEOS) in Glasgow was developed to provide an at-scale research facility designed to help de-risk mine-water geothermal usage. The limited knowledge of the hydrogeological systems altered by former mining activities is a key determinant of the long-term sustainability of water and heat abstraction/reinjection. This work presents a hydrogeological conceptual model developed using groundwater monitoring data obtained during the construction of the Observatory between 2020 and 2022, results from initial pumping tests performed in 2020, and results of hydrochemistry analysis from 25 sampling rounds collected between 2019 and 2022. The analysis of the data provides evidence of the dominant role of mine workings in controlling groundwater flow, with high intra-mine connectivity; increased fracturing in sandstones above mine workings; and limited inter-mine connectivity. Groundwater recharge is meteoric, mean residence times are >50 years, and there is a general upwards circulation from the deeper mine levels to the superficial deposits and the River Clyde. Faults play a significant role in limiting the extent of the highly transmissive mine workings, but there remains uncertainty surrounding the role of the faults in connecting different mine workings and their hydraulic behaviour in nonmined units. The conceptual model, that will be refined as new data become available, will be used to help guide monitoring and sampling programs and plan research activities in the Observatory.

Keywords Site characterization · Geothermal systems · Conceptual models · Mine hydrogeology · UK

Introduction

The low-enthalpy geothermal resource contained in accessible water stored in flooded coal mines has the potential to contribute to decarbonization of heating and cooling across the UK (e.g. Walls et al. 2021). Although temperatures within the mine systems may not be very high (12–20 °C in the UK; Adams et al. 2019), they are typically almost constant over time, and the large volumes of water stored combined with the potential of achieving high abstraction rates make them suitable for space heating using heat pump technology (Banks et al. 2004; Abesser and Walker 2022). As many closed mines are located under major cities, mine water geothermal energy could become a strategic resource providing low-carbon heating to millions of households (Gluyas et al. 2019; NELEP 2022). Flooded mines also have potential to be used for underground thermal energy storage (Menéndez et al. 2019).

A significant challenge to the development of mine-water-geothermal-energy resources is the uncertainty associated with groundwater dynamics in flooded mines (Younger and Robins 2002). Underground voids created by mining activities, which may remain fully open or be partially closed after mine abandonment, have the potential to store large volumes of water and constitute preferential pathways for groundwater flow and transport of heat (e.g. Wolkersdorfer 2008; Loredo et al. 2016). However, uncertainties about the distribution and location of transmissive

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units, their hydraulic properties after mine closure, and the understanding of the current hydrogeological behaviour and hydrochemical evolution of the system represent significant challenges for the exploration, development, and management of mine-water-geothermal schemes (Banks et al. 2022).

The overall objective of this study is to develop a preliminary hydrogeological conceptual model of the UK Geoenergy Observatory (UKGEOS) in Glasgow (Scotland, UK). The Observatory has been constructed with the aim of improving scientific understanding of mine-water geothermal systems, de-risking exploitation, and evaluating the long-term sustainability of the geothermal resource via baseline monitoring and data collection and at-scale research (Monaghan et al. 2021b, 2022). The Glasgow Observatory has been constructed at the scale of a small-medium-sized geothermal scheme and shares geological, mining, and operational settings and characteristics with commercial projects in the UK and worldwide. Previous experiences from the geothermal sector in other countries (The Netherlands, Germany, France) have shown that the availability of at-scale, research or commercial, projects provide invaluable information and experience to reduce exploration, construction and operational uncertainty and costs (e.g. Verhoeven et al. 2014; Hahn et al. 2022).

The aim is to develop a comprehensive and integrated conceptual model of the hydrogeological system that can be used in the interpretation of new data and to support other research activities in the Observatory. To develop the conceptual model the project defined five main objectives to be addressed using available geological and mining information and baseline and experimental monitoring data:

1. Identify the hydraulic boundaries of the mined hydrogeological system
2. Characterise the properties of the main hydraulic units
3. Characterise hydraulic connectivity within and between these hydraulic units, surrounding aquifers and surface-water bodies
4. Identify the main components of the water balance, in particular the main areas of recharge and discharge
5. Describe groundwater circulation in the system, including flow directions, residence times and main flow pathways

Description of the UK Geoenergy Observatory in Glasgow

Site location

The UK Geoenergy Observatory in Glasgow is located within the Clyde Gateway Urban Regeneration District, at the east end of the Glasgow city region (Scotland, UK) (Monaghan et al. 2017, 2021b), with 11 of the 12 boreholes located in a meander of the River Clyde. The Clyde Valley runs in the east–west direction with hills rising to over 500 m to the west, north and south that reflect the local geology (Fig. 1).

The area selected for the Observatory is a post-industrial, urban coalfield setting representative of other mine water heat schemes in the UK and abroad. The Observatory was developed after 4 years of planning, design, borehole drilling and testing (Starcher et al. 2021), and installed with geothermal infrastructure typical of a small mine water scheme, comprising a heat pump/chiller, a sealed pipe loop and heat exchangers, all commissioned in 2023.

Geological context

The Glasgow Observatory lies within the Central Coalfield of the Midland Valley of Scotland. The bedrock geology of the area consists mainly of Upper Carboniferous rocks of the Clackmannan and Scottish Coal Measures Groups. The Clackmannan Group comprises, from oldest to youngest, Lower Limestone, Limestone Coal, Upper Limestone and Passage formations. The Scottish Coal Measures Group consists of cyclical sequences of sandstone, siltstone, mudstone, root-bearing palaeosol (‘seatearth’) and coal (Hall et al. 1998), and are divided into Lower, Middle and Upper formations (Fig. 1). The Middle Coal Measures (Westphalian B) contains the thickest mined coal seams in the area, including the Glasgow Upper (GU), Glasgow Ell (GE) and Glasgow Main (GMA) that are intersected by the Observatory boreholes. The Clyde Plateau Volcanic Formation, of Lower Carboniferous age, formed by a thick succession of basaltic to trachytic lavas and volcanoclastic sediments, outcrops at rockhead some 2 km to the south of the observatory in the footwall of the Dechmont Fault (Fig. 1a). Igneous intrusions, mainly dolerite sills and dykes of late Carboniferous–early Permian age, crop out further north and south of the Shettleston and Dechmont faults (Hall et al. 1998).

The Carboniferous sequence is folded into an open fold plunging to the east with E–W strike (Monaghan et al. 2017). In the area of the Observatory itself, and immediately to the north and east, the strata have a general gradual dip towards the south. 2 km to the west of the observatory, the dip is towards the east, and ~3 km to the south of the Observatory the strata dip towards the north. A number of northwest, west-northwest and north-trending faults cut through the Carboniferous rocks in this area (Fig. 1a). The Observatory lies within a geological block bounded to the north by the Shettleston Fault and to the south by the Dechmont Fault (Fig. 1). Within this

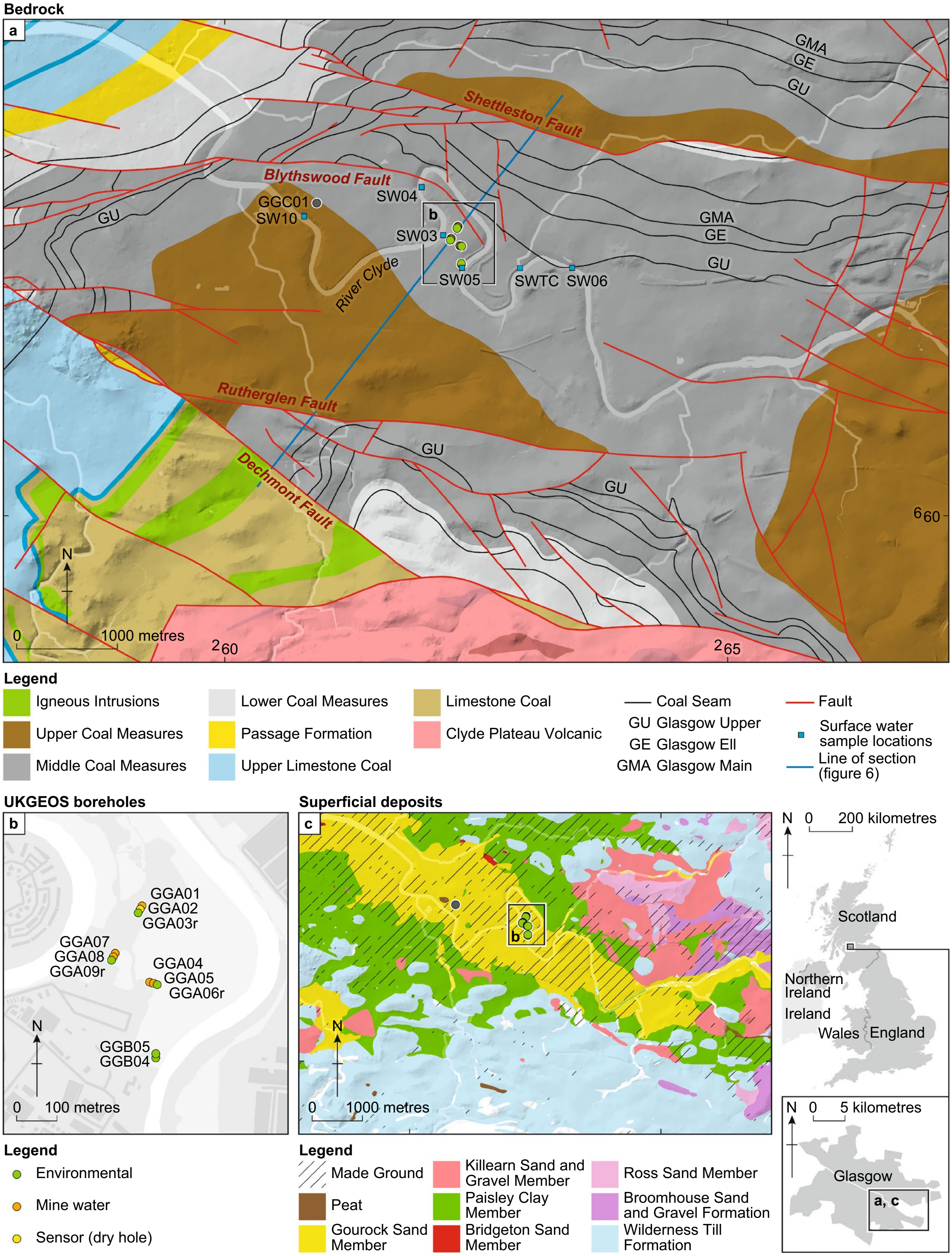

Fig. 1 **a** Bedrock geology map. **b** Layout of the UKGEOS boreholes at Cuningar Loop. **c** Map of superficial deposits. Contains Ordnance Survey data ©Crown Copyright and database rights 2023. ©BGS, UKRI 2023

block, smaller faults—of shorter extent and with smaller displacement—can be grouped into two general systems with east–west and north–south trends. Two faults of particular interest to this study are the Rutherglen Fault to the south of the Observatory, and the Blythswood Fault, an extension of which crosses the Observatory itself within the Cuningar Loop (Fig. 1a). The traces of both can be inferred from mine working plans (Fig. 2), and they separate or communicate workings in different coal seams at different depths in the Farme Colliery, which was the mine below the Cuningar Loop that included the mine workings intercepted by the Observatory.

