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South Seeds renewable heat: Potential minewater heat recovery in the South Side of Glasgow

Geology and Landscape Scotland Programme

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BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE SCOTLAND PROGRAMME

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South Seeds renewable heat: Potential minewater heat recovery in the South Side of Glasgow

R Ellen, S Loveless and H F Barron

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Foreword

This report contains the British Geological Survey (BGS) contribution to a collaborative project between Ricardo-AEA, BGS and John Gilbert Architects to develop a heat masterplan for the South Seeds project area that is accurate, reliable and evidence based. This project will identify where the key heat loads are in the South Seeds project area, how these loads could be met from low carbon sources and provide South Seeds with the essential information to take to stakeholders about moving forward with implementing the heat masterplan.

The BGS component as described in this report comprises an initial assessment of minewater “geothermal” resources beneath the South Seeds area of interest, in the south side of Glasgow, based on 3D geological modelling of the mine workings, and preliminary estimates of the volume and temperature of the minewaters.

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Summary

This report contains the BGS contribution to a collaborative project between RICARDO-AEA, BGS and John Gilbert Architects to develop an accurate, reliable and evidence based heat masterplan for the South Seeds project area in Govanhill and Crosshill areas in the South Side of Glasgow.

The BGS component comprises an initial assessment of minewater “geothermal” resources beneath the South Seeds area of interest, in the south side of Glasgow, based on 3D geological modelling of the mine workings, and preliminary estimations of the volume and temperature of the minewaters

1 Introduction

Glasgow is underlain in many parts by a network of abandoned mines from which were extracted coal, ironstone and other minerals. The coal mines existed as a network of shafts and roadways that led to the coal seams from which coal was extracted. Most of the seams were allowed to collapse in a controlled fashion soon after the coal had been extracted, but the void spaces created in these rubble collapsed layers can still store and transmit significant volumes of groundwater. When the mines are active water is pumped out of the mines, however once this has ceased the mines can fill with groundwater from surrounding rocks (**Error! Reference source not found.**). The area that was previously mined can then act as an enhanced aquifer from which water can be pumped and used as a source of geothermal energy. The residual increase in void space is influenced by the type of mining. Two types of mining were used in Glasgow, “stoop and room”, whereby pillars of rock are left unmined to support the roof of the mine, or “longwall” whereby the coal seam is worked between two parallel access roadways and the roof is allowed to collapse as the workings advance. In mines that underwent “stoop and room” mining voids can be around 50%, except where shallow mineworking have been grouted to prevent subsidence (Figure 2). However, Campbell et al. (2010) suggest that longwall mining was a more common practice in Glasgow, in which only 20% voids may remain (Younger and Adams, 1999 in Gillespie et al., 2013). Nevertheless an increase in fractures associated with rock collapse and changes in rock stress is likely to increase porosity to around 30%. In addition, mine shafts, roadways or drifts are likely to remain as open voids with high permeability thus would increase the volume estimations and provide connections between the different worked seams.



Figure 1 Conceptual model of an aquifer in rock that has been used for coal mining (Ó Dochartaigh et al. 2015)

Because the mine workings exist over a range of depths within the ground, the water temperature can vary quite significantly between the uppermost and lowermost levels due to the geothermal gradient – the increase in the Earth’s temperature with depth. More energy can be extracted from warmer water so water with the greatest temperature is most likely to be utilised for geothermal. The depth and temperature of this water needs to be established in order to assess the geothermal potential. The shallower mine levels can be utilised for re-injection of the used, cooled water.

As part of its Clyde Urban Super Project (CUSP), BGS has developed detailed 3D geological models of the complex deposits and rocks beneath much of Glasgow and adjoining areas. These models integrate large amounts of disparate information held in various formats by the BGS and other organisations and provide a platform for interpreting the groundwater systems associated with the mine workings.

In this project, data from these existing 3D models plus newly-digitised information from mine abandonment plans have been used to build a new 3D model of the mine workings below the Area of Interest (AOI) (Figure 2). The 3D model was used to calculate the estimated total volume of mined rock and so the potential volume of groundwater contained in the mined rock, and the potential heat recovery from the mine workings.

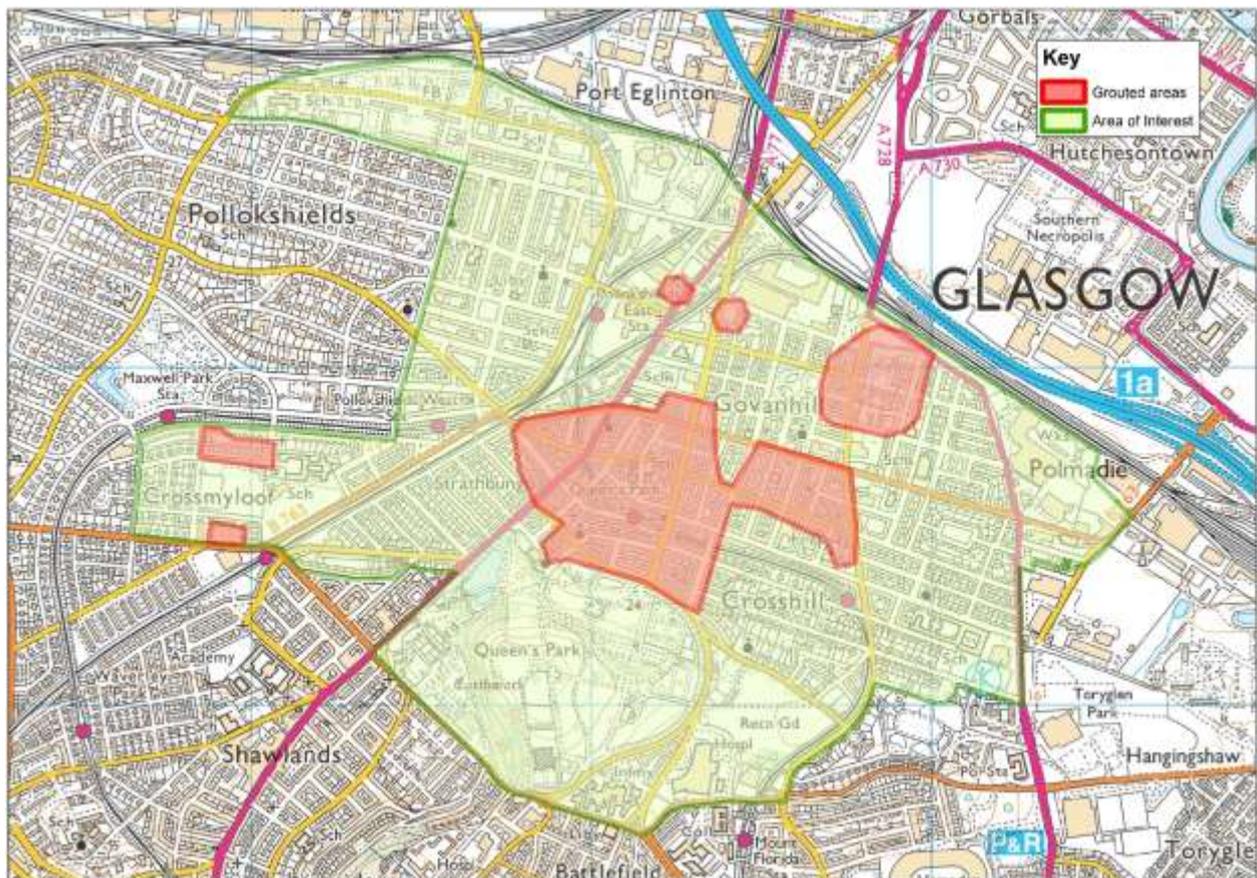


Figure 2 Project Area of Interest (AOI) and grouted areas of shallow mining in the South Side of Glasgow

1.1 DATA IMPORT AND WORKFLOW

Digital scans of mine workings from coal mine abandonment plans held by the BGS were used to create GIS files of the disused mine workings and shafts in and around the project area. Spot height and contour data, where recorded, were also digitised. However, these data were sparse and often contradictory within mine plans within the project area. Out of a total of 45 recorded

locations of shafts available from BGS records, only 2 had recorded depth information. Where unrecorded, the base of the shaft is modelled as a minimum length, taken as the shallowest coal working recorded, since BGS have no information to constrain how deep these shafts may have been. Spatial information on locations of adits and roadways within the mine workings were not available in BGS records, although this does not preclude their existence.

The shapefiles were then imported into MoveTM software for production of the 3D model of the mine workings. The available data within the project area comprised shaft locations and outlines of mine workings within nine coal seams (in stratigraphic order from oldest to youngest): the Knightswood Gas, Kiltongue, Airdrie Virtuewell, Virgin, Glasgow Splint, Humph, Glasgow Main, Glasgow Ell and Glasgow Upper. Of these coal seams, the Glasgow Upper, Glasgow Ell, Kiltongue and Knightswood Gas were available as 3D bedrock surfaces already produced as part of the BGS 3D Central Glasgow Bedrock Model (Arkley et al., 2013). These surfaces, representing the base of each coal seam, were imported into the model. Additional data imported into the 3D model also included a digital terrain model (DTM), the AOI of South Seeds provided by Ricardo AEA, fault surfaces and borehole data from the BGS 3D Central Glasgow Bedrock Model (Arkley et al., 2013).

As no pre-existing 3D surfaces were available for the five coal seams between the modelled Glasgow Ell and Kiltongue (Arkley et al., 2013), and sparse spot height or contour data within the project area was of insufficient detail to construct 3D surfaces for them, the Glasgow Ell surface was duplicated and copied for each seam. These copied surface were then adjusted to known constant thickness between the Glasgow Ell and the Glasgow Main, Humph, Glasgow Splint, Virgin and Airdrie Virtuewell (Table 1). A borehole from the east of the site [NS56SE291; NS 59250 62260] which penetrated most of the seams (in a continuous succession) was used as a measure for a standard depth between seams. In seams that the borehole did not penetrate (Airdrie Virtuewell and Kiltongue), an average value between available spot heights from mine plans at a similar location within each seam's mine plans was used. However, it is probable that the depths between these five surfaces vary across the project area, reflecting natural changes in the geological deposition of these units. Therefore the sub-surface geometries of the Glasgow Main, Humph Coal, Glasgow Splint, Virgin and Airdrie Virtuewell are based on the geometry of the overlying Glasgow Ell and probably do not represent the true extent or depths at which these seams actually occur (see recommendations section for future work which could be carried out to reduce this uncertainty). Depths are provided in metres above/below Ordnance Datum (OD).

