Accepted Manuscript

Quarterly Journal of Engineering Geology and Hydrogeology

GIS analysis for the selection of optimal sites for mine water geothermal energy application: a case study of Scotland's mining regions

D. B. Walls, D. Banks, Y. Kremer, A. J. Boyce & N. M. Burnside

DOI: https://doi.org/10.1144/qjegh2023-050

To access the most recent version of this article, please click the DOI URL in the line above. When citing this article please include the above DOI.

This article is part of the Mine Water Energy collection available at:
https://www.lyellcollection.org/topic/collections/mine-water-energy

Received 14 May 2023
Revised 1 April 2024
Accepted 10 May 2024

© 2024 The Author(s). This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 License (http://creativecommons.org/licenses/by/4.0/). Published by The Geological Society of London. Publishing disclaimer: https://www.lyellcollection.org/publishing-ethics

Supplementary material at https://doi.org/10.6084/m9.figshare.c.7235866

Manuscript version: Accepted Manuscript
This is a PDF of an unedited manuscript that has been accepted for publication. The manuscript will undergo copyediting, typesetting and correction before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Although reasonable efforts have been made to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record once published for full citation and copyright details, as permissions may be required.

Title: **GIS analysis for the selection of optimal sites for mine water geothermal energy application: a case study of Scotland's mining regions.**

Abbreviated Title: Mine Water Geothermal Resource Atlas for Scotland

Authors:

D. B. Walls[1]*, D. Banks[2], Y. Kremer[1], A. J. Boyce[3], N. M. Burnside[1].

*david.walls@townrock.com

[1]Department of Civil and Environmental Engineering, James Weir Building, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XW, UK

[2]James Watt School of Engineering, James Watt Building South, University of Glasgow, Glasgow G12 8QQ, UK

[3]Environmental Research Centre, Scottish Universities, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride G75 0QF, UK

Current addresses: DBW, Townrock Energy, UK

Abstract

Water within flooded coal mines can be abstracted via boreholes or shafts, where heat can be extracted from (or rejected to) it to satisfy surface heating (or cooling) demands. Following use, water can be reinjected to the mine workings, or discharged to a surface water receptor. Four criteria have been applied, using ArcGIS, to datasets describing mine workings and mine water below the Midland Valley of Scotland, to provide an initial screening tool for suitability for mine water geothermal energy exploitation. The criteria are: (i) presence of two or more worked coal seams below site, (ii) absence of potentially unstable shallow (<30 m) workings, (iii) depth to mine water piezometric head <60 m, (iv) depth of coal mine workings <250 m. The result is the Mine Water Geothermal Resource Atlas for Scotland (MiRAS). MiRAS suggests that a total area of 370 km^2 is "optimal" for mine water geothermal development across 19 local authority areas, with greatest coverage in North Lanarkshire. This result should not be taken to suggest that mine water geothermal potential does not exist at locations outside the identified "optimal" footprint. The MiRAS does not preclude the necessity for specialist engineering and geological input during full feasibility study.

Supplementary material: Enlarged maps for each local authority area covered by the MiRAS are available at https://doi.org/10.6084/m9.figshare.c.7235866

Mine Water Geothermal Resource Atlas for Scotland (MiRAS) which can be found on the Improvement Service's Spatial Hub platform: https://www.spatialdata.gov.scot/geonetwork/srv/eng/catalog.search#/metadata/63ccefed-0165-461d-a5a5-025b0b2463c5