Overlying the bedrock there is a heterogeneous sequence of variably thick superficial Quaternary deposits (Browne and McMillan 1989; Ó Dochartaigh et al. 2019), which were accumulated during and after the last glacial period, and

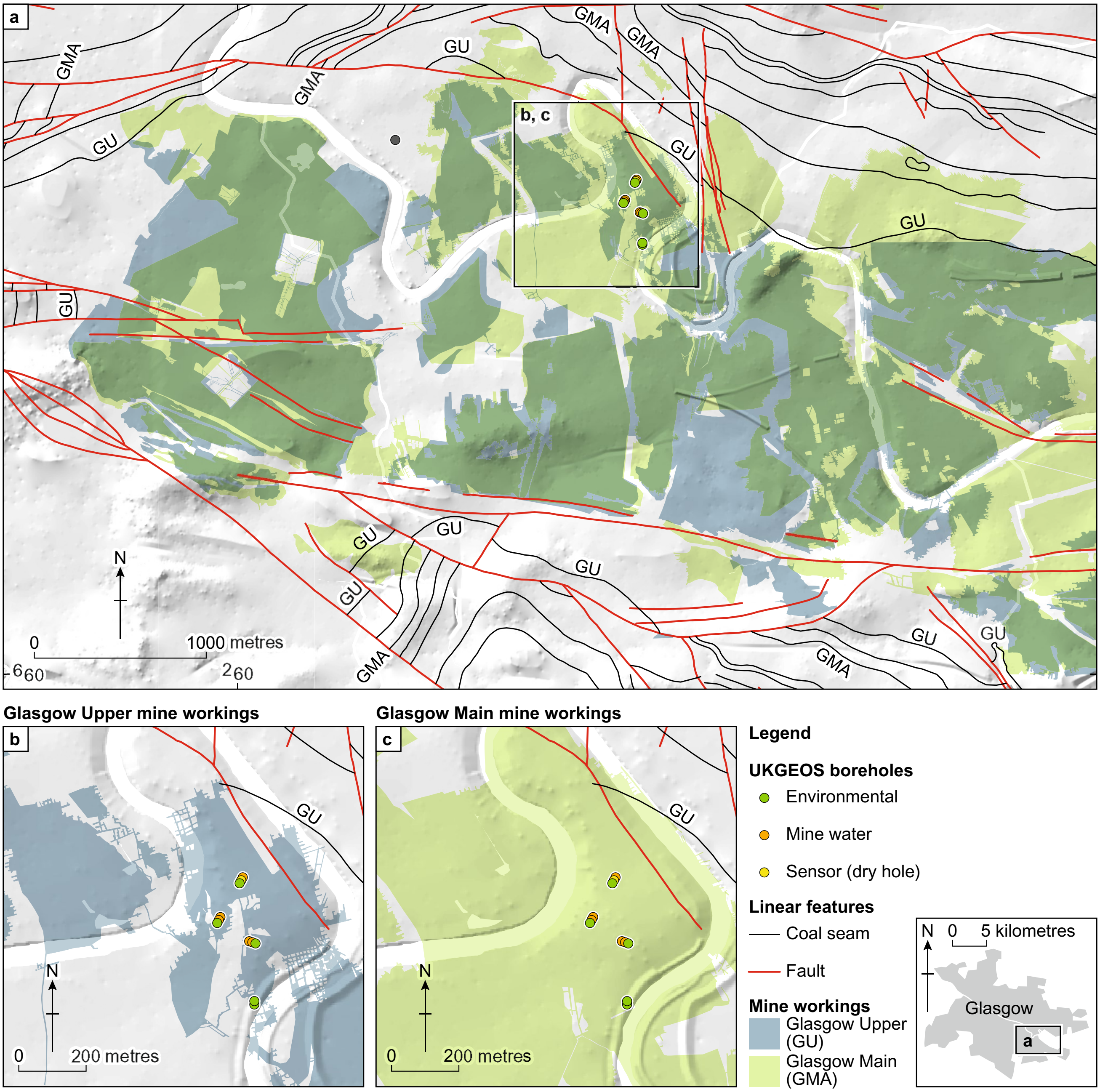

Fig. 2 **a** Glasgow Upper (GU) and Main (GMA) mine workings areal extent. **b** Detailed view of the mapped extent of the GU, and the **c** GMA below the Cuningar Loop. Borehole IDs are shown in Fig. 1. Contains Ordnance Survey data ©Crown Copyright and database rights 2023. Mine workings digitised from plan scans ©The Coal Authority 2023 by ©BGS, UKRI 2023

are thickest along the Clyde Valley (Fig. 1c). In the most urbanised areas, which are mainly along the Clyde Valley, there is also a heterogeneous distribution of disturbed and made ground with variable thicknesses and compositions that reflects past industrial activities in the area (Monaghan et al. 2021b).

Geological information collected during drilling and testing of the Observatory boreholes, including from rock samples obtained during drilling, core logging, and downhole geophysical logging and camera surveys, provide more detail on the local lithology, texture and fractured nature of the unmined Carboniferous strata. The observations after drilling confirmed the overall regional lithology of Carboniferous strata and the heterogeneous nature of the superficial deposits (see Monaghan et al. 2021b for more details).

Coal mining history

Coal mining history in the Glasgow area spans almost 300 years, from the seventeenth to the twentieth centuries, with the last colliery in the east of the city being closed in the 1960s (Hall et al. 1998). Beneath the Cuningar Loop, where the Glasgow Observatory is located, seven coal seams from the Lower and Middle Coal Measures were worked at the Farme Colliery between 1805 and 1928. The most common mining method is likely to have been ‘pillar and stall’ (‘stoop and room’), sometimes with subsequent ‘total extraction’ where initially pillar and stall zones were later ‘robbed’ of the remaining pillars (Findlay et al. 2020; Monaghan et al. 2021b).

Hydrogeology of the Glasgow area

The unmined bedrock Carboniferous sequence typically constitutes a multilayered aquifer of fine-grained, well-cemented sedimentary rocks, classified as aquifers of low to moderate productivity (Robins 1990; MacDonald et al. 2005; Ó Dochartaigh et al. 2015). Within the Carboniferous sequence, sandstone units have the highest natural transmissivity and storage capacity and tend to act as discrete aquifer units, interspersed by lower permeability siltstones, mudstones and coal seams. There are many faults in the area, which may be associated with enhanced fracturing of the surrounding rocks. Mining activity significantly modified natural rock properties and groundwater dynamics by creating open fractures and other voids, and depressing groundwater levels via pumping for mine dewatering (MacDonald et al. 2017). At the peak of dewatering activity, the estimated total abstraction from mines across the Glasgow area was 215,000 m^3/day (Ó Dochartaigh et al. 2019). Mine dewatering drew down groundwater levels in the Carboniferous aquifer to the depth of the deepest mines, which in the area of study was the Kiltongue Coal (Lower Coal Measures) recorded at depths of 268.5 m (Monaghan et al. 2017). When mining and pumping stopped, mines flooded naturally in a process known as groundwater rebound (Younger and Adams 1999). The general regional groundwater flow is believed to be from areas of generally higher elevation to the north, northeast and southeast, towards Glasgow and the Clyde Valley (Robins 1990; Hall 1998), following flow paths that may be many kilometres long and up to hundreds of metres deep (Ó Dochartaigh et al. 2015).

The Quaternary superficial deposits form a shallow complex aquifer system (Turner et al. 2015; Ó Dochartaigh et al. 2019) typically 10–30 m thick, and highly heterogeneous. Units with a higher proportion of coarse-grained deposits, and correspondingly higher hydraulic conductivities—including Gourock Sand and Bridgeton Sand members—, alternate with others with a higher proportion of fines, and correspondingly lower hydraulic conductivities—including the Paisley Clay and the Wilderness Till formations (Williams et al. 2018). The River Clyde has been shown to be in hydraulic continuity with the Quaternary aquifer, especially with the more permeable Gourock and Bridgeton Sand members (Ó Dochartaigh et al. 2019). The general groundwater flow in the Quaternary aquifer is thought to be downgradient along the valley throughout the most permeable sandy and gravel deposits, and locally towards the river (Turner et al. 2015; Ó Dochartaigh et al. 2019).

Groundwater in unmined Carboniferous sedimentary aquifers across central and southern Scotland is typically moderately to highly mineralised (specific electrical conductivity (SEC) 353–1,450 µS/cm) with near neutral to slightly alkaline pH (6.8–8.0), while groundwater from mined Carboniferous aquifers typically shows slightly higher values of mineralisation (SEC 311–1,700 µS/cm) with near neutral pH (6.3–7.7; MacDonald et al. 2017).

The climate in the area is temperate maritime with an average annual precipitation of 1,153 mm/year for the period 1991–2020 (MetOffice values at Glasgow Springburn station, ~5 miles to the north of the Observatory). Potential evaporation rates are in the order of 500 mm/year (Turner et al. 2015) and long-term average recharge for the area, estimated using ZOODRM (Mansour and Hughes 2004), is ~100–150 mm/year.

Regional and local geothermal settings

A limited number of deep thermal measurements collected in the Glasgow area (Gillespie et al. 2013; Monaghan et al. 2017; Busby 2019; Watson et al. 2019) have been used for estimations of the heat flow and thermal properties. The average regional geothermal gradient in the Midland Valley of Scotland was estimated to be 22.5 °C/km with heat flow of 54.5 mW/m^2 (Browne et al. 1987). In the Glasgow area, the heat flow was estimated to be around 60 mW/m^2 (Busby et al. 2011), slightly higher than average, and could be as high as 80 mW/m^2 after applying paleoclimate corrections (Westaway and Younger 2013; Watson et al. 2019).

Temperature data collected in GGC01, drilled in an unmined area—Figs. 1 and 2 for location; a temperature log plot is shown in Fig. S1 in the electronic supplementary material (ESM)—shows a zone of slightly higher temperatures near the surface (measured temperature of 11.2 °C at the surface) that decreases to almost 11 °C at 11–14 m depth and then a gradual increase to a maximum of 14 °C at 197 m depth (Monaghan et al. 2021a). This would result in a geothermal gradient of ~16 °C/km, estimated to be caused by a local heat flow of 28–33 mW/m^2 (Watson and Westaway 2020), lower than previous values provided for the region, and explained by Watson et al. (2019, 2020) as the resulting effect of historical mining and heat flow entrained and dispersed laterally through the flooded mines.

Methods and data

Mining plans and geological mapping and modelling

Abandonment plans of the Farme Colliery from 1810 to 1934 record the mine workings in the area, including coal seams, extents, depths, mining type, stone and coal roadways, etc. (Monaghan et al. 2021b). The mine plans have been digitised and used in the development of the new geological and mine models (Fig. 2). Earlier 3D geological models (e.g. Browne and McMillan 1989; Hall et al. 1998; Monaghan et al. 2014) were updated for the bedrock (Kearsey and Burkin 2021) and superficial deposits (Arkley and Callaghan 2021) with new information obtained during the construction of the Observatory.