Coal Seam	Distance between seams (m)
Glasgow Upper – Glasgow Ell	14.6
Glasgow Ell – Glasgow Main	8.8
Glasgow Main – Humph Coal	27.9
Humph Coal – Virgin Coal	12.3
Virgin Coal – Airdrie Virtuewell	40

Table 1: Vertical distance between coal seams within the project area, based on one borehole [NS56SE291] and spot height data from mine plans.

1.2 INCORPORATION OF MINE WORKINGS INTO 3D MODEL

The BGS holds records of digitised mine workings and probable mine workings (where there is a high likelihood of another seam having been worked but with no mine plans recorded).

However, as we have no evidence to confirm the existence of these, they are not included in the 3D model. The extents of the digitised mine workings are shown in Figure 3.



Figure 3: Extent of 'probable' mine workings. Dashed red line represents AOI boundary. GU=Glasgow Upper, GE=Glasgow Ell, GMA=Glasgow Main, HUC=Humph Coal, GSP=Glasgow Splint

In addition to this, recorded mine workings from the Airdrie Virtuewell and Virgin are recorded within the AOI. However, the mine workings contain no spot heights and since the Glasgow Ell surface (Arkley et al., 2013) does not extend into this part of the model it cannot be used as a proxy for subsurface geometry, as was possible elsewhere in the model. Therefore these mine workings are not included in the 3D model as we do not have enough information on them to model them in 3D. The estimate of volumes below may therefore be an underestimate. Their extents are shown in Figure 2. From selected borehole records, the Airdrie Virtuewell is found at depths of between 11 m and 45 m beneath surface level under the site (12 m OD and -27 m OD respectively) within the AOI, and is shallower at the south-west margin and deeper at the north-east margin. The Virgin Coal in borehole records, is found at depths of 10 m and 39 m beneath surface level within the AOI (14 m OD and -15 m OD respectively), and is shallower at the south-west margin and deeper at the north-east margin. In order to constrain these depth ranges further, it is recommended a more detailed study on all borehole records available in the project area should be carried out in order to construct a sub-surface model of these mine workings in 3D space.

The remaining mine working plans were converted into 3D surfaces. Those mine workings which met the following criteria were included for the 3D mine workings model:

1. Overlapped the AOI provided by Ricardo;
2. Overlapped an over- or under-lying coal seam (assuming any potential mine waters may be connected by an increase in fractured rock between mined seams).

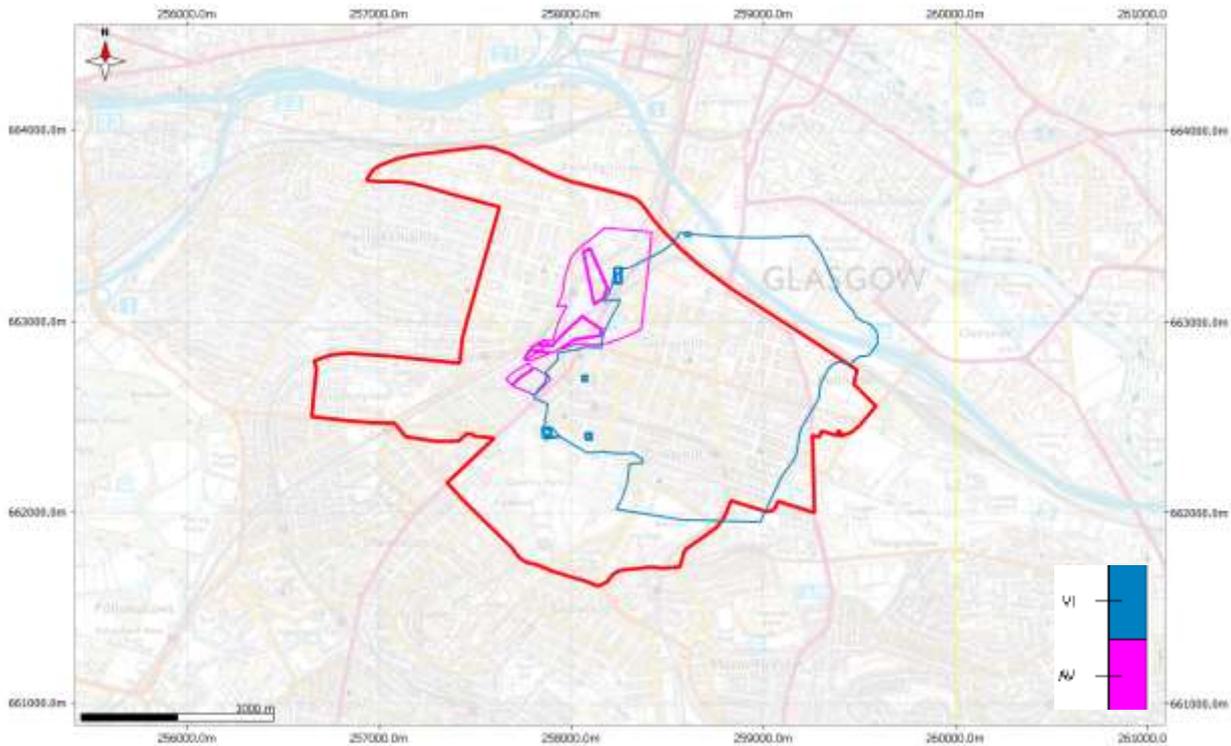


Figure 4: Extent of Airdrie Virtuewell (AV) and Virgin (VI) mine workings within AOI. As no depth data was available for them, they were not included in the 3D model. See text for minimum and maximum depth across the AOI

The outlines of the mine workings were projected directly downwards on to their equivalent 3D surfaces. Where faults crossed the area, the outlines were projected down onto their planes so as not to lose the detail of the workings – had the mine workings been projected down into the gaps between fault blocks, their extents would have been lost. Therefore where there are steep ‘ramps’ in the 3D surfaces, these represent the locations of faults that were modelled in the Glasgow Bedrock Model (Arkley et al., 2013). The surfaces were then cut using the outlines of the mine workings to produce a 3D model of the mine workings at depth.

The maximum and minimum depth (relative to OD) was calculated from the model for each seam, as well as the estimated volume of mine workings. It is likely that the worked coals across the area will vary in thickness and therefore an average value of 1 m (taken from boreholes) was chosen for volume calculations. We have no record for the technique used for mining in these areas. The extent of each modelled seam with elevation (OD) is shown in Figures 3 to Figure 11, and the results are summarised in Table 2. Figure 12 shows an outline of all the 3D modelled surfaces and location of shafts, and Figure 13 shows all 3D modelled surfaces and the faults from the Glasgow Bedrock Model to compare with where sudden changes in depth occur across modelled seams.

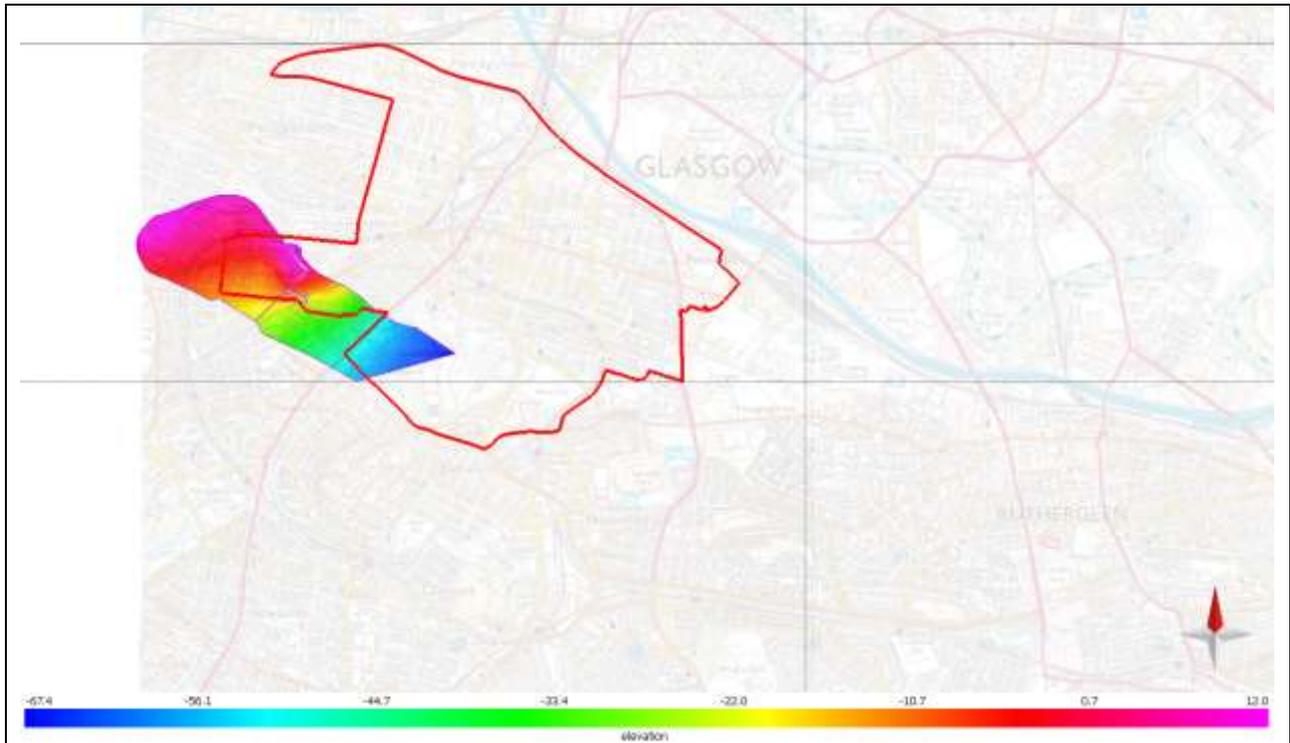


Figure 5: Knightswood Gas mine working extent, colour mapped for elevation (OD)