1. Introduction

Heating and cooling accounts for more than 50% of energy use in Scotland (Scottish Government, 2020c) but has not progressed significantly towards decarbonisation (Energy Saving Trust, 2021). Renewable sources comprised 6.4% of Scottish heating and cooling in 2020, failing to meet the target of 11% for the same year (Energy Saving Trust, 2021). Mine water geothermal (MWG) energy describes the practice of using groundwater stored in, or discharging from, flooded mines to satisfy surface heating and cooling demands (Banks, 2016, Banks *et al.*, 2004, Hall *et al.*, 2011, Jessop *et al.*, 1995, Ramos *et al.*, 2015, Walls *et al.*, 2021, Younger, 2016). The relatively low temperature of mine water (pumped mine water is typically between 10 and 20°C in the UK - Farr & Tucker, 2015; Farr et al. 2021) requires heat pump technology to upgrade thermal energy to usable space-heating temperatures for homes or industry (Athresh *et al.*, 2016). For cooling purposes, a heat pump may (active cooling) or may not (passive cooling) be required. The use of mine water as a thermal source or store is becoming increasingly popular but has had a slow overall uptake since its inception in the 1980s (Bracke and Bussmann, 2015). Global case studies are presented and discussed in Hall *et al.* (2011), Ramos *et al.* (2015) and Walls *et al.* (2021). Along with other forms of shallow and deep geothermal technology, MWG has the potential to contribute to the decarbonisation of heating and cooling demand; indeed, Gillespie *et al.* (2013) have estimated a potential Scottish mine water thermal resource of 12 GW_{th}.

There are several available configurations of MWG system, detailed in Banks *et al.* (2019) and Walls *et al.* (2021), depending on local factors such as presence of open shafts, existing discharges and treatment requirements, and mine water head. If mine water is discharging at the surface, either as a gravity discharge from a flooded, overflowing mine, or as a deliberate pumped discharge to dewater a mine or keep water levels under control, the discharged water can be simply passed through a heat exchanger coupled to a heat pump to extract heat, and the thermally depleted water discharged to a surface water recipient, often via a treatment system, depending on water quality. This concept is employed in Mieres, Spain (Loredo *et al.,* 2017, and Seaham, UK (Bailey *et al.* 2013; Wood and Crooks, 2020; Coal Authority, 2020). We refer to an existing mine water discharge as a "surface mine water resource" in this paper.

Another common configuration is "open loop with reinjection" (Banks *et al.,* 2019), where (i) mine water is pumped from a borehole or shaft in one location, (ii) heat is extracted from the mine water via a heat exchanger and heat pump, and (iii) the water is reinjected back to the mine system via a second borehole or shaft. This concept is employed in Heerlen, Netherlands (Verhoeven *et al.*, 2014), Gateshead, UK (Banks *et al.*, 2022), Springhill, Canada (Jessop, 1995, MacAskill *et al.*, 2015) and was formerly employed at Shettleston (Glasgow) and Lumphinnans (Cowdenbeath) in Scotland (Banks *et al.*, 2009). We refer to the potential for such a system as a "subsurface mine water resource" in this paper.

Compared with more conventional resources of shallow geothermal energy, mine water presents a number of specific challenges: ground stability issues in areas of shallow mines; verticality / directionality challenges of intercepting narrow (e.g. mine roadway) targets at great depth; expensive well construction (e.g. stainless steel) due to saline or corrosive environments, which increase substantially with depth; chemical fouling / scaling due to ferric oxyhydroxide precipitation from mine water; excessive pumping costs or difficulties with reinjection in cases where mine water levels are very deep or very shallow (or artesian), respectively (Townsend *et al.*, 2020; Walls *et al.*, 2021, 2023). In other cases, attractive mine water resources may be available, but heat demand in the locality may not be dense enough to justify capital expenditure on developing the resource (James Hutton Institute, 2016).

The benefits of being able to match mine water geothermal resources against maps of heating and cooling demands (Scottish Government, 2023) suggest the need for an "early stage" screening tool to identify the most promising locations for mine water geothermal development. It is the development of exactly such a GIS-based screening tool (Mine Water Geothermal Resource Atlas for Scotland – MiRAS), that this paper describes. The study has combined over 100,000 data points pertaining to coal (and other mineral – shale, limestone and ironstone) mines in Scotland (Table 1), relying heavily on The Coal Authority's (TCA) archive of digitised mine abandonment plans. MiRAS can be used in conjunction with maps of heating and cooling demand, such as the Scottish Heat Map (Scottish Government 2023a; heatmap.data.gov.scot) (or other datasets hosted by the Improvement Service on their Spatial Hub https://data.spatialhub.scot/), which shows heat demand from Scottish buildings alongside existing or planned heat networks and areas with high density social housing.