Borehole infrastructure

The UK Geoenergy Observatory infrastructure in Glasgow comprises 12 boreholes, 11 of them located at the Cuningar Loop. Five boreholes were drilled and screened in mine workings: three in the Glasgow Upper (GU) (GGA01, GGA04 and GGA07) to ~50 m depth and two in the Glasgow Main (GMA) (GGA05 and GGA08) to ~85 m depth (Fig. 1; Table 1). Another borehole (GGA02) was drilled into the GMA mine workings but encountered problems during construction and was not screened. Five environmental monitoring boreholes, between 16 and 45 m, were drilled and screened in superficial deposits or bedrock above the GU, to characterise baseline conditions and to monitor the impact of the geothermal infrastructure. More information of the borehole infrastructure and additional data, logs and schematic diagrams are available in "Borehole Information Packs" accessible and downloadable from BGS (2024a).

Table 1 Details and results from interpretation of the pumping tests

Borehole	Unit	Screened section	SDT pumping rates (L/s)	Max. SDT drawdown (m)	Avg. CRT pumping rate (L/s)	Max. CRT drawdown (m)	Estimated Transmissivity (m^2/day)
GGA06r	Superficial	Sand and gravel	0.12/0.26/0.4/0.62	1.23	0.52	1.01	79–225
GGA09r	Superficial	Sand and gravel	0.12/0.22/0.42/0.62	1.36	0.51	0.99	225
GGA03r	Bedrock	Sandstone below rockhead	0.13/0.17/0.28/0.28	30.16	0.1	8.04	2.6
GGB05	Bedrock	Sandstone below rockhead	1/2/2.8/3.5/4.3	2.18	4.3	2.25	580–990
GGA01	Glasgow Upper	Packed backfilled mine waste and overlying sandstone roof	4.8/10.3/15/19.7/24.9	1.73	19.9	1.34	1020–1130
GGA04	Glasgow Upper	Overlying sandstone roof, intact/collapsed coal, and mudstone	4/7.9/11.7/15.5/19.8	28.78	14.8	18.24	240–950
GGA07	Glasgow Upper	Overlying mudstone and part of pillar and void	5/10.1/15/20/25	3.11	20	2.27	1020–1050
GGA05	Glasgow Main	Overlying sandstone roof, open void and mudstone floor	5/10/14.9/19.9/25	0.35	19.8	0.3	1976
GGA08	Glasgow Main	Overlying sandstone/siltstone and open void and waste (roadway)	5/10.1/15.2/20.2/25.2	0.37	20	0.35	1750–2100

SDT step-drawdown test; *CRT* constant rate test

The mine working boreholes are equipped with downhole electrical resistivity tomography (ERT) and fibre-optic distributed temperature sensing (DTS) cables. Data loggers were installed in all the boreholes for continuous monitoring of physical (pressure, temperature) and chemical (electrical conductivity) properties at 15-min intervals. Complete groundwater level time series are accessible in the UKGEOS data releases and the online sensor data platform BGS (2024b).

The final borehole, GGC01, 199 m deep, fully cased and located ~1.5 km WNW of the Cuningar Loop was cored, geophysically logged and imaged (Monaghan et al. 2021a), and a string of five downhole seismometers provide baseline monitoring.

Preliminary pumping tests

Step drawdown (SDT) and constant rate (CRT) tests were performed in all boreholes except GGB04 (Shorter et al. 2021). The length of each step in the SDTs was 1 h, and each CRT was 4–5 h. Water levels were measured with data loggers at 15-s intervals and manual measurements were made regularly for quality control. Physicochemical parameters, including temperature and specific electrical conductivity (SEC), were measured at regular intervals during each test. Groundwater chemistry samples were collected during the CRTs to provide an initial hydrochemical characterisation and to measure changes in selected constituents during pumping to complement observed hydraulic responses (Palumbo-Roe et al. 2021). Transmissivities were estimated using type-curve matching analyses, except in GGB04, which were estimated using the BGS PT code (Barker and Macdonald 2000). More details about the methodological approach are in Shorter et al. (2021).

Hydrochemistry

Surface-water samples were taken for analysis of major ions, trace elements and a range of organic carbon compounds, and stable isotopes ($\delta^{2}H$, $\delta^{18}O$, $\delta^{13}C$). For groundwater, the same suite of samples was taken, with the addition of dissolved gases CFC-11, CFC-12 and SF_6 to determine groundwater residence times. Mean groundwater residence times were calculated using a piston-type flow model (Chambers et al. 2019).

The surface-water monitoring began in February 2019, ahead of the completion of the boreholes in January 2020. Five monitoring locations were established on the River Clyde, comprising three sites (SW03, SW04, SW05) proximal to the Observatory at Cuningar Loop and two control sites ~1.5 km upstream (SW06) and 2 km downstream (SW10; Fig. 1). An additional monitoring point (SWTC) was established on the Tollcross Burn, a small tributary of the River Clyde 0.5 km to the east of the Observatory (Fordyce et al. 2021). Surface-water sampling continued until January 2022 with 25 sampling rounds conducted approximately monthly, from February 2019 to March 2020 and April 2021 to January 2022. No sampling was conducted from the onset of the COVID-19 pandemic in April 2020 until September 2020. Sampling was more sporadic between September 2020 and April 2021. In total, 137 surface water samples were collected.

Groundwater monitoring of each of the 10 boreholes began in September 2020, with one more sampling in December 2020. Groundwater sampling resumed after the COVID-19 pandemic (first national lockdown began in Scotland the 26th March 2020), approximately monthly from March 2021 until January 2022, with a total of 12 rounds of sampling and 120 groundwater samples collected.

Hierarchical cluster analysis (HCA) was conducted using the surface-water and groundwater chemistry data from monthly monitoring in Fordyce et al. (2021), and Bearcock et al. (2022, 2023). The parameters used can be found in the ESM. The data were standardised to convert all variables to a common scale by subtracting the means and dividing by the standard deviation before the distance matrix was calculated, to minimise the effect of scale differences. The Ward linkage rule and Euclidean distance with standardised variables (Templ et al. 2008) were used to investigate how the samples relate to each other on the basis of their chemical composition, to infer possible connectivity within and between the various aquifers sampled, and between groundwater and surface water.

Results

Mine working characteristics

New data from drilling logs, downhole geophysical logging and camera surveys provides evidence of considerable variation in type and distribution of mine workings and post-mine-closure conditions in the GU, GE and GMA across the Observatory. The presence of mine voids and unmined pillars, left as part of 'pillar and stall' mining, including pillars in the GU that were partially exposed by the drilling of boreholes GGA04 and GGA07 provide evidence of the different mining methods used. Observations of post-mine-closure conditions include:

- *Open voids*, such as in borehole GGA07 surrounding a pillar.
- *Goaf*, which is formed by the collapsed roofs of mine workings, and characterised by a heterogeneous, chaotic

distribution of broken rock, wooden pit props and other mine materials. Borehole GGA08 partially intersected a goaf zone in the GMA.

- *Waste*, which comprises open voids backfilled with a variety of densely packed materials to provide structural support. Waste was seen in the GE in boreholes GGA05 and GGA08 as well as the GU in boreholes GGA01 and GGA02. The waste in the GE was most densely packed.
- *Unmined coal*, in unworked seams or remaining pillars which sometimes can be fractured. Unmined coal was intersected in the GU in boreholes GGA05 and GGA04.

Connectivity of mine workings

Mine abandonment plans were used to estimate the maximum extent of connected mine workings around the Cuningar Loop boreholes and the Observatory (Fig. 2). Connected GU mine workings appear to extend over a total area of more than 4.67 km^2 to the south (Rutherglen) and to east (Cambuslang) of the Observatory (Fig. 2a, b). The Observatory itself is located in the Farme Colliery, which constituted a smaller underground mine with an approximate extent of 0.2 km^2. Mine working plans show that Farme was connected to other collieries that exploited the GU in the area to the west via roadways with the Dalmarnock Colliery and to the south and the east through zones of ‘pillar and stall’ workings to the coalfields underlying Rutherglen and Cambuslang (Eastfield Colliery). A notable feature observed in the GU mine plans is the presence of ‘wants’ (sandstone channel washouts of the coal), including a N–S ‘want’ located between Observatory sites 2 (GGA04) and 3 (GGA07) (Fig. 1).

The total extent of the GE is approximately 6.87 km^2 (Fig. 2a). Stone roadways connect the GE with both the GMA (less than 100 m to the northeast of the northern boreholes of the Observatory) and the GU, but current conditions and the degree of connectivity are uncertain. Mine workings in the GE identified during drilling at the Observatory were either open void (GGA02) or very densely packed waste (GGA05 and GGA08).

The GMA workings are connected across a total area of ~8.5 km^2, but beneath the Observatory they have a relatively minor extent of ~1.34 km^2 (Fig. 2a, c) that extends to the west and east of the Observatory, under the River Clyde; the GMA mine workings are ~1.35 m thick here. The main mining method recorded on the abandonment plan was pillar and stall followed by total extraction. Collapsed areas and open voids in the workings were identified in boreholes GGA02, GGA05 and GGA08.

The worked extent of deeper coal seams in the Farme Colliery, below the mine workings screened in the Observatory boreholes, is of similar connected extent for the Humph Coal, the Glasgow Splint, and the Glasgow Virgin mine workings coal (6–8 km^2), while the deeper Kiltongue coal seam has a much more limited worked area of ~0.88 km^2.

Groundwater levels, aquifer properties and hydrochemistry

Groundwater level monitoring

Groundwater levels (heads) in the GMA boreholes (GGA05, GGA08) are the highest of all the hydraulic units in the Observatory, during the period July 2020 to January 2022 they fluctuated between 10.1 and 11.3 maOD (metres above Ordnance Survey Datum). Maximum groundwater levels occurred in January–March 2021 and minimum in August–October 2021 (Fig. 3a, b).

Groundwater levels in the GU (GGA01, GGA04, GGA07) and bedrock (GGA03r, GGA05) boreholes are at very similar elevations—generally ~1 m lower in elevation than those in the GMA—and show synchronous fluctuations (Fig. 3a, b), ranging between 9.1 and 10.3 maOD over the study period. Groundwater levels in the mine and bedrock respond fast to rainfall events (Fig. 3), rising between 0.1 and 0.5 m after periods of precipitation and then rapidly dissipating after rainfall has ended. Fluctuations in the GU/bedrock groundwater levels are generally slightly larger than those observed in the GMA but patterns and duration of responses are similar (Fig. 3b).