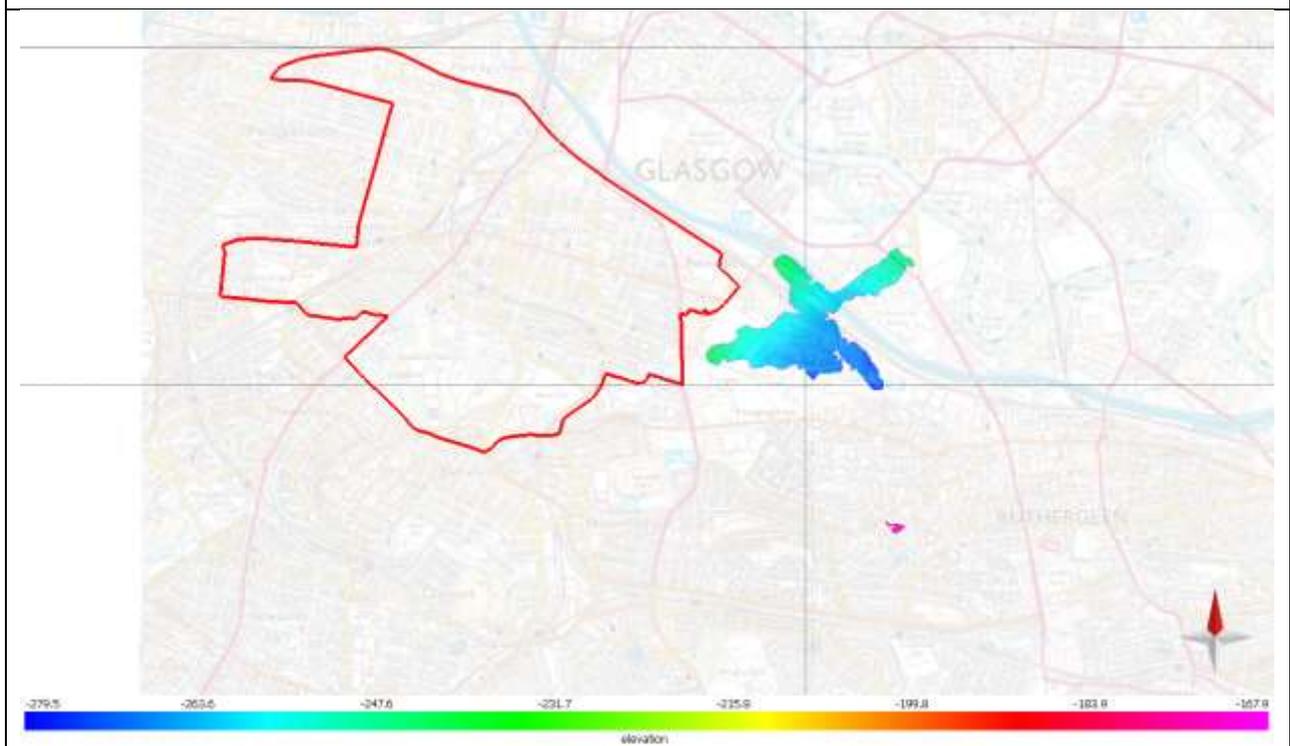


Figure 6: Kiltongue mine working extent, colour mapped for elevation (OD)

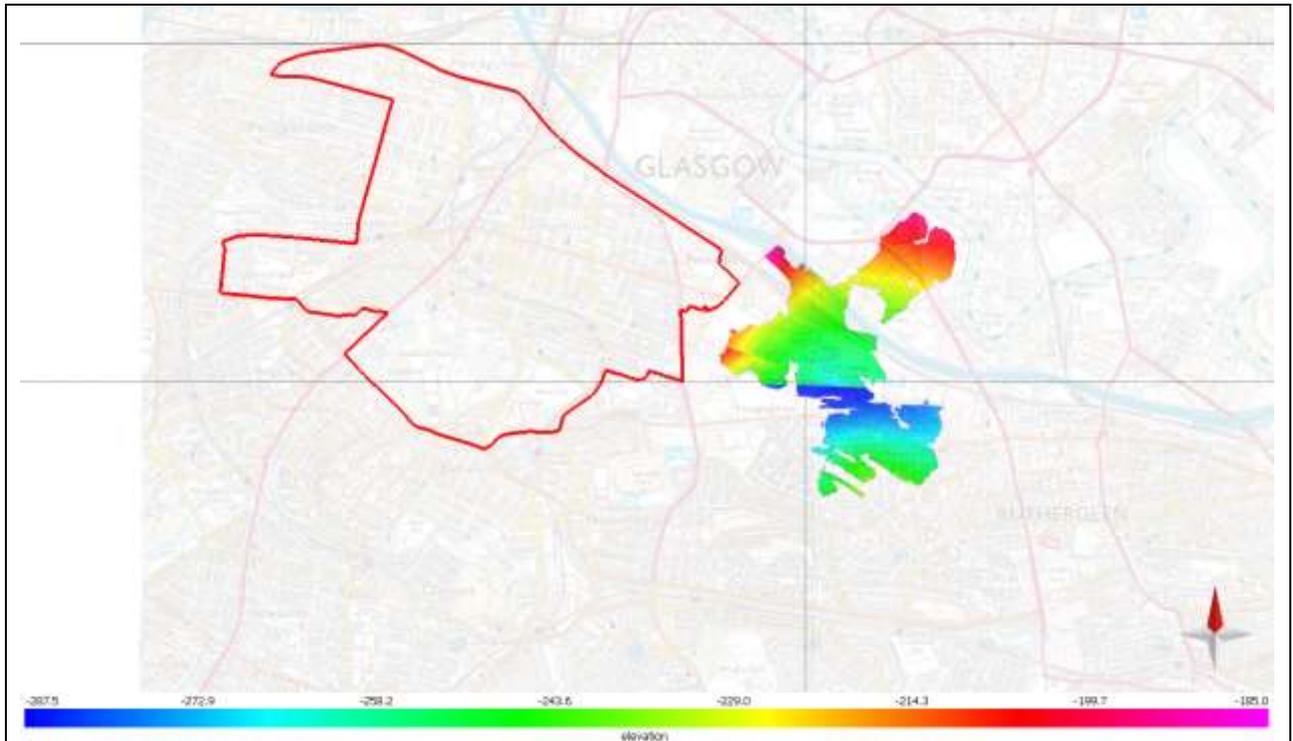


Figure 7: Airdrie Virtue well mine working extent, colour mapped for elevation (OD)

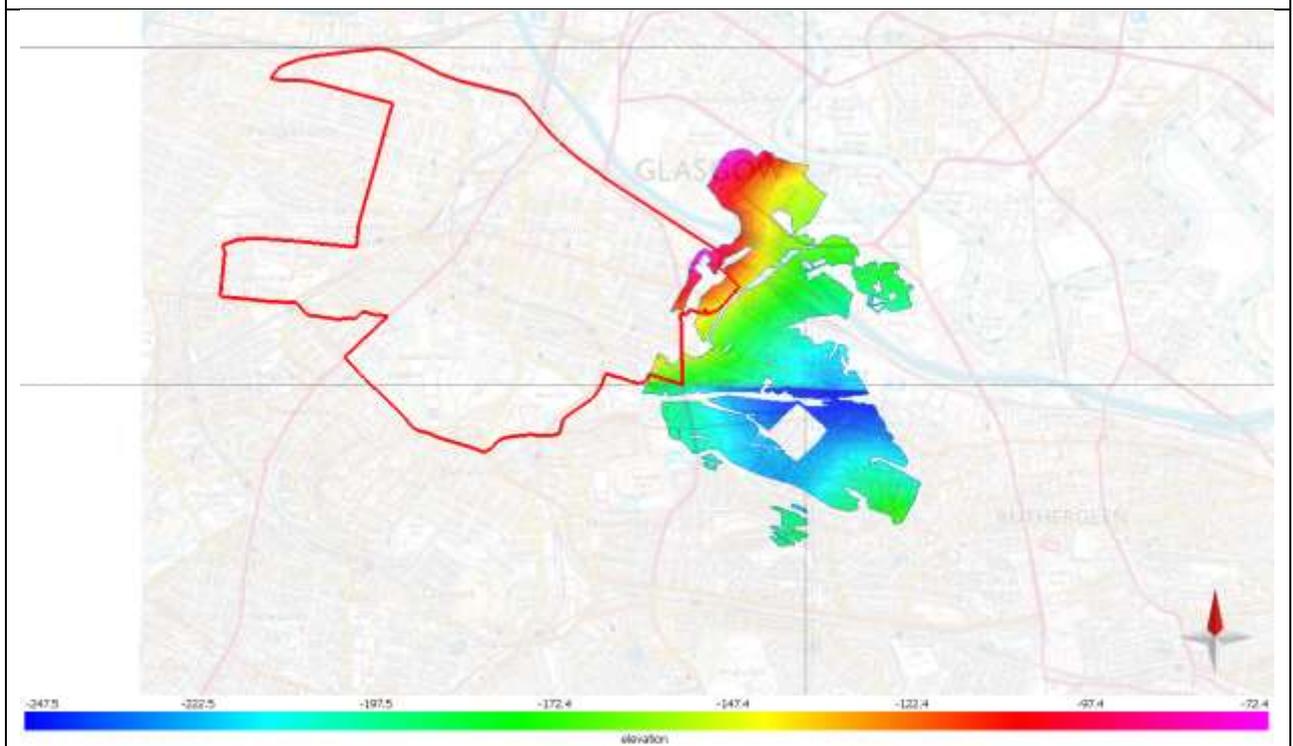


Figure 8: Virgin mine working extent, colour mapped for elevation (OD)

