Reply to Discussion on '**Borehole temperature log from the Glasgow Geothermal Energy Research Field Site: a record of past changes to ground surface temperature caused by urban development**' by Watson and Westaway 2020 (*SJG*, 56, 134–152, 2020).

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Watson and Westaway (2020) (WW) quantified subsurface temperature variations caused by anthropogenic climate change and urban/industrial development in Glasgow, using temperature data from the Glasgow Geothermal Energy Research Field Site (GGERFS) well GGC-01 (at site G-10; Fig. 1), noting implications for the thermal physics of this site. Monaghan, Manning and Shipton (2021) (MMS) have queried points, noted in passing by WW, on other aspects: the GGERFS purpose, location, design, heat resource, and cost.

Purpose

MMS suggested that WW misunderstood the purpose of the GGERFS, mistaking it for a demonstrator site. However, WW described it as subsurface infrastructure to investigate the geothermics of flooded mineworkings, also calling it a 'test site', consistent with the MMS description as 'research infrastructure'.

Location

MMS appear to regard the history of the GGERFS as unimportant, whereas the site has the potential for significant groundwater contamination through the legacy of the Shawfield Chemical Works (Cr in Fig. 1). Between 1820-1968 this works produced millions of tonnes of chromite ore processing residue containing carcinogenic chromium-VI, which was widely used for landfill at local construction sites. Many workers (cited by WW) have investigated chromium-VI pollution near the GGERFS. Fordyce et al. (2020) noted, following their documentation of chromium-VI and other contaminants, that 'the GGERFS facility was rescoped such that boreholes have not been constructed at sites GGERFS 04 and 06b' (Fig. 1). The presence of chromium-VI at any locality in this area is significant, because GGERFS activities (e.g., test-pumping; see below) can be expected to displace groundwater across horizontal distances of many hundreds of metres.

Design

The GGERFS design issues noted by WW and challenged by MMS concern three aspects: the <200m depth of well GGC-01; the shallow depth of the other wells; and their close spacing. MMS state that 'boreholes >200 m deep require additional planning and environmental permitting at additional cost and time-scale', and that the adopted depth-limit required weighing 'many trade-offs and balances'. Nonetheless, well GGC-01 is cased and hydraulically-isolated from the surrounding area that has apparently not been mined for hundreds of metres in any direction (Fig. 1). Thus, the SEPA (2019a,b) environmental permitting procedure for drilling beyond 200m would have been straightforward: complete an application form and pay a £2101 fee. However, the design of well GGC-01 in 2018 followed the Monaghan et al. (2017) survey, which regarded mining of several coal-seams beneath its site as 'probable'. For well GGC-01 to have been drilled beyond 200m depth, potentially through abandoned mineworkings, would have required additional permitting (SEPA, 2014), and may explain why this option was excluded. Nonetheless, the limited depth of well GGC-01 certainly hampered the WW analysis, making the critique by WW of this aspect demonstrably correct.

The other GGERFS wells (11 wells grouped at four sites; Fig. 1) are open to their surroundings, with the deepest accessing ~90m-deep mineworkings, with waters at temperatures of ~12°C that WW showed were of anthropogenic (not geothermal) origin and considered too low to be useful. Conversely, MMS regarded the GGERFS design as representative of future minewater projects.

However, Farr et al. (2020) have since reported that most of the British minewater geothermal resource is at depths and temperatures far greater than those in the GGERFS reservoir. The GGERFS well-spacings, including the 119m separation of the ~90m wells (sites G-02 and G-03; Fig. 1) were also queried by WW. MMS suggested that these were designed to facilitate research tasks rather than to optimise heat output, citing Monaghan et al. (2019), although this reference does not include any quantitative design details. One such task might be test-pumping, with results analysed using the standard Theis (1935) method. The pressure response at radial distance r thus depends on the hydraulic diffusivity D,

$$D \equiv \frac{k\,B}{\eta}, \qquad (1)$$

with k, B and η, respectively, the permeability, bulk modulus and viscosity of the reservoir. With k=100D (in reasonable agreement with 30D from Westaway and Younger, 2016) and B=0.27 GPa, after Todd et al. (2020), and η=1.25mPa s for water at 12°C, one obtains D=21.6m^2 s^{-1}. With this high value, test-pumping from either ~90m well would significantly affect the pressure within minutes at r=119m (the well-spacing) and after ~2 hours at r≈700m (the radial limit of the Farme Colliery workings, the GGERFS minewater reservoir; Fig. 1). After ~2 hours, the pressure variations at r=119m would be sensitive to the boundary-condition at this radial limit, a key unknown, hydraulic isolation being potentially detectable by departure from the Theis (1935) prediction. On this basis, the GGERFS well-spacing makes sense, although this aspect was not previously explained.