MiRAS has been tailored to find locations favourable for the "open loop with reinjection" mode of operation (Walls *et al.*, 2021). These require at least two boreholes completed into mine voids, where one abstracts, and one reinjects water. This mode of operation was selected since it is typically the configuration which can be scaled up to provide multi-megawatts of thermal energy, without causing major extensive changes in mine water head (Walls *et al.*, 2021). In order to achieve an acceptably long flow pathway (and thus subsurface heat exchange area) and to minimise the risk of thermal feedback between the subtraction and reinjection wells, it is often regarded as beneficial to complete the wells in two different worked seams (i.e. vertical separation as well as lateral). Since there is no net abstraction of water from the mine system, this mode of operation has few or no associated water treatment costs and there is no risk of long-term depletion of mine water hydraulic head.

It was intended that MiRAS should provide non-experts, planners and decision makers, together with consultants carrying out initial feasibility studies, with a “first-pass” high-level summary of the potential MWG resource located within their area of interest. It is acknowledged that MiRAS cannot replace the need for more detailed hydrogeological and mining geological feasibility at a later stage. It is emphasised that the MiRAS tool should not be regarded as a “final product” that cannot be modified, but rather as an approach which can be developed further as more data become available, and as mine water hydrogeology evolves (some mines are still in the process of hydraulic recovery following mine closure in recent decades). Moreover, some of the screening criteria applied in the current version of MiRAS may be regarded as somewhat arbitrary, but these can be modified as the needs and opinions of industry and users become apparent.

This paper presents the evolution of the MiRAS tool. It firstly describes the study area to which MiRAS has been applied (Section 2), and goes on (Section 3) to detail the GIS-based methodology – the data sets that form the foundation of MiRAS and justifications for the criteria that have been applied to screen out sub-optimal sites. Section 4 concisely presents the results (although these can be best viewed via the online MiRAS portal), and describes the “ground truthing” of the tool by examining MiRAS output at locations of empirically investigated geothermal potential. Section 5 evaluates the limitation of MiRAS and suggests possible avenues for future development.

2. Study Area

The study area spans the principal coalfields of the Midland Valley of Scotland (MVS). This is a large graben-like structure, bounded to the north by the Highland Boundary Fault and the south by the Southern Upland Fault (Cameron & Stephenson, 1985). It contains the cities of Edinburgh and Glasgow and also the catchments of the Rivers Clyde (flowing west) and Forth (flowing east). The Valley preserves a thick sequence of post-Caledonian-orogeny sedimentary rocks of Devonian and Carboniferous age, together with volcanic lavas and intrusive dolerite sills of similar age. The Carboniferous of the Midland Valley can be subdivided (Monaghan, 2014) into

- the Scottish Coal Measures Group (Westphalian age),
- the Clackmannan Group (Namurian and Visean age), which can further be subdivided into the Passage Formation, the Upper Limestone Formation, Limestone Coal Formation and the Lower Limestone Formation. These comprise deposits of shelf carbonate, fluviodeltaic and deltaic facies.
- the Strathclyde Group (Visean age), which hosts the West Lothian Oil Shale Formation.
- the Inverclyde Group (Visean)

The majority of the workable coal seams are hosted by the fluviodeltaic sediments of the Westphalian Scottish Coal Measures and the Namurian Limestone Coal Formation. Laterally, the worked coal deposits can be subdivided into the Central, Ayrshire, Lothian, Fife, Sanquhar, and Douglas coalfields (Fig. 1). The coals have been worked for many centuries but especially in the 19th and 20th Centuries. The last mines to be closed were Frances (Fife, in 1995), Monktonhall (near Edinburgh, in 1998) and the very extensive Longannet complex (Fife, in 2002). Following abandonment, dewatering pumping typically ceased and mine water heads recovered over the course of the subsequent years. Rising mine water levels have often been controlled by continued pumping (and water treatment at surface) on the part of the Coal Authority to prevent uncontrolled surface breakout (e.g. at Frances, Blindwells and Polkemmet; Chen *et al.,* 1999; Nuttall and Younger, 2004; Younger, 2012; Wyatt *et al.,* 2014; Zebec Biogas, 2022). In some coalfields, the process of rebound is still underway (e.g. the Midlothian coalfield, where mine water is breaking out near Dalkeith – Jackson, 2022).