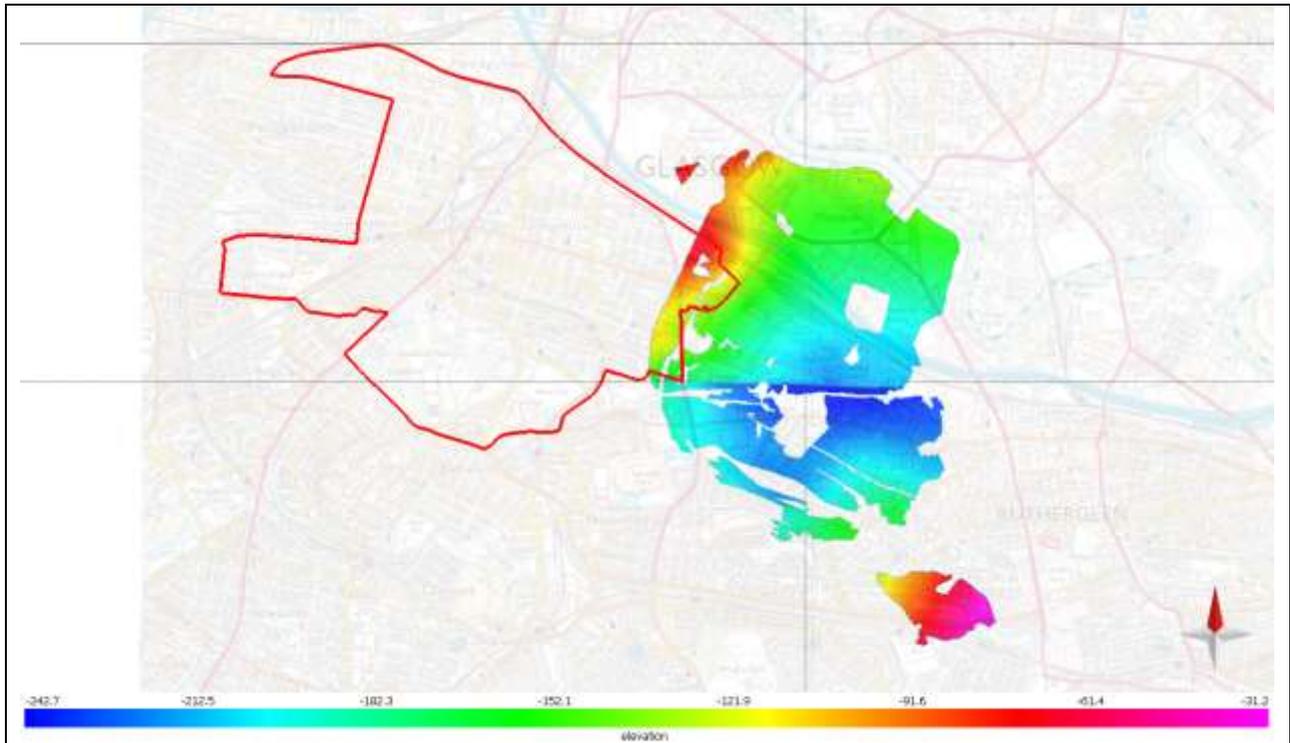


Figure 9: Glasgow Splint mine working extent, colour mapped for elevation (OD)

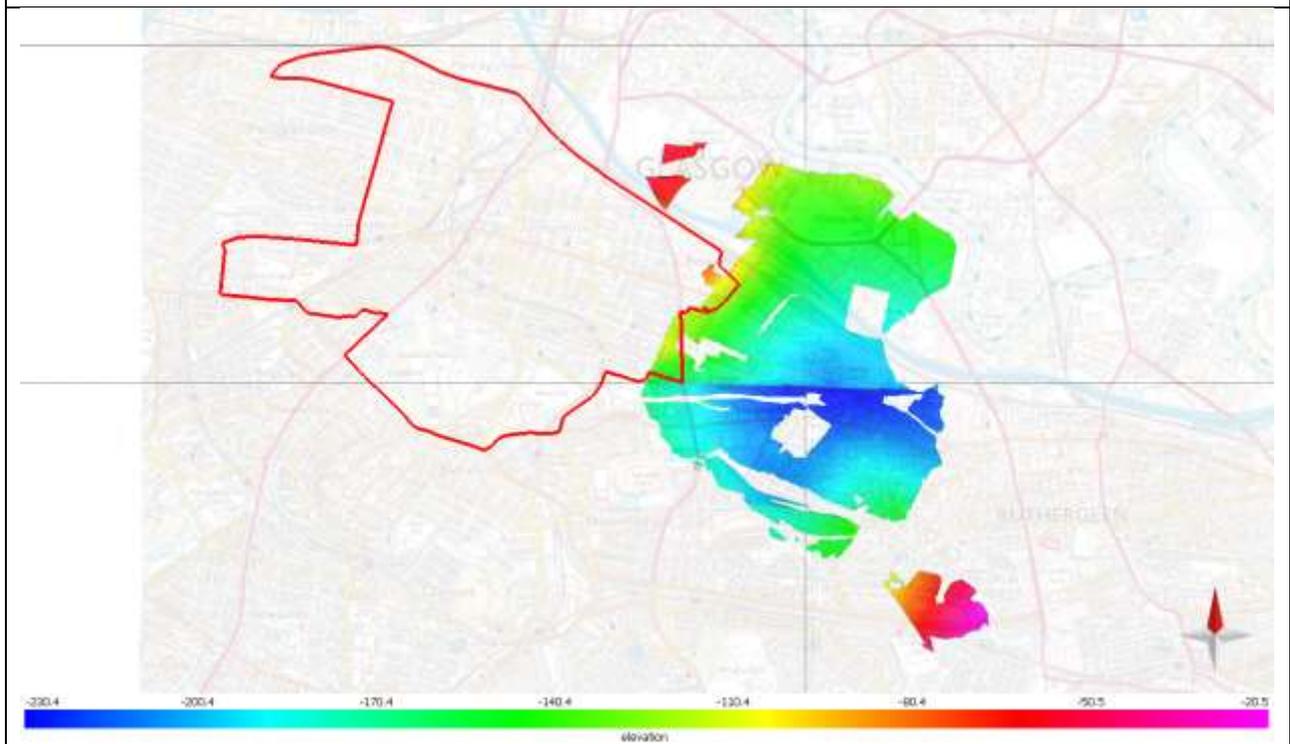


Figure 10: Humph Coal mine working extent, colour mapped for elevation (OD)

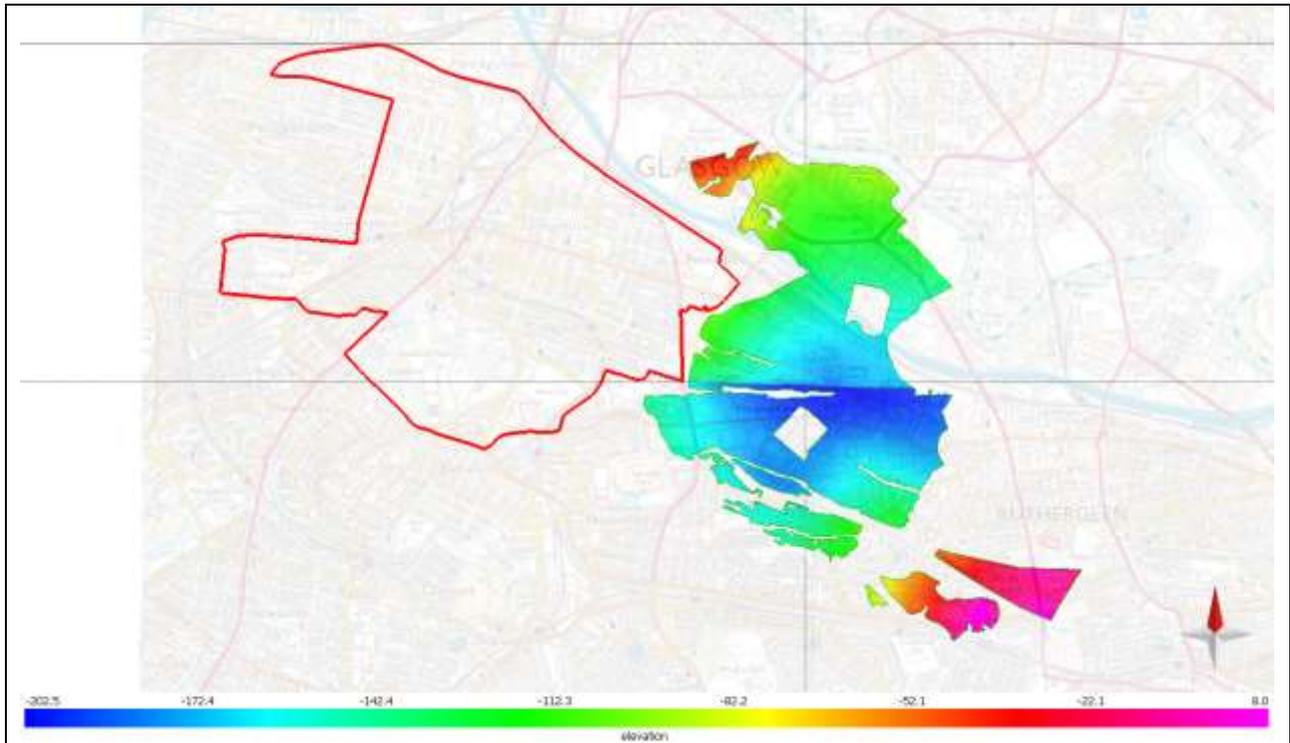


Figure 11: Glasgow Main mine working extent, colour mapped for elevation (OD).