Output

MMS suggest that the GGERFS was 'designed at the scale of a small, low temperature mine water scheme', but provide no indication of its potential heat-output. A conservative assumption about the radial extent of heat-extraction by WW indicated ~8kW. A better estimate of the sustainable heat-output W that might be 'captured' from an area A of the subsurface, receiving heat flow q from below, is

$$W = A\,q \qquad (2)$$

(e.g., Westaway and Younger, 2016). Taking q≈30mW m^{-2} for site G10, from WW, and A≈1.4km^2 (Fig. 1) for the Farme Colliery workings, equation (2) indicates W=42kW for either ~90m GGERFS well. However, at Hallside (~5.5km ESE, Fig. 1), q≈14mW m^{-2} (Watson et al., 2019), giving W≈20kW for the Farme Colliery workings. For comparison, the Shettleston minewater heat project, developed in 1999, produced water from the Westmuir Colliery workings (Banks et al., 2009, 2019; Fig. 1), two Danfoss BW10-025 heat pumps (Danfoss, 2020) outputting ~64kW of heat and consuming ~16kW of electricity, requiring W≈48kW from the production borehole. Again, assuming q≈30mW m^{-2}, these A≈0.7km^2 workings (Fig. 1) might sustain W≈21kW. The actual ~48kW requires a ~1.6km^2 reservoir, consistent with the production borehole being hydraulically connected to the workings of both Westmuir Colliery and Eastbank pit farther east (Banks et al., 2009; Fig. 1). The above estimates of sustainable heat-outputs at the GGERFS site of several tens of kilowatts supersede the WW analysis. Future release of GGERFS data (e.g., from test-pumping; see above) might demonstrate that the Farme Colliery workings are not hydraulically isolated, potentially justifying further upward revision.

Cost

WW noted the disparity between the £9M GGERFS budget and the value of the heat that might be produced. When first promoted to the Glasgow public, in September 2017, the project flyer announced that 'we want to invest £9 million in creating an underground observatory in Clyde Gateway so scientists can explore and understand geothermal energy' (UKGEOS, 2017), giving the impression that the proposed infrastructure in Glasgow would cost £9M. WW noted this GGERFS budget to highlight its disproportion, in an attempt to reassure readers (including potential investors) that a commercial minewater geothermal project with the output estimated for the GGERFS would cost <<£9 million. MMS list many GGERFS budget items that would be omitted from a commercial project. However, the only component itemised is the reported £1.4M capital cost of the new BGS core scanner (Damaschke, 2018). As an indication of essential expenditure, Springhill

(2018) reported a representative cost of a ~60m-deep, ~200mm diameter borehole in Carboniferous rocks in northern England as ~£15k.

Conclusions

GGERFS data will undoubtedly contribute to the development of minewater geothermal energy in Scotland and the wider UK. However, it is not an ideal site: as WW showed, its shallow depth means that the heat-in-place is anthropogenic, not geothermal, and the geothermal heat flow into the instrumented minewater reservoir is very low. Furthermore, the small scale of these 19th century mineworkings limits their potential heat output. WW did not attempt to mislead regarding the GGERFS, only to clarify; it is hoped that the present text provides additional clarification.