In the superficial deposits, borehole water levels were significantly and consistently lower in elevation than those in the GU/bedrock (~6 m) and the GMA (~7 m), ranging between 2.5 and 4 maOD in the study period (Fig. 3). Water levels in all three superficial boreholes were generally at similar heads to each other, varying by up to ~0.2 m (Fig. 3b). However, they showed different fluctuation patterns, rising at slightly different rates in response to rainfall and receding at different rates afterwards (Fig. 3b). For example, groundwater levels in borehole GGB04 generally show lower hydraulic heads, and a faster rise and decline in response to rainfall events and river level changes than those in GGA06r and GGA09r (Fig. 3b).

There is an upward hydraulic gradient from the GMA to the GU/bedrock to the superficial deposits, with gradients between the GU/bedrock and superficial deposits boreholes (~5/40) some 4–5× higher than those between the GMA and GU/bedrock boreholes (~1/40).

Pumping tests: aquifer properties and groundwater level response

Pumping step and constant rate tests carried out on the Observatory boreholes are summarised in Table 1. Representative drawdown curves are shown in Fig. 3c and

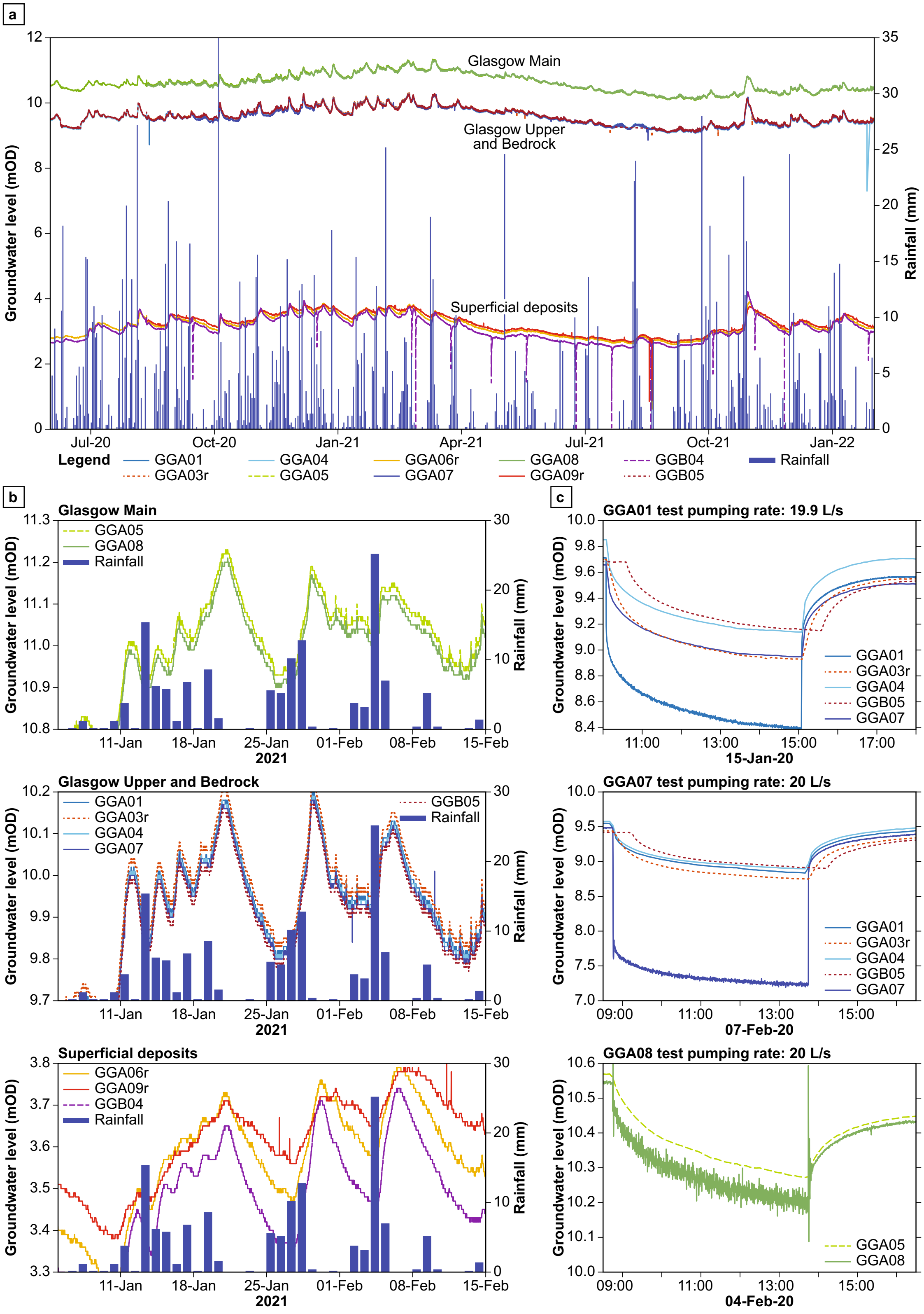

Fig. 3 **a** Long-term groundwater level monitoring data from the Observatory boreholes covering June 2020 to Jan 2022. **b** Detail of groundwater level monitoring data in different hydraulic units over an identical period in January–February 2021. **c** Examples of groundwater level response to a constant rate pumping test in the GU (GGA01 and GGA07) and the GMA (GGA08). Levels given in metres above Ordnance Datum (maOD). ©BGS, UKRI 2023

additional log–log plots are included in the ESM. Further details of the tests can be found in Shorter et al. (2021).

Superficial deposits boreholes Test pumping in the superficial deposits boreholes showed that they are characterised by heterogeneous aquifer properties, with the maximum achieved pumping rates in the constant rate tests on GGA06r and GGA09r ~0.5 L/s. In GGB04 a slug test was performed because its yield was too low for a constant rate test. There was a negligible groundwater level (drawdown) response to pumping in each of the superficial boreholes in the other superficial boreholes, and no measurable response in the mine and bedrock boreholes. The transmissivities estimated for the superficial deposits at the site are highly variable. Estimated transmissivities calculated from the falling head and rising head tests for GGB04 were 0.04 and 0.018 m^2/day, respectively. Estimations for GGA06r and GGA09r range between 79 and 225 m^2/day (Table 1).

Bedrock boreholes Test pumping on the two bedrock boreholes gave very different results, with estimated transmissivities of 2.6 m^2/day for GGA03r and 580–990 m^2/day for GGB05 (Table 1). The lower value reflects expected transmissivities for poorly fractured sandstone, while the high transmissivity reflects extensive fracturing possibly induced by mining. Maximum pumping rates during constant rate tests on both boreholes were moderate to low: 4.3 L/s for GGB05, which caused a maximum drawdown in the pumped borehole of 2.25 m, and 0.28 L/s for GGB03r, which caused a maximum drawdown of ~8 m (Table 1). During the constant rate test on GGB05, measured drawdowns in the other bedrock borehole GGA03r and in the GU boreholes (GGA01, GGA04 and GGA07) were ~0.1 m. During the constant rate test on borehole GGA03r, no significant drawdown was observed either in GGB05 or the GU boreholes.

Glasgow upper (GU) boreholes On GGA01 (Fig. 3c) a constant pumping rate of 19.9 L/s produced a maximum drawdown of 1.34 m after 5 h, at which time drawdown in the other GU boreholes (GGA04 and GGA07) was ~0.8 m. A similar drawdown was observed in the bedrock borehole GGA03r, while in bedrock borehole GGB05, the maximum measured drawdown was 0.54 m. Water level recovery in GGB05 did not start until almost 30 min after pumping in GGA01 stopped. The constant rate pumping test on GGA07 was carried out at a similar pumping rate and showed similar drawdowns in pumping and observation boreholes. The constant rate test on GGA04 was at a lower pumping rate of 14.8 L/s, but caused the largest drawdown measured in any of the mine water boreholes, reaching a maximum of 18.24 m after 5 h, while drawdown in the other GU and the bedrock boreholes was ~0.4 m at the same time. Drawdown in the two GMA boreholes (GGA05, GGA08) during all three GU tests was small, between 0.05 m and 0.08 m. The GU boreholes give consistent transmissivity values in the range 950–1,020 m^2/day (Table 1) despite the different characteristics of mine workings intersected (mine waste, coal pillar, part of a pillar and open void; see Monaghan et al. 2021b), which would likely be a consequence of the duration of the test and extension of the cone of depression integrating the pressure response.

Glasgow main (GMA) boreholes Test pumping in GGA05 produced a small drawdown in the pumped borehole of 0.3 m after 5 h, for a pumping rate of 19.8 L/s. This caused an associated drawdown of 0.25 m in the other GMA mine working borehole (GGA08). The test pumping in GGA08 (Fig. 3c) showed similar results, with a maximum drawdown in the pumped borehole of 0.35 m after 5 h, and in GGA05 of 0.28 m, for a pumping rate of 20 L/s. In both tests, the drawdown observed in the GU and bedrock boreholes was ~0.1 m after 5 h. Estimated transmissivities for the GMA mine working boreholes were the highest measured at the Observatory, with values ranging between 2,000–2,100 m^2/day (Table 1). These high transmissivity values may reflect the existence of voids that remain open in the GMA compared to the more heterogeneous nature of mine workings in the GU.

Groundwater chemistry from baseline monitoring

The baseline groundwater chemistry monitoring, between September 2020 and January 2022, reveals that all groundwaters are highly mineralised compared to most groundwaters in Scotland—median specific electrical conductivity (SEC) 1,600 µS/cm—with circumneutral pH, and comprise bicarbonate–type waters (Fig. 4).

The groundwaters from the mine working boreholes are typical of other Scottish Carboniferous mined aquifers (Ó Dochartaigh et al. 2011; MacDonald et al. 2017). They have a median SO_4 150 mg/L (excluding GGA01), contain sufficient alkalinity (median HCO_3 is 790 mg/L) to neutralise mineral acidity, and may therefore be classed as net-alkaline mine waters, in common with many other flooded mine workings in Scotland (Younger 2001). Groundwaters in the superficial deposit boreholes are highly mineralised and of variable quality, as previously described (Ó Dochartaigh et al. 2019).