Scottish mine water blocks were found to have mean geothermal gradients of 29.8 ºC/km in Central Scotland, 26.8 ºC/km in Ayrshire, 24.2 ºC/km in Lothian, 22.2 ºC/km in Douglas and 21.9 ºC/km in Fife (Farr *et al.*, 2021).

3. Methodology

3.1 Data Sources

In this study, six datasets were compiled, as summarised in Table 1 and discussed below. Datasets 1-4, on the geometry of mine workings and monitored mine water head, were obtained from TCA.

Dataset 1 - Underground workings

The "Underground working" vector dataset consists of 2-dimensional polygons that represent the geographical extent of underground mine workings (mostly coal, but the dataset also includes some Carboniferous limestone, oil-shale or ironstone workings associated with the coal-bearing strata), georeferenced and digitised from the comprehensive collection of mine abandonment plans hosted by TCA. The data set was originally created by TCA for automated provision of coal mining reports on ground stability and potential mining hazards (Tipper, 2015b). The geographical accuracy of this data set will be affected by human error during original surveying (which is likely to decrease with time as surveying methods became more standardised and accurate), and possible inaccuracies introduced when georeferencing the paper plans for digitisation. It is also accepted that not all mines in Scotland are recorded: the age of the first workings (12th century) greatly pre-dates legislation to ensure documentation (1870s - Younger and Adams, 1999), leaving some shallow mines undocumented. Mine abandonment plans in the UK became more reliable, and of uniform quality after nationalisation in 1946. Whilst the polygons in this dataset define the areal extent of mined coal seams, they do not show any detail concerning the layout of shafts, roadways or individual worked panels, which may influence preferred locations for drilling and accessing mine water. Moreover, they do not distinguish between collapsed longwall panels and pillar and room workings, the latter being more likely to be hydraulically open. This data set does not contain explicit elevation data (elevation data is contained in Dataset 3).

Dataset 2 - Shallow workings

The "Shallow working" vector dataset consists of 2-dimensional polygons that represent worked portions of mined seams within 30 metres of the surface. TCA created this derived dataset by extraction from the "Underground working" shapefiles and keeping only portions of polygons that were within 30 m of the surface (although the surface model from which the depths were extracted is not recorded). The uncertainties inherent in the "underground working" shapefiles are carried over, and many old shallow workings are likely to be absent from the dataset, since they predate mandatory documentation.

This data set does not contain explicit elevation data, other than the fact that they are < 30 m from the surface (elevation data is contained in Dataset 3).

Dataset 3 – In-seam level

The "In-seam level" dataset comprises of a series of points in longitude (X)-latitude (Y) space, each associated with an elevation (Z) of the seam, relative to Ordnance Datum (OD, or mean sea level). These spot elevations are digitised directly from original abandonment plans, and the spatial accuracy is subject to the same challenges as the previous two datasets (surveying and georeferencing errors), as well as potential typographical errors and errors in conversion to metric units. The information in the dataset is not uniformly distributed, and some areas have sparse "In-seam level" points.

Dataset 4 – Monitored mine water head

The mine water head (i.e., piezometric head within mine void aquifers) was obtained for each of TCA's monitoring stations (typically shafts or boreholes; n=48) in the Midland Valley of Scotland. These are point data (X,Y) with associated elevation (Z) values representing water head in m relative to OD. Georeferencing of these features (X,Y) is highly accurate and the mine water head readings have accuracies of 0.01 m. The spatial distribution of the monitoring stations is uneven: for example, there are many monitoring points in Lothian and Fife, but few in the Central or Ayrshire coalfields. Mine water levels can change significantly over time; they can vary diurnally (tidal response), seasonally, in response to pumping within the mine system, or (especially) during post-closure mine flooding. The TCA mine water head data used in this study to create Dataset 4 were derived from Autumn 2021 (i.e. current data at the time of this study).