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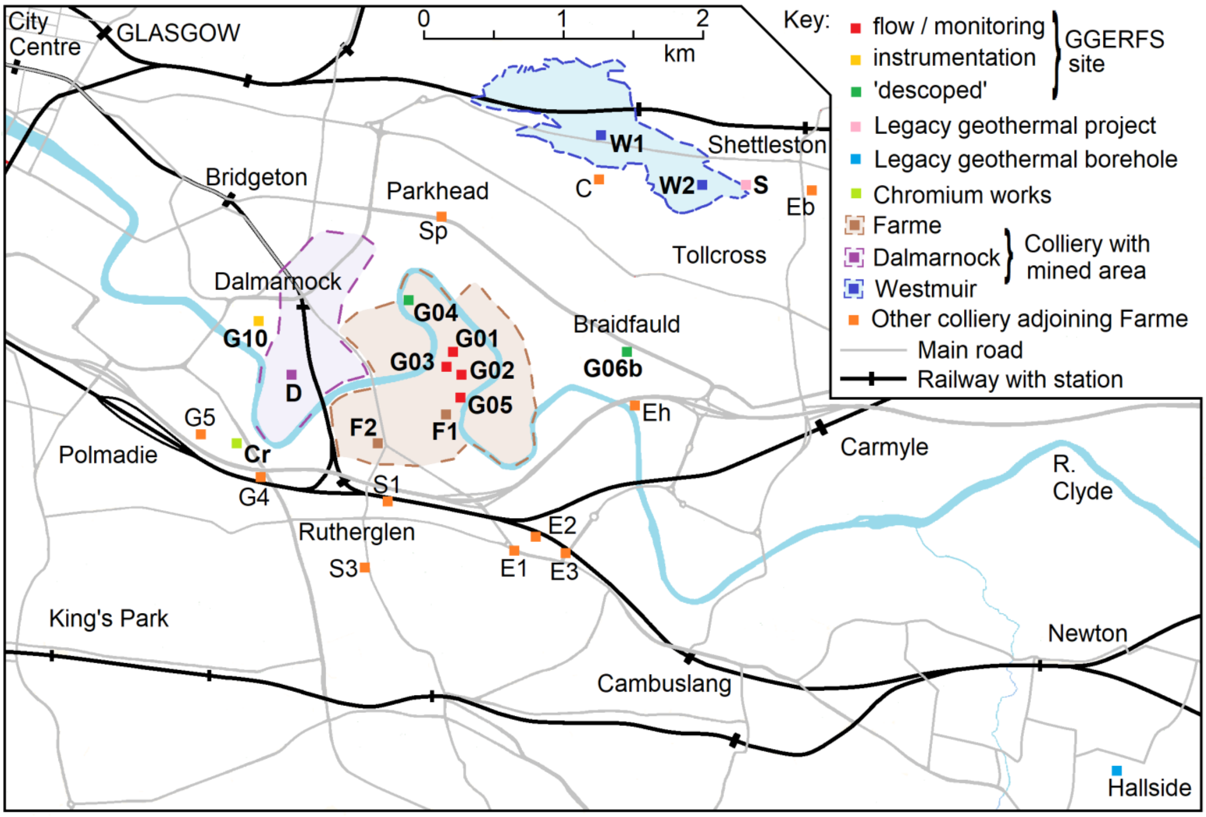
Figure captions

Figure 1. Map of the study area, southeast of Glasgow city centre, showing actual and 'descoped' GGERFS sites and other localities discussed in the text. For Dalmarnock Colliery, at British National Grid reference NS 61181 62715 (D), the 'old' and 'new' pits of Farme Colliery, circa NS 622 624 (F1 and F2), and Westmuir Colliery, represented by Carntyne pit, circa NS 634 644 (W1), and Wellshot pit, circa NS 641 639 (W2), the areas of workings are illustrated schematically, after Monaghan et al. (2017); these are ~0.7 km^2 each for Dalmarnock and Westmuir collieries and ~1.4 km^2 for Farme Colliery. Surface workings of former collieries surrounding these mined areas include: Caroline pit, circa NS 634 640 (C); Eastbank pit, circa NS 649 639 (Eb); Easterhill Colliery, circa NS 636 624 (Eh); three pits of Eastfield Colliery, circa NS 627 614, 629 615, and 631 614 (E1, E2, and E3); pit 4, circa NS 609 620, and pit 5, circa NS 605 623, of Govan Colliery (G4 and G5); pit 1, circa NS 616 613, and pit 3, circa NS 618 618, of Stonelaw Colliery (S1 and S3); and Springbank pit, circa NS 623 638 (Sp). The Shawfield Chemical Works is circa NS 60720 62250; the Shettleston minewater heat project is circa NS 644 640.

Editor's note: This Reply now concludes all correspondence on this paper

Figure 1



City Centre
GLASGOW
0
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km
Key:
flow / monitoring
instrumentation
'descoped'
GGERFS site
Legacy geothermal project
Legacy geothermal borehole
Chromium works
Farme
Dalmarnock
Westmuir
Colliery with mined area
Other colliery adjoining Farme
Main road
Railway with station
Bridgeton
Parkhead
Shettleston
W1
W2
S
C
Eb
Sp
Tollcross
Dalmarnock
G04
G01
G10
G03
G02
D
G05
F2
F1
Braidfauld
G06b
Eh
G5
Cr
Polmadie
G4
S1
Carmyle
R. Clyde
Rutherglen
S3
E1
E2
E3
King's Park
Newton
Cambuslang
Hallside