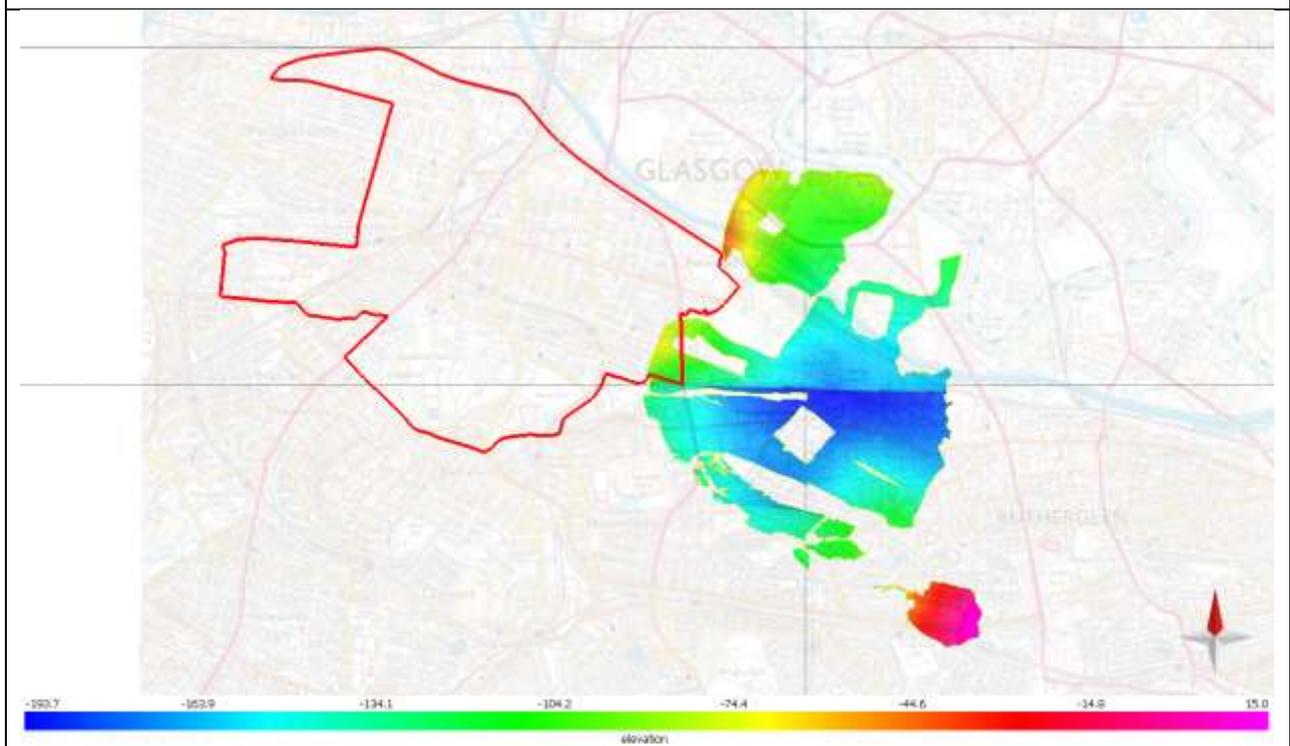


Figure 12: Glasgow Ell mine working extent, colour mapped for elevation (OD).

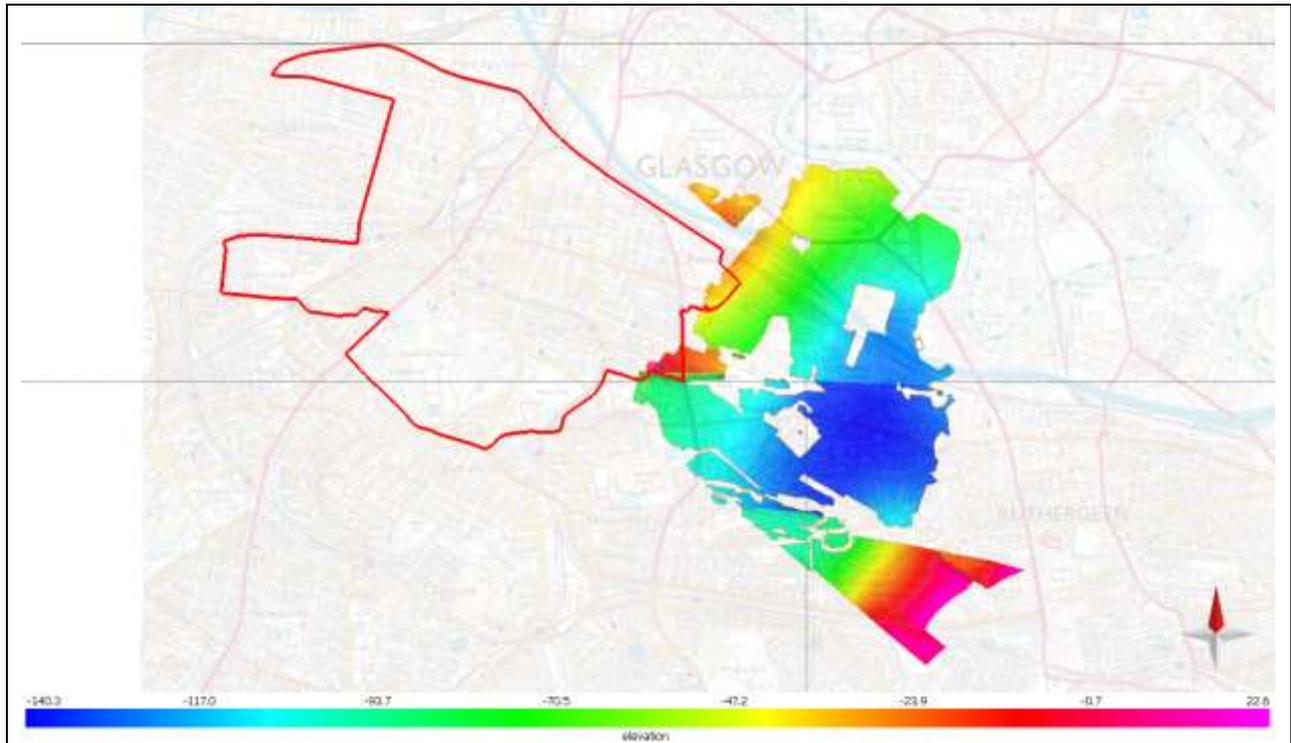


Figure 13: Glasgow Upper mine working extent, colour mapped for elevation (OD).

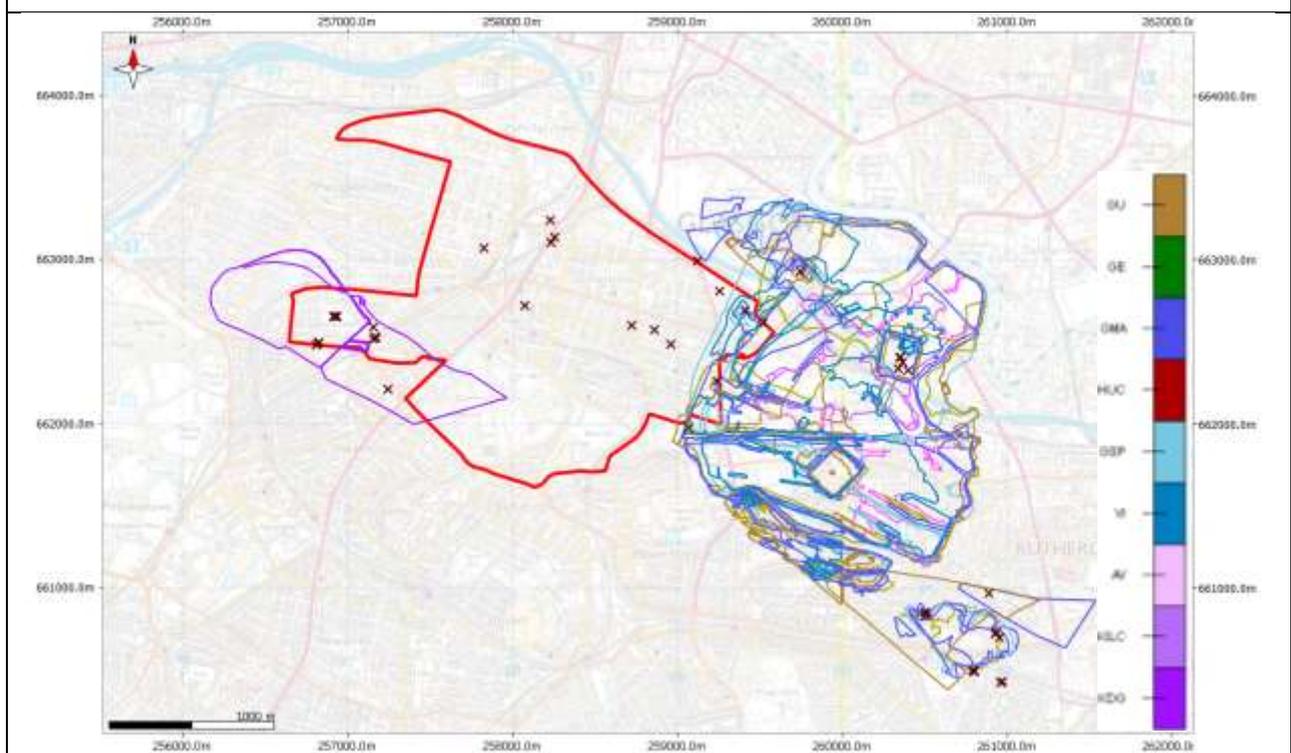
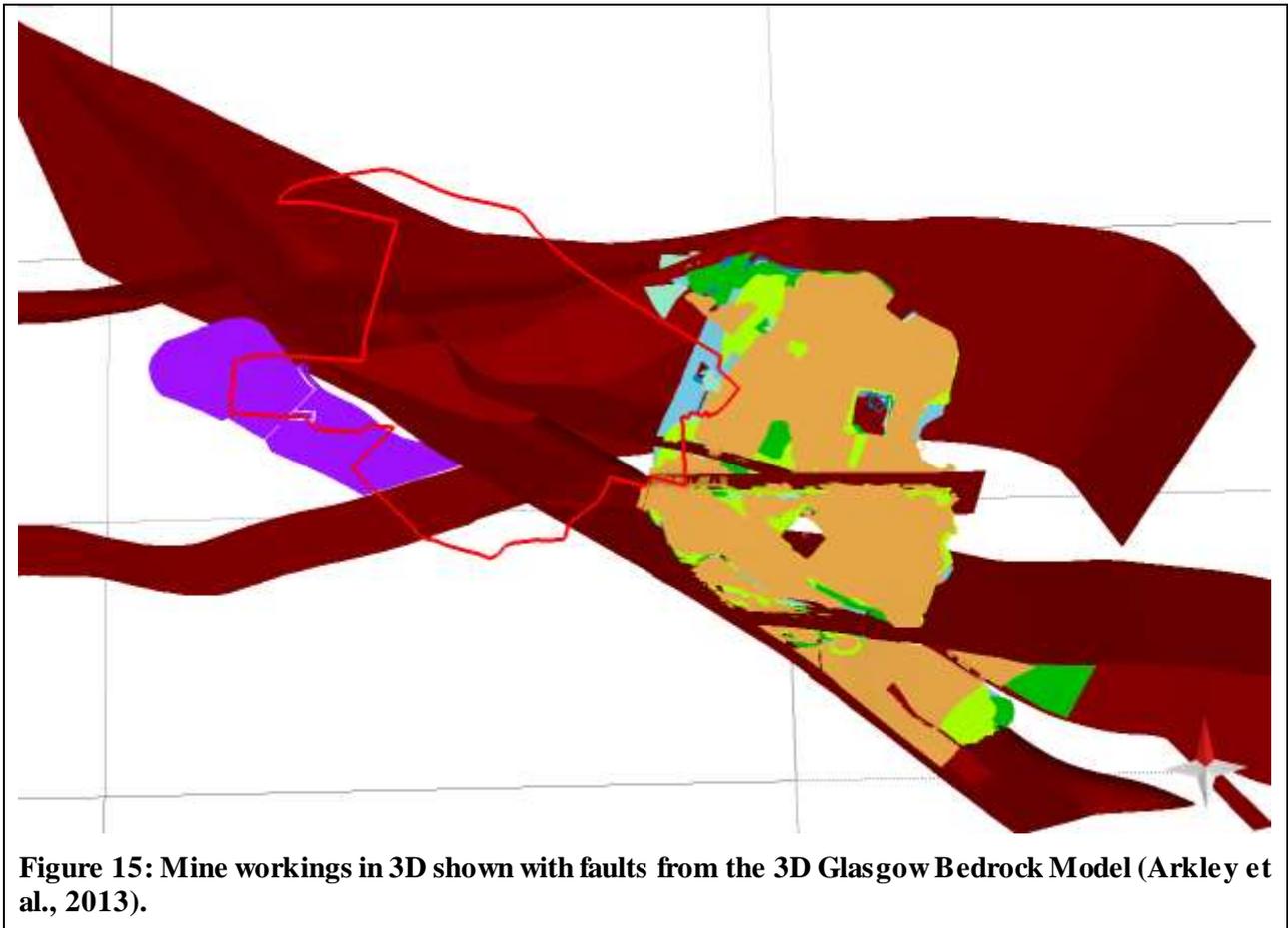