Dataset 5 – Mine water discharge locations

The mine water discharge locations (n=81) are X and Y coordinates where water drains from coal mine workings under gravity. Locations were recorded using a GPS device during field work in November 2021 and published by Walls *et al.* (2022). The accuracy of the X and Y values is related to GPS error, which is usually ±3 m. The dataset is not exhaustive; there remain other unmonitored discharges in the MVS which were not captured as part of this research. Dataset 5 was used to provide another indicator of mine water head, which could be combined with Dataset 4. For Dataset 5, it is assumed that, at the location of the discharges, the mine water head is effectively at the elevation of the ground surface. The elevation (Z) value for each of the discharge locations was extracted from the Digital Terrain Model (DTM, Dataset 6) for each of the mine water discharge locations in Dataset 5.

Dataset 6 - Digital terrain model

The digital terrain model (DTM) was compiled from 370 tiles of Ordnance Survey Terrain 5 at scale 1:10,000, July 2021 version. The raster tiles are 5 km by 5 km with 5 m spatial resolution. The elevation data has a root mean square error (RMSE) of 1.5 m for Urban areas, and 2.5 m for rural, moorland and mountainous areas (Ordnance Survey, 2017).

3.2 Screening criteria

For this study, four screening criteria were employed to identify the most promising locations for abstraction-injection well doublet exploitation of mine water geothermal. In theory, other screening data could be employed in future improvements of the tool if reliable data were available: these will be discussed later. The criteria have been implemented by manipulating the layers represented by Datasets 1- 6 in a GIS (ArcGIS by Environmental Systems Research Institute, Inc., Redlands, California, USA) environment (Fig. 2).

Criterion 1 - Areas with overlapping mined seams

Rationale

For the development of an abstraction-injection well doublet, placing both wells into the same worked seam risks very rapid breakthrough of reinjected water (cool water, if the scheme is used for heating purposes) in the abstraction well, unless there is very significant horizontal distance between the wells (Loredo et al. 2017a, 2018), or some form of thermally attenuating barrier between the wells (e.g. goaf). It is regarded as beneficial if the abstraction and reinjection wells can be developed in different worked seams, thus achieving long, tortuous flow pathways by stratigraphic, rather than lateral separation. It is a philosophy that has been employed at mine water geothermal schemes in Gateshead (Banks et al., 2022; Adams et al., 2023, Triple Point Heat Networks, 2023). Some city-wide mine water district heating and cooling networks are not constrained to a single plot of land, and have thus been able to achieve both stratigraphic and lateral separation (e.g. Heerlen, Netherlands, Verhoeven *et al.*, 2014). In the case of many small-medium projects, however, the developer may be constrained to a relatively limited plot of ground.

Implementation

Dataset 1 was analysed to determine the number of overlapping polygons across the study area using the processes outlined in the flow diagram of Fig. 3. By this means, all areas where there were >1 worked seams (mostly coal, but some oil shale, limestone and ironstone workings are included in Dataset 1) below the surface were identified (Fig. 4). Areas with none or a single worked seam only were rejected as unpromising for MWG.

Criterion 2 – Absence of shallow workings

Rationale

Areas underlain by shallow mined workings may be subject to a subsidence or ground instability risk (The Coal Authority, 2017). Drilling, pumping and reinjection operations could conceivably enhance this risk. For example, rising mine water head levels can result in mm-scale uplift across coal workings which may induce deformation at pillar edges. This process, along with thermal oscillations may induce localised collapse (Todd *et al.*, 2019). While the actual zone of collapse and compression above a longwall seam is variable and is a function of the width of the panel (Younger and Adams, 1999), a commonly used ‘rule of thumb’ states that for every meter of coal abstracted, 10 m of overlying rock is potentially affected by subsidence (Bell, 1986, Healy and Head, 1984). Given that the UK hosts some coal seams greater than 2 m thick, with roadways possibly around 3 m, a 30 m value is suggested by TCA as ‘at risk shallow workings’ (Abbate, 2016). The presence of shallow voids may also give rise to issues of loss of drilling flush when drilling through them to access deeper horizons. Moreover, shallow workings may already have been grouted for stability, or require future grouting prior to development, and are hence unsuitable as a geothermal resource as void spaces become filled.