Applying hierarchical cluster analysis (HCA) to the samples based on their chemical composition, the resulting clustering broadly reflects the principal lithological units represented by the superficial deposits, the bedrock, and the mine workings (Fig. 4d). A relatively greater chemical variability between boreholes from the same target horizon is,

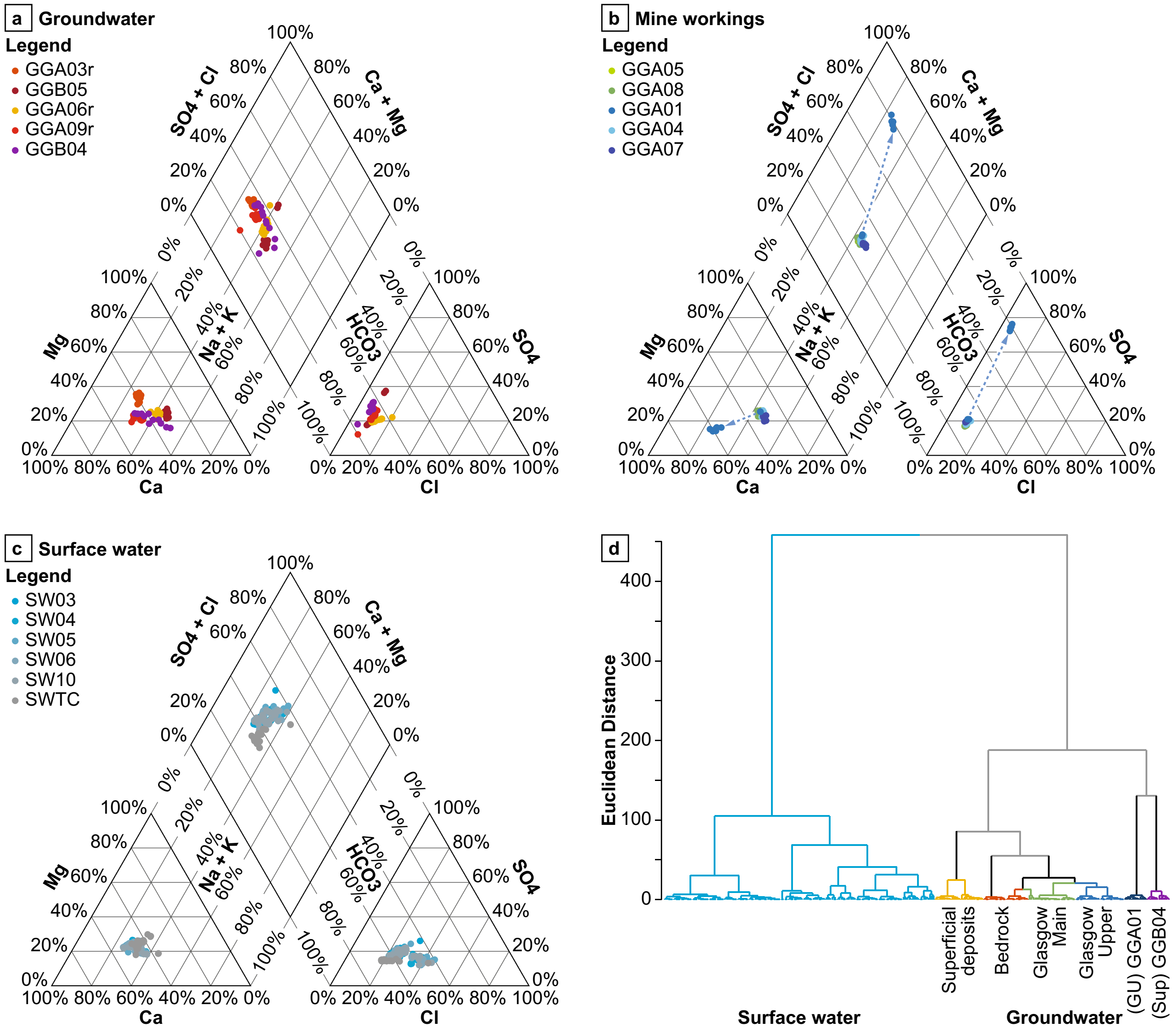

Fig. 4 Piper diagrams of major ion chemistry of groundwater from **a** environmental boreholes in bedrock and superficial deposits, **b** mine working boreholes (arrows show the evolution of GGA01); and **c** surface water, based on monitoring between February 2019 and January 2022 (for details see text). **d** Hierarchical clustering of groundwater samples from the baseline monitoring. ©BGS, UKRI 2023

however, observed within the bedrock and the superficial deposits units. HCA indicates that surface-water chemistry is distinct from groundwater chemistry (Fig. 4d).

Groundwater chemistry is stable through time, apart from borehole GGA01 in the GU, which evolved after the pumping test from bicarbonate–type to calcium sulphate–type water (Fig. 4b marked with an arrow). SEC also increased from 1,750 µS/cm to ~3,000 µS/cm (Bearcock et al. 2022). This shift in groundwater character may have been induced by sulphide oxidation of the mine waste material around the borehole (identified from the borehole log) and subsequent acid neutralisation as the pH remains circumneutral. The borehole forms a distinct cluster from the main mine working group in Fig. 4d.

Values for groundwater δ^2H and $\delta^{18}O$ fall on the global meteoric water line (GMWL; Fig. 5a). This is in line with previous isotopic studies of abandoned and flooded coal mine workings (Burnside et al. 2016; Loredo et al. 2017), and it indicates that groundwater in the mine workings at the Observatory, as well as in the unmined bedrock and superficial deposits, is dominated by recharge from rainfall in conditions consistent with the current local climate. Isotopic values for surface water samples from the River Clyde showed substantial temporal variability during the baseline monitoring sampling (δ^2H range −66.9 to −39.3‰; median −48.7‰; $\delta^{18}O$ range −9.51 to −6.65‰; median −7.39‰), with lower $\delta^{18}O$ more

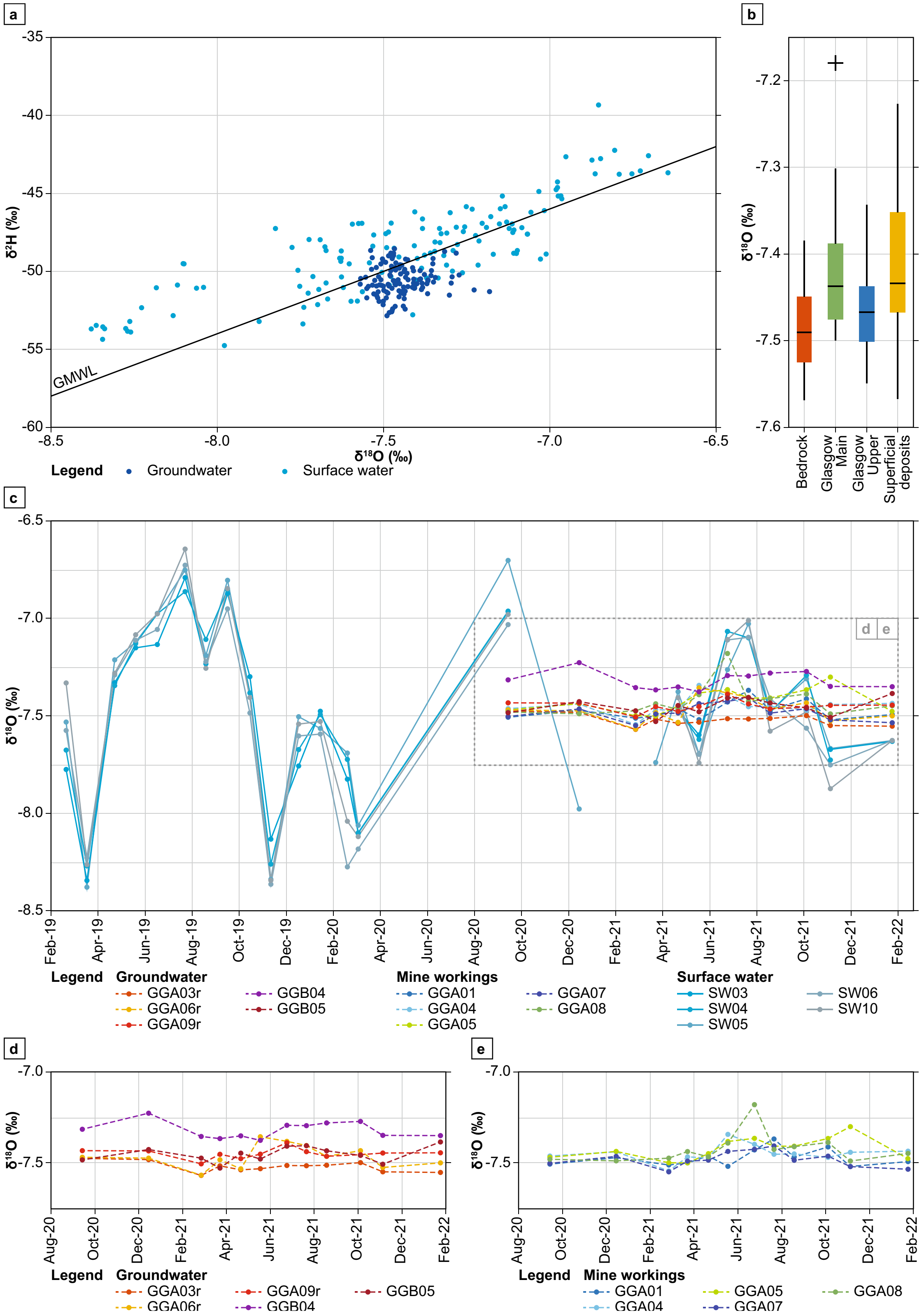

Fig. 5 **a** Plot of groundwater and surface water δ^{2}H versus δ^{18}O isotope data with reference to the Global Meteoric Water Line (GMWL). **b** δ^{18}O distribution across the hydraulic units, **c** Temporal variation of δ^{18}O for groundwater, mine working and surface water from the River Clyde (a zoomed in view of the groundwater is given (**d**) as is the mine water data (**e**). The monitoring periods were Feb-2019 to Jan-2022 for the surface-water data, and Sept-2020 to Jan-2022 for the groundwater and mine water data. ©BGS, UKRI 2023

common during colder sampling events and higher $\delta^{18}O$ in warmer months (Fig. 5c). By contrast, a fairly uniform groundwater isotope signature was observed in all the hydraulic units during the groundwater monitoring period (September 2020–January 2022) (δ^2H total range –52.9 to –48.6‰, median –50.7‰; $\delta^{18}O$ total range –7.57 to –7.18‰, median –7.46‰), typical of well-mixed aquifers resulting in high degree of isotopic homogeneity (Darling et al. 2003). Water isotope median values and ranges in each hydraulic unit are similar (with only GGB04 slightly offset, Fig. 5b).

Estimated residence times derived from CFC and SF_6 concentrations, have similar ranges for each of the hydraulic units, with all showing mean residence times of at least 50 years: 1968–1974 for the GMA; 1948–1957 for the bedrock and the GU; and 1950–1973 for the superficial deposits (Palumbo-Roe et al. 2021).

Groundwater chemistry (major ion composition) during pumping tests

The relative percent difference (RPD) was analysed for major ion concentrations in the 2–4-h groundwater samples collected during CRTs on each borehole. The observed small changes in major ion composition induced by pumping were relatively lower in the GMA mine working boreholes (an average RPD of 0.6 and 0.3%, respectively, in GGA05 and GGA08), compared to both the GU mine working boreholes (an average RPD of 1% in GGA04 and GGA07, and 4% in GGA01) and bedrock boreholes (average RPD of 3% in GGB05).