Figure 14: Outline of all 3D modelled surfaces, and positions of shafts (black crosses). GU=Glasgow Upper, GE=Glasgow Ell, GMA=Glasgow Main, HUC=Humph Coal, GSP=Glasgow Splint, VI=Virgin, AV=Airdrie Virtuewell, KILC=Kiltongue and KDG=Knightswood Gas.



Coal Seam	Full name	Potential total mined volume m ³ (assuming 1 m thick workings)	Minimum and maximum elevation (OD)	Average elevation (OD)
GU	Glasgow Upper	2767494	22.6 m to -140 m	-92.4 m
GE	Glasgow Ell	2175171	15 m to -194 m	-126 m
GMA	Glasgow Main	2512896	8 m to -202 m	-131.3 m
HUC	Humph Coal	2583589	-20 m to -230 m	-161.2 m
GSP	Glasgow Splint	2736400	-31.2 m to -242.7m	-177.3 m
VI	Virgin Coal	1662669	-72 m to 247.5 m	-189 m
AV	Airdrie Virtuewell	930244	-185 m to -287 m	-244.6 m
KILC	Kiltongue	356870	-165 m to -280 m	-252.8 m
KDG	Knightswood Gas	781079	12m to -67 m	-9.8 m

Table 2: Summary of mined workings within coal seams in AOI, and associated mined volume and elevation (OD) ranges.

1.3 UNCERTAINTIES

1. Estimates of error on mining data points, and therefore constructed surfaces, range from 0–5 m in Z and 0–25 m in XY;
2. It is likely that the distance between the worked seams is not at a constant thickness, as is modelled in the project's 3D model. It was beyond the scope of the present study to account for thickness variation between worked seams, and it is recommended that in future work, the construction of a detailed 3D model informed by new borehole investigation;
3. There is no information to suggest over- and underlying coal seams are connected in 3D space, however it is likely there will be an increased fracture zone between these seams due to subsidence over time between levels;
4. There may be other undocumented worked mines, shafts, adits and roadways within the AOI that BGS do not have access to;
5. Some of the shallower mines may be grouted.
6. The potential use of longwall or shortwall mining would have closed up 80–90% of the void.

1.4 RECOMMENDATIONS

If a more rigorous assessment of the mine workings is required, a more comprehensive study of borehole records should be carried out in order to constrain the sub-surface geometries of the following seams at depth: Glasgow Main, Humph Coal, Glasgow Splint, Virgin and Airdrie Virgin well. It was beyond the scope of this work to construct a new 3D geological model based on such records, but a more detailed geological model would help constrain the depths of these surfaces more than the current model is able.

There are three potential geothermal resources within and surrounding the AOI:

1. Shallow mine workings associated with the Knightswood Gas in the west of the site are found at 12 m to -67 m elevation (OD).
2. Shallow mine workings associated with the Virgin and Airdrie Virtuewell in the north and middle of the site are found between 14 and -27 m elevation (OD) – however the 3D structure of these workings are not known due to lack of available data.
3. Deeper and more extensive mine workings are situated to the east of the site, to a depth of potentially -280 m. Whilst outside the AOI, a large 'pillar', left in place to reduce surface subsidence, is still intact within the subsurface above the Toryglen area of Glasgow. It is possible that shafts exist within this pillar (as historically it may have formed a stable area of ground from which to extract coal), and that a series of well connected roadways may link into that, thus potentially enhancing groundwater extraction. There is an open stretch of ground across Toryglen Park which could be used to link this source to the AOI, if viable.

2 Estimation of heat potential

The energy that can be produced from extracted mine water can be estimated through the equation:

$$G = Q \cdot \Delta\theta \cdot S_{VCwat}$$

Where: G is the geothermal potential (Wth)

Q is the flow rate from the mine ($L s^{-1}$)

$\Delta\theta$ is the temperature drop across the heat pump ($^{\circ}K$) (a difference in $1^{\circ}C$ equals a difference of $1^{\circ}K$)

S_{VCwat} is the specific heat capacity of water ($4180 J K^{-1} L^{-1}$)

According to this equation, the thermal energy that might be extracted from a particular mine system depends on two parameters of the mine systems; the flow (or pumping) rate and temperature of the water. This section outlines the methods used and estimates of these parameters based on current knowledge.

2.1 ESTIMATION OF WATER VOLUME IN THE MINE

2.1.1 Workflow

The flow rate that can be sustained from the mine workings depends to a degree on the volume of water that is stored within the mine workings. The volume of water in the mines depends on the 1. the overall mined volume, 2. the void space remaining after collapse of mine workings following mining and 3. the proportion of the mine workings that are saturated with water.

1. The mined volume was taken to be the mined workings within coal seams, calculated from the 3D mine model (Table 2). Shafts and roadways were not included because their location is not currently known.
2. There is a large uncertainty with respect to the remaining volume of void space in the mine. A range has been estimated from the mined volume in the 3D model (Table 2) assuming a minimum void space of 20% accounting only for longwall mining, a maximum void space of 50% accounting for contributions from longwall mining with some stoop and room, and also open shafts and roadways and an average of 30 % accounting for void space from longwall mining and surrounding damaged (fractured) zones.
3. The proportion of the mined volume that is saturated is dependent on the water level in the mine. It is assumed that the water level is contiguous with the surrounding groundwater levels within the region. Records from twelve boreholes close to the AOI been used to reconstruct groundwater levels in the AOI and connected mines (Mine Area of Interest, MAOI) (Figure 16). These records date from 1990–2001 and all measure water levels in the Carboniferous bedrock strata in which the mines are located. It should be noted that while these are the most recent records of water levels, it is possible that changes may have occurred in the subsequent period. Indeed, borehole records, also in the Carboniferous bedrock, from 1888–1939 show groundwater levels in the AOI to be ~10m higher than post mine-dewatering (maximum de-watering for Glasgow was early 1960s) (Robins, 1990 and Ó Dochartaigh, 2009, BGS internal report). However there have been no reported issues with rising groundwater by the City Council suggesting that there have been no dramatic rises (Ó Dochartaigh, 2009, BGS internal report). In addition, these water levels are assumed to be rest (or close to rest) water levels but this is not indicated on most of the records. It is assumed that only mined volumes below the expected water level were saturated. The proportion of the mines that lay above the estimated water level was determined from the 3D mine maps using ArcGIS and subtracted from the mined volume.