Implementation

Once overlapping seams were identified, Dataset 2 was used to exclude from MiRAS areas where there are shallow (<30 m depth) workings below the surface (Fig. 3). The resulting polygons were rasterised in preparation for combination with rasters from other criteria. Fig. 4

shows locations associated with Criteria 1 and 2 – multiple overlapping worked seams, where shallow workings are not present.

Criterion 3 – Optimal depth of mine water head

Rationale

Mine water head is not inherently linked to the depth of worked coal seams; for example, at the UK Geo-Energy Observatories (UKGEOS) site in Glasgow a static mine water head of 0.5–3 m below ground level (bgl) is recorded in mine workings of c.45 - 85 m depth bgl (Palumbo-Roe *et al.*, 2021). It is, of course, possible that shallow worked seams are dry in areas with a deep mine water level and it may even be the case locally that perched water tables exist in shallow, poorly connected mine systems.

However, depth to mine water head is a crucial factor when considering the environmental risk, engineering and cost effectiveness of a MWG system. Firstly, the energy expended for pumping (and, thus, monetary pumping cost) is directly proportional to the pumping head depth. In their analysis, Athresh *et al.* (2015) found that for 50 L/s, a pumping head of 10 m bgl gives annual pumping costs of £3700, compared to £37,000 for a head at 100 m bgl. In terms of energy, assuming a pump efficiency of 55%, the first scenario would expend around 9 kW power, the second would expend 89 kW. The latter figure would probably represent an unacceptable pumping power expenditure to recover a thermal resource of maybe 1 MW_{th} from 50 L/s discharge.

Thus, deep mine water heads are disadvantageous from an energy and cost perspective. Large pumping heads will also require larger and heavier pumps, which will require greater engineering costs and possibly greater borehole diameters. Very shallow groundwater heads can also be disadvantageous; reinjection will cause heads to rise in the injection borehole (Banks *et al.*, 2022), possibly requiring pressured well heads and management of groundwater flooding risk around the wellhead. Reinjection operations with shallow groundwater heads also bear the risk of unexpected mine water emergence from old shafts and adits.

Implementation

Points from Dataset 4 (mine water levels from TCA onservation shafts and boreholes) were combined with locations of mine water breakout at the surface (Dataset 5), to create a data set of geolocated (X,Y) points, each associated with a mine water head (Z). This was then used to create a mine water surface elevation layer (Fig. 5). Empirical Bayesian Kriging

(Matheron 1960, Chung et al., 2019) was used to interpolate the mine water head between real data points as the weighted average of surrounding points. The Kriging equation determines a weighting factor for each of the influencing points to minimize variance. It produces a surface which is the best linear interpolation for the available data. As a result, it lacks local or small-scale heterogeneities that could be present in the real potentiometric surface. The accuracy is more reliable in locations where there is a greater density of control points (e.g., East- and Mid-Lothian), and less so where points are few and distal. The resulting raster has been clipped to the extent of Carboniferous mined strata in Scotland, and the vertical difference between it and the surface level (DTM) was calculated. This formed a '*depth to mine water head (m bgl)*' raster layer (Fig. 6), with calculated depths to mine water head mapped in 10 m increments; shallower values (0 m – 20 m bgl) are shown in shades of pink and deeper values (20 m - 60 m bgl) in shades of blue. The raster was clipped to exclude depths greater than 60 m bgl. This depth cut-off is admittedly somewhat arbitrary, but a static water level of 60 m bgl could easily lead to pumping water levels of 80-100 m bgl and thus large parasitic power pumping losses. Thus, the blue shaded zone represents a zone of (in the authors' opinion) optimal mine water heads for both pumping and reinjection. The pink zone represents shallow mine water heads, where difficulties with reinjection may be experienced (but where an operator may want to consider treatment and discharge to a surface water - Walls *et al.*, 2021). Fig. 6 also shows areas where the mine water head is predicted to be above ground level - this interpretation may be "real" and represent an area characterised by mine water discharge. Due to interpolation errors, it is arguably more likely that these simply represent "very shallow mine water".