Groundwater temperature

Groundwater temperatures measured by the data loggers in the mine boreholes are in the range of 11–12 °C. Slightly higher in-year fluctuations of 0.1–0.2 °C were observed in the two GU boreholes intersecting higher transmissivity units, GGA01 in the range 11.7–11.8 °C and GGA07 in the range 11.2–11.3 °C, which might reflect groundwater circulation and seasonal influence of recharged waters. In contrast, groundwater temperature readings in GGA04 (screened in a fractured coal pillar in the GU) remain constant throughout the year at ~11.5 °C. GMA temperatures are similar in both boreholes and constant through the year, with GGA08 showing values ~11.3 °C and GGA05 slightly warmer, at ~11.5 °C. It must be noted that data loggers in the mine boreholes are located above the mine workings and temperatures measured over the period described in this study are only provided as a reference and do not reflect the water temperatures at depth in the mine workings. During the test pumping, temperature variations of up to 0.5 °C were observed but were possibly influenced by the position of the loggers with respect to the pump (see Shorter et al. 2021) and the upwards flow of water abstracted from the mine workings.

Groundwater temperatures in the bedrock boreholes are constant over the year. Temperatures in GGA03r are ~11.7 °C, similar to temperatures measured in GGA01 which could reflect the connectivity between the GU mine workings and the fractured bedrock in this area as suggested by groundwater levels. Measured temperatures in GGB05 are colder, at ~11.3 °C. Groundwater temperatures in the superficial deposits show wider seasonal influence with values ranging between 11 and 11.5 °C.

Conceptual hydrogeological model for the UK Geoenergy Observatory in Glasgow

This section presents a general conceptual model of the baseline hydrogeological system at the Observatory before the start of geothermal interventions. This model will be refined as future data from ongoing monitoring and geothermal research become available. The conceptual model is illustrated at two different scales in Fig. 6, with labels referring to the key elements described in the following.

The conceptual model is intended to provide the best possible understanding of the groundwater flow system in, and around, the Observatory, in order to support researchers carrying out abstraction/reinjection geothermal experiments over the next 10–15 years. The model highlights and explains the hydrogeological behaviour that may affect mine water geothermal activities and highlights important gaps in understanding that may be prioritised for future research.

Hydraulic units and key aquifer properties

Mine workings

The perceived potential of abandoned mine workings for geothermal resource abstraction is largely based on their general representation as highly transmissible aquifers with large storage potential. The hydraulic separation of individual mine workings by low(er) transmissivity unmined bedrock can also make them suitable for thermal energy storage. However, mine workings are highly heterogeneous, both in their original type and distribution and in post-mine closure impacts, which can strongly influence their actual hydrogeological and geothermal potential. Evidence from drilling the Observatory boreholes confirms there is a high degree of heterogeneity in mine workings even in this relatively small

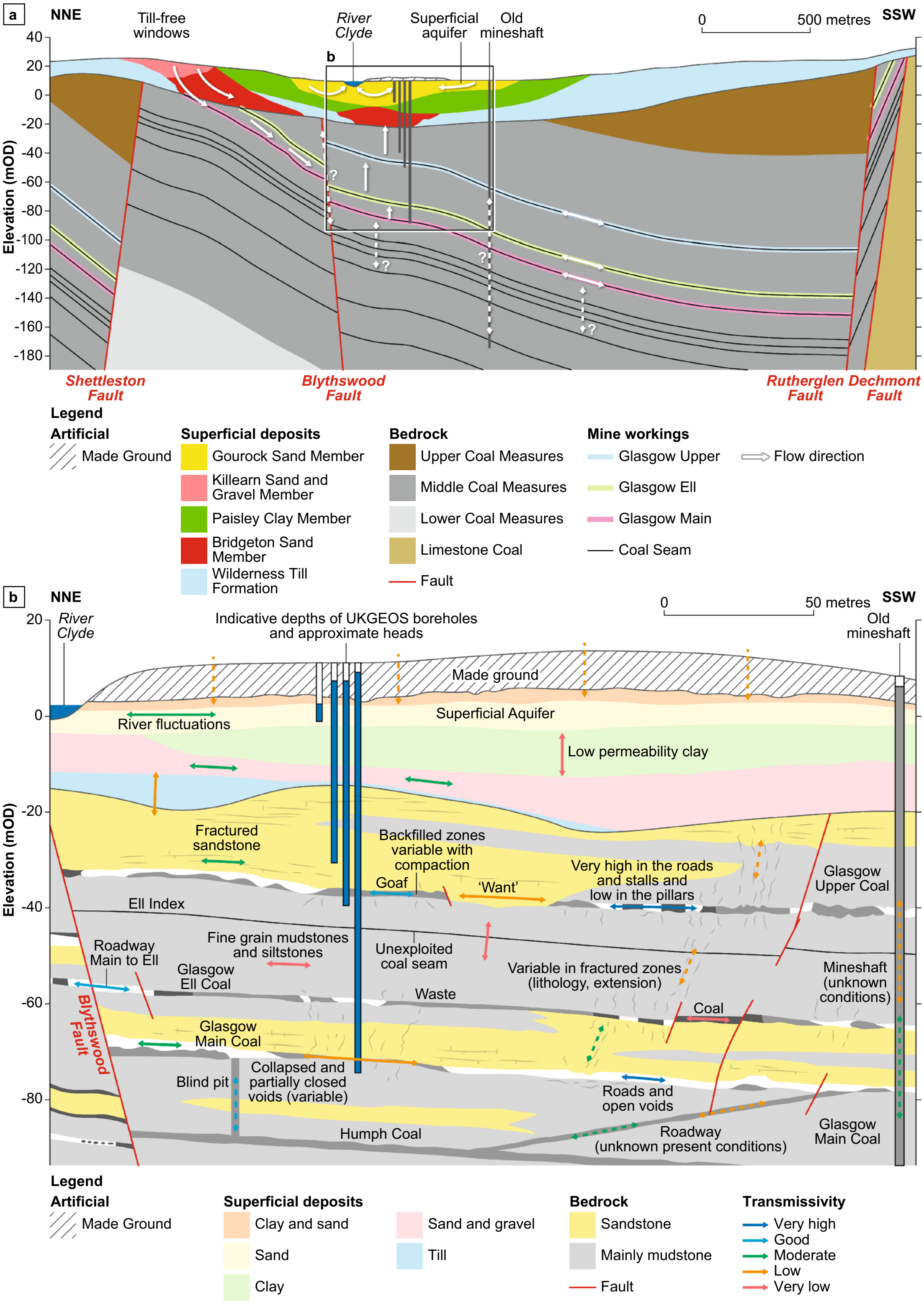

Fig. 6 General hydrogeological conceptual model illustrating the main components of the system at two different scales: **a** geological cross section marked in Fig. 1, and **b** conceptual diagram of the UK Geoenergy Observatory illustrating the main elements of the model. Vertical scales of both figures are exaggerated but with different ratios. Uni-directional arrows show the interpreted as general flow directions with the conceptual model explained in this work with the hydraulic data measured in the Observatory boreholes and under natural conditions. These may change when the Observatory is in operation under the influence of pumping and reinjection. ©BGS, UKRI 2023

area, and that different types and/or conditions of the workings could affect local groundwater flows and heat transport (Monaghan et al. 2021b). Four types of mine workings with different characteristics encountered at the Observatory, which are likely to show different local hydrogeological behaviour, have been identified. Key aspects of these are discussed in the following regarding new evidence from the Observatory, bearing in mind that the hydrogeological evidence is derived from limited available points—three boreholes in the GU and superficial aquifers and two each in the GMA and unmined bedrock—and that all extrapolation from these points is postulated.

1. *Voids* are zones that remain fully or partially open after mine closure and flooding. Workings with extensively connected voids are likely to have the highest storage and transmissivity. Voids may be more likely in workings that had engineered supports to reduce collapse, such as roadways and workings in ‘pillar and stall’ style. Evidence from drilling at the Observatory identified open voids in the GMA in three boreholes: GGA02, GGA05 (0.7 m high) and GGA08. In GGA05, a 0.7-m-high open void is underlain by a 1.7-m-thick disrupted zone interpreted as affected by postmining floor lift. A void intercepted by GGA08 is interpreted as the remains of a roadway. The GMA in this area is shown in mine records as having been mainly subject to total extraction of previous pillar and stall workings, which is likely to make it more susceptible to post-mining roof collapse. Only one void was encountered in the GU, partially intersected by borehole GGA07 in an area interpreted as stoop and room zone (Monaghan et al. 2021b). Other boreholes screened in the GU (GGA01 and GGA04) did not intersect voids. The higher transmissivities in the GMA (Table 1) may be linked to more extensive and connected voids across this working, while voids in the GU may be fewer and/or less well connected.
2. *Goaf zones* are defined here as formed by roof collapse in workings, and are characterised by a chaotic, heterogeneous distribution of collapsed rock and pit materials such as wooden pit props. They are likely to be zones of high transmissivity because of the likely lack of fine materials. Previous authors (e.g. Younger and Adams 1999; Younger 2011) have suggested moderate values of hydraulic conductivity of ~8.5–85 m/day for goaf zones created by more modern longwall workings. Borehole GGA08 partially intersected a goaf zone in the GMA, interpreted as infilling a former roadway. GGA08 is the highest yielding borehole at the Observatory, and this suggests that the transmissivity of goaf zones can reach high values, although GGA08 also intercepts an open void.
3. *Waste zones* are zones of intentionally backfilled mine workings, with heterogeneous composition that can include fragments of coal, sandstone and mudstone with variable compaction states. Because of their engineered nature, waste zones would generally have lower transmissivity values than goaf zones and voids, although this is likely to be strongly influenced by the waste type, presence of fines and degree of waste compaction. In some cases (not directly observed in the Observatory boreholes), waste, including some types of ash, was compacted in order to minimise permeability and water flow. By contrast, if the main aim of waste infill was to support workings against collapse, the waste is likely to be more heterogeneous and may have higher transmissivity. At the Observatory, waste zones of different compaction were encountered, but only one borehole abstracting from a waste zone, GGA01, could be tested. Relatively compacted waste in the GE was intersected by boreholes GGA05 and GGA08, but they are screened only in the GMA. Relatively loosely packed waste in the GU was intersected by boreholes GGA01 and GGA02, and the tested transmissivity of GGA01 (~1,050 m^2/day) illustrates that such loosely packed waste can have high transmissivity.
4. *Unmined coal*, which can be fractured in situ or collapsed because of the effects of nearby mining. Unmined coal typically has low permeability (Pan and Connell 2012). Unmined coal in the GU was intersected by boreholes GGA04 and GGA05 (although GGA05 was not screened in the GU). Borehole GGA04 showed lower transmissivity than the other two boreholes in the GU (GGA01 and GGA07—both with transmissivity values of ~1,000 m^2/day), neither of which intersected unmined GU coal. The pumping test conducted on GGA04 indicated lower transmissivity within the coal pillar (240 m^2/day) before the cone of depression moved out into the wider mine workings to give a transmissivity of 950 m^2/day.