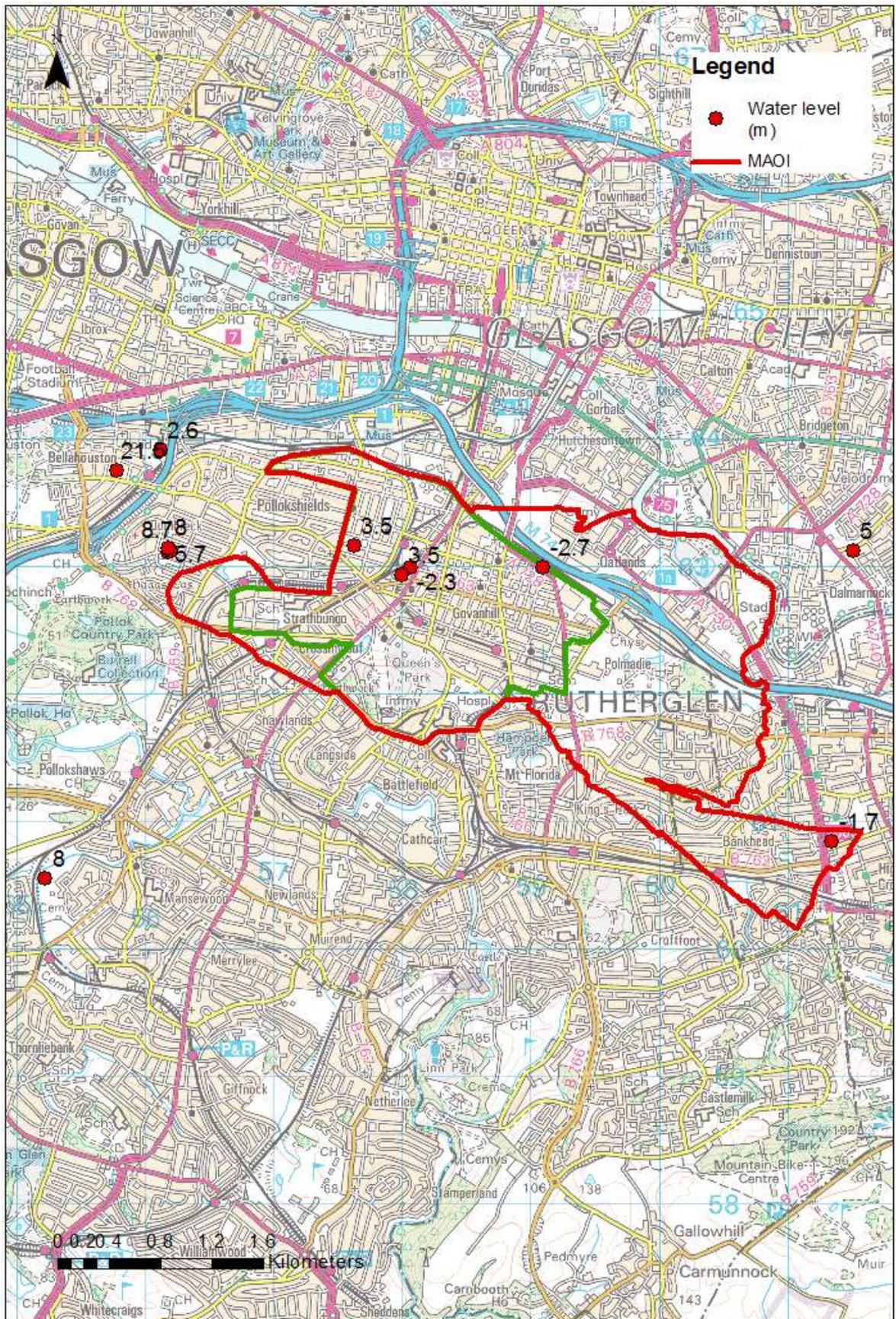


Figure 16 Water levels in eight boreholes close to the AOI since 1990.

2.1.2 Estimated water volume in the mine

The total potential mined volume (assuming 1 m thick workings) is $1.65 \times 10^7 \text{ m}^3$. A range of estimated available volumes according to the water level and expected mine collapse is shown in

Table 3. Borehole records indicate that the water level is between -3 and + 5 m in the MAOI (Figure 16). There are generally higher water levels in the south and east which decrease in the direction of the river, but with a slight depression in the centre of the MAOI where water levels are below OD. As a conservative estimate the depth to the water table is assumed to be the depth to the minimum observed level, -3 m OD. Based on the estimated water level and mine depths about 97% of the mined volume is likely to be flooded.

	Mined volume (m ³)		
	Minimum	Average	Maximum
Total	3.30 x 10 ⁶	4.95 x 10 ⁶	8.25 x 10 ⁶
Saturated	3.21 x 10 ⁶	4.81 x 10 ⁶	8.02 x 10 ⁶

Table 3 Minimum, average and maximum estimated mined volumes according to expected mine collapse (total) and water level (saturated).

If only the deepest mines – Airdrie Virtuewell and Kiltongue – have water with temperatures sufficient for geothermal purposes (section 3.1.2) this volume will be further reduced. The total combined mined volume of these mines is 1.29 x 10⁶ m³. Assuming minimum remaining void space this would be 2.57x10⁵ m³, average 3.86 x 10⁵ m³, and maximum 6.44 x 10⁵ m³, all of which should be fully saturated.

Pumping rates of between 20 to 100 l s⁻¹ km² (average 60 l s⁻¹ km²) (where 1 l is 0.001 m³) are expected to be possible from mines (Gillespie et al. 2013). Based on the mine volumes these pumping rates would not be possible in the medium-long term if only from pre-existing mine water. Recharge from the surrounding rock would replenish mine water but it is not known if this would be at sufficient rates to sustain these yields as such reinjection into the mine system would be necessary.

2.1.3 Uncertainties

1. Mined volume: An uncertainty regarding the 3D volume model of the mine workings from the model remains but a greater uncertainty results from estimates of the remaining void space.
2. Water level: There are limited records of groundwater levels. Most were measured between 1990 and 2001 and may have changed in the following period. It should be noted that the records of groundwater are of varying quality. The recorded levels may not represent long-term rest groundwater levels if they are impacted by local pumping or other fluctuations and it is not clear from the records if the recorded water level will also be influenced by the water table in superficial deposits or by local heterogeneities (Ó Dochartaigh, 2009, BGS internal report). Nevertheless the overall agreement between the water levels and from literature suggests that a large proportion of the mines are likely to be flooded.
3. Recharge: The recharge rate of the water in the mines in the AOI has not been calculated and may be complicated by lateral links to mine workings in the south and east of the area.

2.1.4 Recommendations

1. Improved characterisation of the remaining void space in the mine, including the locations and size of mine shafts, roadways and drifts, and areas of greater/lesser collapse. Such information would be useful as input data for point 3.
2. If available from The Coal Authority, identification of actual pumping rates achieved in these mines during mine-dewatering.
3. A numerical fluid-flow model would help to identify flow rates that can be sustained for the desired period of exploitation, accounting for recharge from surrounding permeable beds and also re-injection.

3 Estimated temperature of water in the mine

3.1.1 Workflow

The temperature of the water that can be abstracted from the mines can be estimated from 1. the geothermal gradient and 2. the depth of the mine.

1. The geothermal gradient varies between regions – geothermal gradients measured within onshore boreholes in Scotland range from 3.7° C to 45.0° C per km. However, plotted together as temperature versus depth the data from these boreholes display a trend defining a temperature gradient of 30.5°C/km that persists throughout the entire depth range (Gillespie et al., 2013).
2. A comparison of depth-temperature for all the measured temperatures from boreholes in Central Scotland shows that there is not a clear geothermal gradient in mines (Figure 18), and very little relation to surrounding temperature measurements, reflecting the influence of greater circulation of shallow waters in mines. According to Gillespie et al., (2013) observed mine water temperatures range from 12 to 21°C, with a mean of 17°C. However the majority of these measurements were made at greater depths than in the MAOI. A hybrid approach will be adopted to estimating the temperature assuming a varying degree of influence of depth (and thus geothermal gradient) on temperature:
 - (i) The minimum temperature will be estimated from the minimum geothermal temperature gradient, taken as the average of Hallside (colliery) and Highhouse Colliery.
 - (ii) The maximum temperature will be estimated from the average geothermal gradient, assuming equilibrium of the water with the rock in the best case scenario.
 - (iii) The average temperature will be estimated based on a value in-between the minimum and the maximum.
3. The depth of the mine workings was extracted from the 3D mine model (**Table 3**Table 2). The temperatures of the deeper mines, Airdrie Virtuewell and Kiltongue, are considered here (average depth greater than -200 m, equivalent to a temperature ~13oC, section 3.1.2). The maximum temperature is calculated from the greatest depth of these mines (Airdrie Virtuewell, -287 m OD), the minimum temperature from the minimum depth of these mines (KILC, -165 m bOD) and average temperature from a weighted average (based on volume) of the depths of these mines (-247 m OD). This method assumes hydraulic connection between the two mines.
4. Estimated temperatures were calculated using inputs from 1. and 2.
 - (i) Maximum temperature = maximum temperature gradient * maximum depth of the two deepest workings.
 - (ii) Minimum temperature = minimum temperature gradient * minimum depth of the two deepest workings

(iii) Average temperature = average temperature gradient * average depth of the two deepest workings.