Criterion 4 – Mined seams not excessively deep

Rationale

Drilling deep geothermal boreholes at large diameters for a suitable pump is very costly in the UK; especially if materials are required (e.g. stainless steel casing) to resist the corrosive (saline, reducing, warm, H_2S-rich) environment prevalent in deep mine workings (Banks et al., 2022). Predictions of drilling costs performed by TownRock Energy (not available in the public domain) have indicated that drilling cost per metre increases significantly beyond 250 m, largely due to the higher mobilisation cost and day rate for a suitably large drill rig (pers. comm., J. Diamond, 2022). A 250 m depth "cut-off" is admittedly somewhat arbitrary and does not imply that projects deeper than 250 m are unfeasible (e.g. Heerlen, Netherlands, Verhoeven *et al.*, 2014). This cut-off was selected to meet the original intention of this study: to identify the economically and technically optimal areas for MWG. One could of course argue that increased mine water temperature with depth could justify deeper drilling, although preliminary analysis (Banks, 2023) suggests that this may not be the case in an economy where drilling is costly the value of heat is relatively low. For an MWG system coupled to a heat pump, the controlling factors for heat delivery are temperature change at the heat exchanger (ΔT) (Banks, 2012) and flow rate (Bailey *et al.*, 2016). A higher minewater temperature would allow a greater (ΔT) or a modestly improved heat pump coefficient of performance.

Implementation

"In seam level" point values (Dataset 3) were converted from m OD to metres bgl by subtraction from surface level estimates derived from the DTM (Dataset 6). The resulting "depth to worked seam" (m bgl) points were assigned different symbols depending on whether they were ≤250 m bgl, or > 250 m bgl (Fig. 6). This was converted to a raster surface by kriging. Inverse Distance Weighting (IDW) was used, whereby values are calculated using a weighted average of the nearest points. The weights are proportional to the inverse of the distance between the data point and the prediction location raised to the power of two. As a result, as the distance increases, the weights decrease rapidly and thus, only the 12 nearest points were considered for each IDW. In areas where multiple seams are worked (Criterion 1), there can be depth differences of tens of metres or more between the various worked seams. If, within a given area, a grouping of mine workings has elevation points above and below the 250 m bgl cut-off, the weighted average produced by the IDW raster layer dictates whether the area is deemed above or below the cut-off.

The MiRAS aims to identify optimal MWG areas based on expected overall project cost and risk. Criteria 1 and 2 aim to mitigate project risk; Criteria 3 minimises operational expenditure (OPEX) while Criterion 4 minimises capital expenditure (CAPEX).

3.3 Combination of Rasters to Produce MiRAS

The raster layers from criteria 1-4 (C1-4) were combined to form a final raster layer. The 'raster calculator' tool was used to find areas which met all of the study optimisation criteria. The algorithm used was as follows:

- IF location has multiple overlapping worked seams AND has no shallow workings <30 m bgl, THEN assign value C[1,2] = 1, ELSE assign value C[1,2] = 0.

- IF depth of mine water head > 60 m, THEN assign value C3 = 0, ELSE assign value C3 = “depth to mine water” (in 10 m increments to 60 m bgl).
- IF depth to workings ≤ 250 (m bgl), THEN assign value C4 = 1, ELSE assign value C4 = 0

$$Raster\ Output = C[1,2]\ (1\ or\ 0) \times C3\ (value\ of\ depth\ m\ BGL) \times C4\ (1\ or\ 0)$$

Equation 1.

Equation 1 has thus generated a value representative of the predicted mine water head only where there are overlapping seams at an average depth of less than 250 m bgl, with no shallow workings present.

3.4 Addition of surface (gravity and pumped drainage) resources

Walls *et al.* (2022) reviewed the occurrence of “at surface” mine water thermal resources: i.e. either:

- locations where mine water drains at the ground surface from flooded mine workings via old shafts, adits, boreholes or fractured ground (gravity drainage), or
- shafts or boreholes which are actively pumped, usually by the Coal Authority, in order to maintain mine water heads at a given level below ground surface and prevent mine water flooding. These locations are often combined with mine water treatment facilities to remove unwanted solutes (typically iron) prior to discharge to surface water courses.