Unmined bedrock

Tested aquifer properties are very different for the two unmined bedrock boreholes at the Observatory, both screened in unmined bedrock in the zone above the GU. Borehole GGA03r showed low transmissivity (2.6 m^2/day); borehole GGB05 showed moderate to high transmissivity (580–990 m^2/day), nearly as high as the least transmissive (GU) mine working and would reflect extensive fracturing possibly induced by mining. Their variability is in line with evidence from other Carboniferous sedimentary aquifers across central and southern Scotland, which show variable transmissivity (an average range in available measured transmissivity values of 100–700 m^2/day; Graham et al. 2009), depending on lithology (sandstone units are likely to have higher transmissivity than finer grained units; Ó Dochartaigh et al. 2015), the degree of natural fracturing, and/or how impacted they are by mining (MacDonald et al. 2005). Higher transmissivities may be related to mining-related stresses—the effects varying with the extent and type of mining as well as by the mechanical properties of the unmined rock (e.g. Younger and Adams 1999; Younger 2011)—but can also be caused by naturally occurring levels of fracturing. Even within the Observatory, lithological variations were observed in the unmined bedrock above the GU: it is largely sandstone dominated in GGA01 and GGA02—although these are adjacent to borehole GGA03r with low transmissivity—but claystone/siltstone dominated in GGA07 and GGA08 (Monaghan et al. 2021b). Borehole GGA03r is screened in sandstone ~10 m vertically above the expected depth of what mine abandonment plans show as a zone of total extraction in the GU, which where it was intersected by adjacent boreholes GGA01 and GGA02 was infilled with loosely packed waste, indicating the working has not significantly collapsed. This may indicate that the overlying sandstone has been less impacted by mining-related fracturing. Borehole GGB05, with higher transmissivity, is screened in sandstone ~5 m vertically above what mine abandonment plans show as a zone of pillar and stall workings in the GU. There is no direct evidence for bedrock fracturing from either of the unmined bedrock boreholes, but camera surveys in boreholes GGA05, GGA07 and GGA08 showed potentially open horizontal fractures or bedding planes in the unmined sandstone, and indicated there is increased fracturing in the unmined bedrock extending ~6 m above and below the GU (Monaghan et al. 2021b). This height is consistent with the 'ten times' rule of thumb for migration of mine working voids (e.g. Mason et al. 2019). Monitoring evidence shows that groundwater levels in both bedrock boreholes respond synchronously to those in the GU boreholes (Fig. 3), suggesting a significant degree of hydraulic connectivity, which may be linked to mining-enhanced fracturing in the unmined bedrock immediately adjacent to the GU working.

Superficial deposits

Evidence from the Observatory shows the superficial deposits sequence at the Observatory is similar to that seen elsewhere in Glasgow (Ó Dochartaigh et al. 2019), with coarser grained gravel and/or sand-dominated units interspersed with finer grained clay-dominated units (Monaghan et al. 2021b). Test pumping of the two boreholes (GGA06r and GGA09r) screened in superficial deposits, both in gravel and/or sand units, also confirms previous studies (e.g. Dochartaigh et al. 2019; Williams et al. 2018) by showing these coarse-grained units can have moderate transmissivity (80–225 m^2/day, Table 1).

Extent and boundaries

The groundwater flow system targeted and observed by the Observatory boreholes has three key hydraulic units with distinct hydrogeological characteristics, as outlined in the previous section. These hydraulic units are connected to various degrees (see the next section) and have different lateral and depth extents and boundaries, and the overall groundwater flow system they create is part of a larger system that extends beyond the Observatory (Fig. 6a). There are groundwater inflows to these hydraulic units from a number of different sources, and groundwater discharges to various receptors, both inside and outside the immediate Observatory area. Defining the boundaries of the groundwater flow system within which the Observatory lies—i.e., over which there are no inflows or outflows, or these flows can be quantified—is a key step towards representative numerical groundwater flow modelling.

On a regional scale, the Carboniferous sedimentary bedrock aquifer is likely to be bounded to the north, west and south of Glasgow by the geological contact with volcanic rocks of the Clyde Plateau Volcanic Formation, which have significantly lower permeability than the sedimentary rocks, such that this is assumed to represent a no-flow boundary. More locally to Glasgow, it is easier to define the boundaries of the mine workings and the superficial deposits, which are more clearly geographically constrained, than the unmined Carboniferous sedimentary bedrock (Fig. 1). A lack of hydrogeological data, especially groundwater levels, for any of the hydraulic units in Glasgow and the surrounding region makes it impossible to precisely define the boundaries of the individual units or the overall groundwater flow, but can be inferred with a degree of confidence from the available evidence and known hydrogeology of the relevant units.

Key lateral boundaries for the mine workings—the most transmissive unit—are formed about 1 km to the north by the Shettleston Fault, and some 2.5 km to the south and southwest by the Dechmont Fault (Figs. 1a and 6a). These faults create a structurally isolated geological block by offsetting the sedimentary strata to such an extent that coal seams are not in lateral continuity across them (Figs. 1a and 6a); mine workings following the seams are not continuous across the faults, and there can be no direct groundwater inflow across these faults through mine workings. There is no direct data on the hydrogeological properties of these faults. Faults that divide the Carboniferous sequence can act either as barriers or as preferential flow pathways, especially those with associated fracturing (Ó Dochartaigh et al. 2015). Although the faults offset the sandstone beds in which most groundwater flow is likely to occur, some groundwater flow is likely in fractures throughout the Carboniferous sequence. The faults are unlikely to form a complete barrier but are likely to allow some inflow through bedrock across them, but because of the generally lower and more variable transmissivity of the bedrock, this is likely to be significantly less than any flow in the mine workings.

A lack of regional groundwater level monitoring data means there is no certainty on regional groundwater flow directions in the unmined Carboniferous bedrock. Based on available historical groundwater data, lithology, stratigraphical dip (including dip of mine workings), and topography, the general regional groundwater flow is thought to be from the north, northeast and southeast towards Glasgow and the Clyde Valley, and from there towards the west and southwest, in the direction of the Clyde estuary (Robins 1990; Hall 1998; Turner et al. 2015). Flow paths may be many kilometres long and up to hundreds of metres deep (Ó Dochartaigh et al. 2015). No specific lateral flow boundary can be drawn to the east for the unmined bedrock, which extends eastwards for many kilometres. Given the expected regional flow directions, groundwater inflows from this direction are likely, but the lack of available information makes it impossible to quantify these inflows. The expected groundwater flow direction means there is likely to be no inflow from the west; instead, there is likely to be some outflow in this direction, in all hydraulic units (see the following section on discharge).

The upper boundary of the overall groundwater flow system is defined by the top of the superficial deposits, including any permeable artificial ground that is in hydraulic continuity with the underlying natural superficial deposits. Because groundwater flow in the mined bedrock system is dominantly through mine workings or fractured bedrock, the lower boundary of the flow system is defined primarily by the deepest local mine workings in the Kiltongue Coal, 270 m below the Observatory, and/or by the depth at which water-bearing fractures in the unmined bedrock become too few, small and/or discontinuous to allow significant groundwater flow. This is not known precisely, but generally, for the Carboniferous in Scotland, it is thought to be up to ~500 m (Ó Dochartaigh et al. 2015). Bedrock lithology may play a role in the extent of water-bearing fractures, as these are most developed in sandstones. At ~300-m depth underneath the Observatory, below the Kiltongue Coal, there is thought to be a ~40-m-thick continuous sequence of unworked coal seams, siltstones and mudstones in the Lower Coal Measures (Hall et al. 1998), in which water-bearing fractures are likely to be less well developed and which may, therefore, have particularly low permeability, and may be a more-or-less effective lower boundary of groundwater flow.

Within this overall system, rockhead forms the lower boundary of the superficial deposits and the upper boundary of the unmined bedrock; and the upper and lower boundaries of individual mine workings against unmined bedrock are defined largely by the original mined ceiling and floor. Evidence from the Observatory shows that there is limited, hydraulic connectivity between superficial deposits and unmined bedrock, and between unmined bedrock and mine workings (see next section), and so these internal divisions are not no-flow boundaries.

The River Clyde is also likely to form a hydraulic boundary. New and previous hydrogeological evidence suggests there is significant hydraulic connectivity between the river and groundwater in the superficial deposits (e.g. Ó Dochartaigh et al. 2019), and there is some suggestion from historical evidence that there has been some interaction between the river and the GU mine workings. These potential hydraulic connections are discussed in the next section.

Hydraulic connectivity within and between units

Intramine working connectivity

The GU includes zones of all four of the mine working subunits defined in section "Mine workings", and the Observatory boreholes in the GU intercept examples of all of them. Although not directly shown during the pumping tests due to the fast pressure travel in these confined systems, these are likely to create different groundwater flow pathways and varying hydraulic connectivity across the GU, controlled by the distribution, extent and varying transmissivity of the subunits. Open voids are likely to form the most preferential pathways and to allow rapid groundwater flow; loosely compacted goaf and waste zones (such as intercepted by boreholes GGA01 and GGA02) are likely to restrict and slow flow; and unmined coal pillars (such as between boreholes GGA04 and GGA07) are likely to act to significantly limit groundwater flow through the mine workings. The significant difference in drawdown responses and low performance during the pumping test on GGA04 may be an indication of reduced connectivity around the screened section in this borehole; however, pumping test data from the other two GU tests show the integrated effect of pumping tests caused by drawdown cone extension that would affect a large area around the boreholes.

The Observatory boreholes in the GMA mostly intersect open voids or goafs, as well as (in GGA05) a disrupted zone interpreted as being affected by post-mining floor lift. Because of the heterogeneity of mining and post-mining history, the GMA may also have zones of other subunits, unproven away from the Observatory boreholes. The evidence to date, including low drawdown during pumping, suggests there is relatively unrestricted flow through the

GMA. However, with only two boreholes abstracting from the GMA, and only three from the GU, there is still much uncertainty about groundwater flow paths and velocities through, and connectivity within, each mine working, and about the implications of this regarding heat transfer under geothermal operations.

Inter-mine working connectivity

According to mine records there are no direct engineered connections such as mine shafts and roadways, between the GU and GMA mine workings within the Observatory. The bedrock sequence between the two workings is dominated by well-cemented mudstones and is, therefore, likely to have low natural permeability. The Glasgow Ell Index coal seam, unmined in this area, also lies within this sequence between the GMA and GU, and like all unmined coals is likely to have naturally very low permeability, such that it could act as a particular barrier to vertical groundwater flow across this sequence.

There are known examples of engineered connections between the GMA and GU outside the Observatory itself, including a roadway on the north of the Blythswood Fault. There are also a number of recorded mine shafts and roadways connecting the GMA with other mine workings in this area, including the GE above it and the Humph Coal below it (Fig. 6). The current condition of most of these, whether open or partially or wholly infilled or collapsed, is unknown, but many, including some at the Farme Colliery below the Cuningar Loop, are known to have been, at least partially, infilled (Ramboll 2018; Monaghan et al. 2021b).

The probability of some limited hydraulic connectivity between these two key units in the Observatory is supported by the hydrogeological evidence to date. Test pumping at high rates (20–25 L/s) for up to 5 h from either unit produced a small drawdown response (<0.1 m) in the other unit (Fig. 3).

Any connections between the GMA and other workings above (i.e. GE) or below that maintain significant transmissivity (whether fully or partially open or infilled with permeable material) may act to increase the groundwater resource accessible to boreholes abstracting from the GMA, affect the temperature of abstracted water, and form flow pathways that influence the rate of thermal breakthrough.