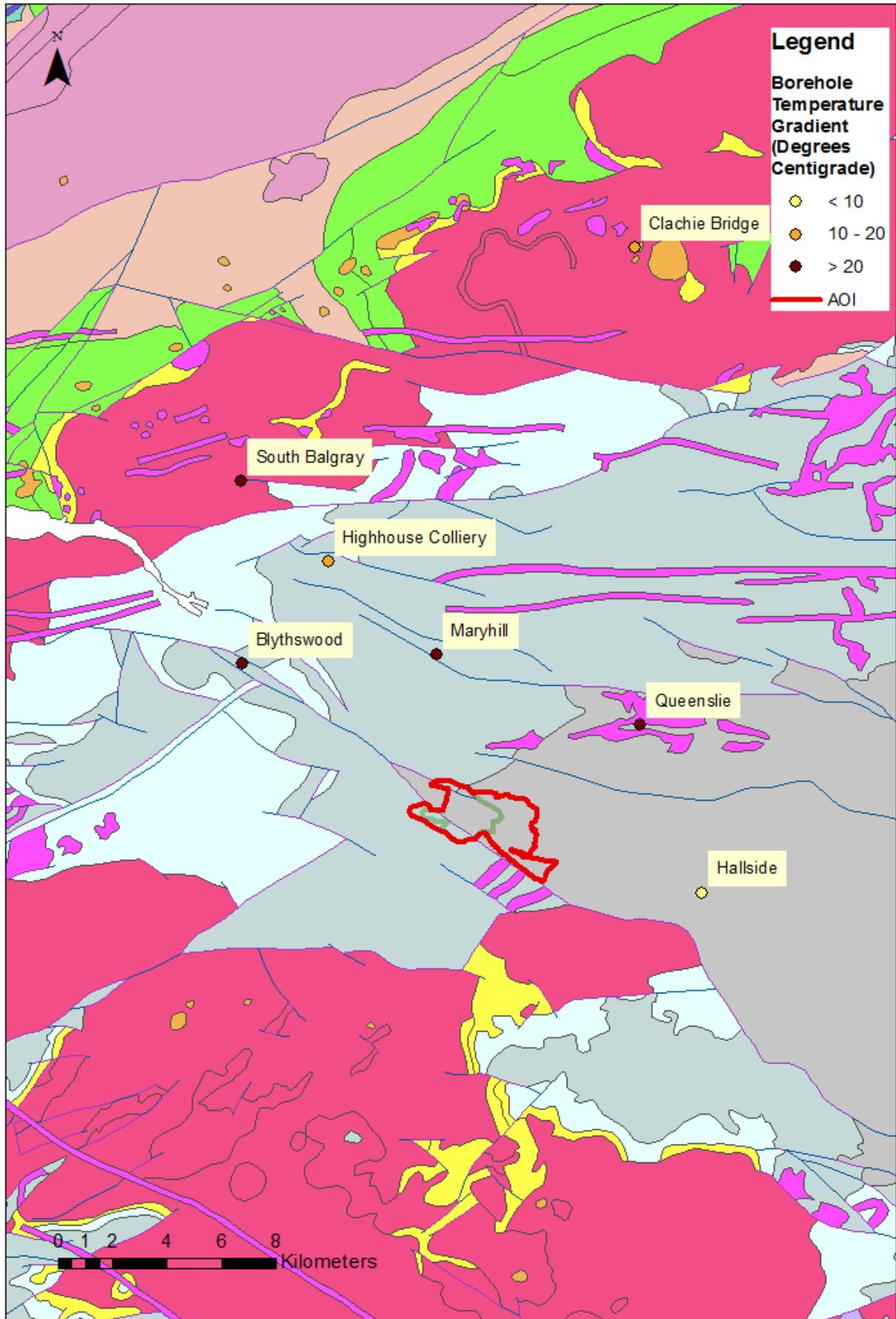


Figure 17 Boreholes with borehole bottom temperatures and depths close to the AOI (green polygon) and MAOI (red polygon) and bedrock geology (1:250k). MAOI predominantly within the Scottish Coal Measures Group but also the Clackmannan Group.

Borehole Name	Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Rock Type (1:10k)	Distance from AOI (km)
Hallside	350	12	6	Scottish upper coal measures formation Limestone coal Formation, Clackmannan	5.6
Blythwood	105	12	37	Group Type Limestone coal Formation, Clackmannan	5.5
Highhouse Colliery	436	18	20	Group Type	9.2
Queenslie	691	36	38	Coal measures Limestone coal Formation, Clackmannan	5.0
Maryhill	303	20	34	Group Type	4.7

Table 4 Temperature, depth and geothermal gradients (calculated for 9°C surface temperature) for the five closest boreholes to MAOI with temperature -depth measurements.

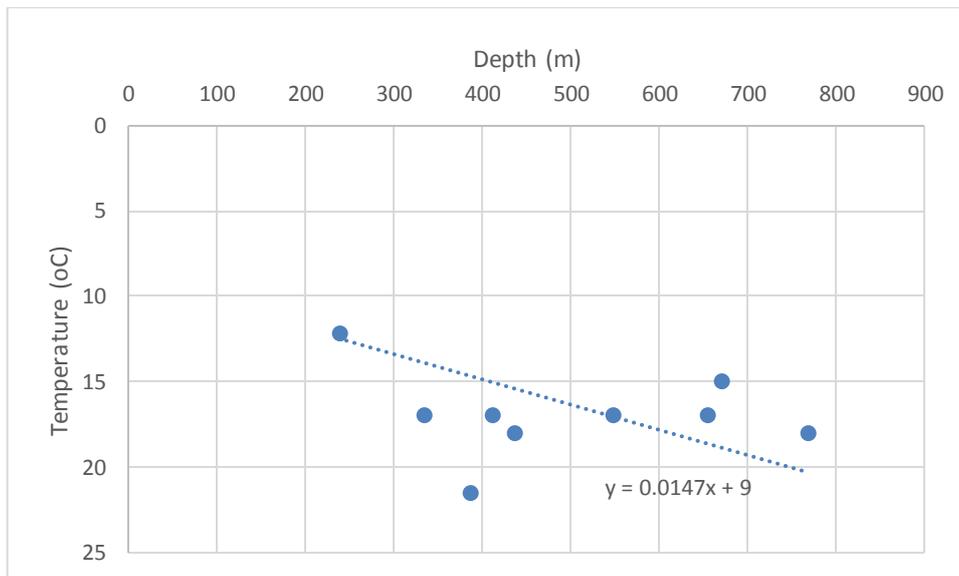


Figure 18 Geothermal gradient from bottomhole temperature -depth measurements in Collieries in the Midland Valley.

3.1.2 Estimated temperature

	Estimated geothermal gradient ($^{\circ}\text{C km}^{-1}$)	Estimated depth (m OD)	Estimated temperature ($^{\circ}\text{C}$)
Average	$22z + 9^{\circ}\text{C}$	-247	14
Minimum	$13z + 9^{\circ}\text{C}$	-165	11
Maximum	$30.5z + 9^{\circ}\text{C}$	-287	18

Table 5 Estimated geothermal gradient and temperature at the lower levels of the mines in the AOI where z is the depth of the mine.

Airdrie Virtuewell and Kiltongue lie between -165 and -247 m OD, with a weighted average of -247 m OD. The estimated average temperature of the two deepest mines is 14°C , within a range from 11°C to 18°C

This estimate is for the initial temperature of minewater, through time water will be drawn in from elsewhere (such as the shallower mine levels and/or surrounding bedrock) and may increase or decrease in temperature depending on the hydrogeological conditions. It should be noted that reinjection in particular might result in thermal breakthrough whereby the cooled water could reach the pumping borehole, reducing temperatures dramatically. The sustainability of such a system is improved if pumping/reinjection is reversed in the summer, with cooler waters abstracted from the shallow mine levels for cooling purposes and warmer waters reinjected into the deeper mine levels, thus replenishing the warmer temperatures.

3.1.3 Uncertainties

The large range of estimated temperatures reflect large uncertainties in the data:

1. There are significant differences in the measured geothermal gradients across Scotland therefore it would be preferable to use a local geothermal gradient. However there is such a large variability within such limited local data that this is not possible at this time.
2. It is not clear to what degree the water in the mine is in thermal equilibrium with the bedrock or influenced by shallow circulation.
3. Uncertainties in mine depth are propagated from section 2.3.
4. It is assumed that abstraction would be preferable from the two deepest mines, but this might not be the case.

3.1.4 Recommendations

1. The significant differences in geothermal gradient should be investigated through re-visiting the original borehole records and identification possible causes of differences, or if possible, access boreholes in the region and to obtain additional temperature measurements.
2. Reduce uncertainty in the 3D model, with a particular focus on the Airdrie Virtuewell and Kiltongue mines.
3. Clarify details of the desired scheme and expected borehole locations.
4. Use a numerical fluid-flow model to model the changes in abstraction temperature over time, and in particular, thermal breakthrough.

4 Energy

As stated previously, the energy that can be produced from extracted mine water can be estimated through the equation:

$$G = Q \cdot \Delta\theta \cdot S_{VCwat}$$

Where: G is the geothermal potential (Wth)

Q is the flow rate from the mine ($l\ s^{-1}$), assumed to be 20, 60 or $100\ l\ s^{-1}$ (section 2.1.2)

$\Delta\theta$ is the temperature drop across the heat pump ($^{\circ}K$), assuming an output temperature of $7^{\circ}C$ (a difference in $1^{\circ}C$ equals a difference of $1^{\circ}K$) and the minimum, average and maximum estimated mine temperatures (section 3.1.2).

S_{VCwat} is the specific heat capacity of water ($4180\ J\ K^{-1}\ l^{-1}$)

Flow rate per km^2 (Q) ($l\ s^{-1}$)	Input temperature ($^{\circ}C$)	Output temperature ($^{\circ}C$)	Temperature difference ($^{\circ}C$)	Geothermal potential (MWth)
20	11	7	4	0.3344
20	14	7	7	0.5852
20	18	7	11	0.9196
60	11	7	4	1.0032
60	14	7	7	1.7556
60	18	7	11	2.7588
100	11	7	4	1.672
100	14	7	7	2.926
100	18	7	11	4.598

Table 6 Range of possible geothermal outputs for a range of flow rates and temperatures

A range of estimates based on the above information and an approximate area of the two deepest mines of $1\ km^2$. Assuming an average flow rate of $60\ l\ s^{-1}$ and temperature of $14^{\circ}C$ an output of $1.76\ MWth$ might be possible, but with a range from $0.33 - 4.60\ MWth$. It should be noted that this estimate assumes the water is recharged at a sufficient rate and similar temperature, which may not be the case.

5 Conclusions

There is a great deal of uncertainty surrounding the estimates of geothermal potential in the mines in the AOI and these should not be forgotten when using the above figures. Nevertheless, it has been estimated that it might be possible to extract 1.76 MWth for geothermal purposes from the deeper levels of the mine workings, from waters at 14°C and a flow rate of 60 l s⁻¹. Recharge of this source at sufficient temperatures is necessary in order for this to be sustainable, but at this stage it is not known if this would be the case.

A number of recommendations have been made and can be summarised as: 1. Mine characteristics; improving knowledge of the mine workings and the 3D model in terms of depth, thickness, location of significant structures through additional data analysis. 2. Fluid characteristics; improve knowledge of possible pumping rates from the mines and temperature of minewater through measurements. 3. Model the sustainability of a geothermal mine system through building a numerical fluid flow model, which would also require system specifications such as desired locations of boreholes and flow rates.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: <http://geolib.bgs.ac.uk>.

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