Faults may also play a role in connecting different mine workings, particularly the Blythswood Fault, which intersects all the mine workings intersected by the Observatory immediately to its north (Figs. 1, 2, and 6). As stated previously, there is insufficient evidence to understand the impact of faults on groundwater flow, or heat transport and storage. In some cases, they are permeable and can act as preferential flow routes, while in others they have low permeability and can restrict flow (e.g. Bense et al. 2013). The role of faults at the Observatory may be an important future research question.

Mine workings - bedrock connectivity

Groundwater levels in boreholes in the GU and the overlying unmined bedrock show synchronous fluctuations during pumping tests and over the long term in response to rainfall (Fig. 3), strongly indicating effective connectivity between these hydraulic units. This connectivity is likely to be through a transmissive zone of extensive natural and/or mining-enhanced fracturing of the sandstone immediately overlying the GU, which has been shown by camera surveys to extend ~6 m above the GU. Chemical evidence also suggests close similarities between groundwater in borehole GGB05, in unmined bedrock, and in both GU and GMA workings, which may indicate close connectivity, although the chemistry of groundwater from the other bedrock borehole GGA03r is less similar (Fig. 4). No Observatory boreholes target unmined sandstones above or below the GMA workings (Fig. 6), but similar mining-related alterations may have also enhanced their fracture transmissivity such that there may be similar connectivity between groundwater in these sandstones and in the GMA.

Mine workings - superficial deposits connectivity

The evidence to date suggests there is limited direct hydraulic connectivity between the superficial deposits and either the GU or GMA mine workings at the Observatory. Groundwater level elevations measured in the superficial deposits are consistently 5–6 m lower in elevation than those in the GU/bedrock and the GMA (Fig. 3a), indicating upward flow in the system. Groundwater level fluctuations in the superficial deposits also show slightly different patterns in response to rainfall events (Fig. 3b); and the chemistry of groundwater from the superficial deposits is similar to the groundwater chemistry from the unmined bedrock or mine workings (Fig. 4). The limited connectivity is likely to be due to the presence of clay-dominated, low permeability layers in the lower part of the superficial deposits sequence, below the screened levels of the superficial deposit boreholes (Fig. 6b), in particular the Paisley Clay and the Wilderness Till formations. These formations may restrict the flow of groundwater between the permeable zones of the superficial deposits and the underlying bedrock and/or mine workings. On the other hand, there is some uncertainty about the current conditions and infilling of historic mine shafts and the locations of old adits that could communicate with the mine workings and lead to groundwater leaking up into the superficial aquifers.

Mine workings - surface water (River Clyde) connectivity

Any hydraulic connectivity between the GU and the river such as created by permeable coarse-grained superficial deposits and/or permeable zones of fractured bedrock above the GU, could have led to water from the river reaching the GU in the past, when groundwater levels in the mine were artificially depressed by pumping. There are records of inflows (“dripping”) into the GU mine working at the Bogleshole pit during its operation, about 2 km east of the Observatory. Mine abandonment plans also show that wider pillars were left in place in the GU where it is present ~30–35 m below the Clyde, indicating there was a perceived enhanced risk from mine and rock instability (mine working collapse and resultant subsidence) in this zone. The depth of the GU below the River Clyde to the northeast of the Blytshwood Fault is shallower and mine working plans show zones of backfilling with selected ash and dams, possibly to prevent or mitigate collapse and subsidence, and intercolliery water flows.

Evidence from the Observatory clearly shows that modern groundwater levels in both GU and GMA workings are significantly higher than the water level in the adjacent River Clyde, such that there is now an opposite hydraulic gradient between these two units than there was during mine operation and dewatering. Any flows between them would result in groundwater discharge from mine workings to the river. There is no direct evidence for groundwater from the mine workings discharging into the river, and geochemical and stable isotopes show clear differences between groundwater in the mine workings and surface water (Fig. 5). However, this does not preclude discharge of water from mine workings into the river because it is likely that any discharge occurring would be so diluted by the volume of water in the Clyde that it would not be distinguishable.

If there is any hydraulic connectivity between the mine workings and the River Clyde, this may have implications for future geothermal operations at the Observatory. If hydraulic heads in the mine workings fall below the level of the River Clyde, which could happen as a result of abstraction from one or other working, the current hydraulic gradient could be modified. Although such flows seem likely to be limited, it may be an important future research topic to collect more evidence for hydraulic connectivity between these units.

Recharge

A previous study (Turner et al. 2015) modelled recharge rates across Glasgow at between 0.17 and 1.6 mm/day with an average value of 0.75 mm/day. This includes recharge from urban sources—leakage from mains and wastewater pipe networks as well as through permeable urban areas, such as gardens and parks—but proposed that recharge to the bedrock aquifer occurs preferentially over higher elevation ground where the Wilderness Till Formation is thin or absent (till-free windows in Fig. 6a). Recent geological models (Arkley and Callaghan 2021) indicate that there are such zones on higher elevation ground ~1–3 km to the east and northeast of the Observatory, north of the River Clyde, which include urbanised and nonurbanised land (Fig. 1c). This is in agreement with previous assessments of the dominant groundwater flow direction in the bedrock aquifer, from the higher ground in the north and northeast towards the lower elevation Clyde Valley (Robins 1990; Turner et al. 2015).

Recharge to the mine workings is likely to have predominantly the same sources, via groundwater flow through overlying unmined bedrock, as indicated by the evidence for close hydraulic connectivity between the GU working and overlying bedrock, and by inference potentially similar connectivity between the GMA and overlying bedrock. There is also potential for preferential recharge to mine workings where they reach closer to rockhead, where flow paths through overlying bedrock will be shorter. There are such zones coinciding with the proposed recharge areas to the north and east, where the GMA and GE coal seams are closer to rockhead than they are beneath much of Glasgow. This may have been more significant in the past when groundwater levels in the mine workings were artificially lowered by dewatering, and there were stronger downward hydraulic gradients from superficial deposits but may still be occurring in areas at higher elevation than the current water levels in the mine workings. CFC and SF_6 results indicate that water in the mine workings is from modern recharge, although it is more than 50 years old (Palumbo-Roe et al. 2021; Bearcock et al. 2022), further indicating limited recharge from the Clyde.

Groundwater discharge (outflows)

There is little evidence for groundwater discharge (outflows from the system) in the area of the Observatory or elsewhere in the region. The available information indicates that a large proportion of groundwater in the GMA and GU workings and in unmined bedrock discharges upwards, within the Glasgow area, into permeable superficial deposits by slow groundwater flow through intervening low permeability superficial deposits or through any of the existing mine shafts and associated drainage network, and from there, discharges into the River Clyde. There is also likely to be a proportion of groundwater flow through mine workings and unmined bedrock that continues westwards, following the dip of sedimentary structures. This may subsequently also flow upwards, ultimately forming submarine discharge in the Clyde estuary, either directly from mine workings and/

or bedrock, or more likely via overlying superficial deposits. As discussed earlier, there may be some direct, but probably limited current connectivity between mine workings and the River Clyde, including in the vicinity of the Observatory; and because groundwater levels in the GMA and GU are higher than river level, any connectivity will lead to groundwater discharge from mine workings into the river, although this is likely to be minor.

Discussion

The conceptual model of groundwater flow through the aquifer system in and around the UK Geoenergy Observatory is based on the best available evidence and understanding of the hydrogeology of mined systems, as well as previous studies in Glasgow and more widely and the Carboniferous aquifer in Scotland to date.

There are still many aspects of the conceptual model for which there is insufficient data to prove their accuracy, but it is internally logical and fits the available evidence. There is still uncertainty about the role of faults to create pathways or act as flow barriers between the mine workings, the spatial distribution and hydraulic properties of mine workings, the extent of bedrock fracturing above mine workings and its impact on groundwater flow, and the variability of superficial deposits to control recharge and discharge.

Nevertheless, hydrogeological characterisation and the development of a hydrogeological conceptual model of the system are important considerations for the development of mine water geothermal resources, especially due to the spatial heterogeneity of mine water aquifers. Groundwater level responses during pump testing in the Observatory vary between high productivity and low drawdown in the GMA boreholes and a response typical of confined aquifers, with noticeable drawdown in the GU boreholes. These observations are consistent with recent works and observations in commercial mine water schemes (Banks et al. 2022). Further understanding of the relationships between hydraulic response to pumping/injection in flooded mine workings and the transport and distribution of heat will provide invaluable information for mine water geothermal development.

The conceptual model provides a sound basis to help steer future research at the Observatory; in particular, how geothermal operations will impact on the existing hydrogeological and wider environmental systems. Key knowledge gaps highlighted here may also be useful to focus future research and data collection. As an updatable product, the hydrogeological conceptual model presented in this work will be revised periodically in the future using the continuous stream of data and the inputs from various monitoring techniques, experiments, innovative investigation approaches and multiple users.

Conclusion

The demand for hydrogeological understanding of abandoned and flooded coal mines has grown in the last decade after identifying the potential of low-temperature geothermal energy resources in old mine workings. However, because of the complexity of mined systems, there is large uncertainty about the general hydrogeological and hydrochemical conditions, dynamics and evolution, as well as potential environmental and operational risks involved in their further development for mine water geothermal.

The Glasgow Observatory aims to de-risk mine water geothermal by providing an at-scale research site for further study and better understanding of flooded coal mines used for geothermal energy. This report, has proposed a preliminary hydrogeological conceptual model of the system, including a general groundwater flow circulation, based on monitoring and experimental data obtained during the construction of the Observatory. The results show the dominant role of the mine workings in controlling groundwater flow in the area, which is interpreted to follow a general circulation with rainfall recharge through clay and till-free zones located at higher elevations to the north and east of the Observatory. The discharge of the system towards the River Clyde follows the vertical upwards flow below the Cuningar Loop, with vertical connectivity controlled by the potential existence and present-day conditions of old mine workings, the existence of altered and fractured bedrock, and the distribution of coarse-grained superficial deposits. The flooded mines are the main storage units and flow pathways of the system, but observations from pumping tests show the heterogeneity of the mine workings and their influence in the hydrogeological dynamics.

Key issues that require further research to improve the understanding of mine water systems with similar characteristics include: the distribution and hydraulic properties of mined zones, grouped as hydraulic units, to constrain or facilitate groundwater flow; the spatial extension of bedrock alteration above, and potentially below, mine workings; the role of faults to create flow pathways between mine workings; the spatial variability and hydraulic properties of the superficial deposits that control the recharge and discharge of the system; the regional flow regime of the Carboniferous aquifer; and the impact of modifying the natural gradients by pumping during use of the Observatory. In addition, to facilitate groundwater flow, some of these preferential pathways may have a role in the transfer of heat by advection once the infrastructure is under operation, which in the case of a commercial scheme would impact the geothermal performance. As the site is increasingly utilised for research and industrial uses and further data is collected, the conceptual model developed here will be reevaluated and updated over time.

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Declarations

Conflicts of interest The authors declare that there is no conflict of interest.

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