This point data set has been overlaid on the MiRAS raster layers to provide an integrated MWG resource map. An indicative thermal magnitude of the surface MWG resource (G) is calculated according to Equation 2:

$$G = Q \cdot \Delta T \cdot S_{VCwat} \qquad \text{Equation 2}$$

G = heat available (kW), which is a function of

Q = water discharge rate (pumped or gravity) (L/s),

S_{VCwat} = volumetric heat capacity of water (kJ/L/°C)

T_{MW} = measured temperature of mine water discharge (°C),

ΔT = nominal temperature change across a heat exchanger (Bailey *et al.*, 2016), which is taken to be (T_{MW} – 6°C). 6°C is taken to be the nominal temperature of thermally spent water exiting a heat exchanger.

The surface MWG resources are symbolised corresponding to their origin, e.g., existing treatment schemes (active, passive; gravity fed or pumped) and the symbol size is related to magnitude of *G*.

4. Results

4.1 MiRAS optimal subsurface resource maps

Table 2 and Fig. 8 show the outputs of the MiRAS GIS-based methodology as areas of the Scottish Midland Valley which are judged optimal for mine water geothermal exploitation, by means of abstraction-injection well pairs, based on the following criteria:

- overlapping seams, without shallow workings
- mine water head between 0-60 m bgl
- average depth to workings less than or equal to 250 m bgl

Cumulatively, there is a total of 370.3 km^2 across 19 local authority areas which are judged optimal for MWG development (Table 2). North Lanarkshire comfortably hosts the largest optimal area of 90.9 km^2. The Supplementary Material contains output for each local authority area, or the output can be viewed online at

https://www.spatialdata.gov.scot/geonetwork/srv/eng/catalog.search#/metadata/63ccefed-0165-461d-a5a5-025b0b2463c5

or added to the Spatial Hub preview map:

https://maps.spatialhub.scot/data_preview_map/

In Fig. 8, optimal areas for MWG are shown, with the colour scheme corresponding to the predicted mine water head. The most densely populated area with MWG potential stretches between SE Glasgow, Wishaw and Airdrie (see Fig. 9), with mine water heads largely 0 – 20 m bgl. Other optimal sites, with mine water heads at 20 – 60 m bgl, are primarily located beneath densely populated centres including Ayr, Kilmarnock, Bathgate, Stirling, Alloa, Cowdenbeath and Lochgelly, together smaller clusters of towns in Midlothian, East Lothian, and along the Fife coast to the NE of Kirkcaldy.

4.2 Integration of surface MWG resources

Fig. 10 shows an example of the locations of surface MWG resources (gravity mine water drainage or mine water pumping stations), overlaid on the MiRAS raster maps. Their label number for the surface MWG resources corresponds to the reference number in the supplementary material of Walls *et al.* (2022). Specifically, Fig. 10 shows the western extent of the East Lothian local authority area, hosting Blindwells treatment scheme (#3 from Walls *et al.* (2022)): a surface MWG resource with an estimated $G = 6.9$ MW$_{th}$ heat availability. It is regarded as the most promising mine water geothermal resource in Scotland (Bailey *et al.*, 2016, Walls *et al.*, 2022, Younger, 2012), being in proximity to urban areas and extensive local development plans (Optimised Environments Ltd., 2020)..

This type of map allows the identification of Local Authorities with the greatest potential for MWG (Table 3). North Lanarkshire comfortably hosts the largest area of subsurface MWG resource, suitable for abstraction-injection well doublets, at 90.9 km^2. The Local Authority areas of Fife, East Lothian and West Lothian have the highest heat availability via existing surface gravity or pumped discharges, largely due to them hosting three of the largest Coal Authority pumping and treatment schemes (Frances, Blindwells and Polkemmet, respectively: Chen *et al.,* 1999; Nuttall and Younger, 2004; Younger, 2012; Wyatt *et al.,* 2014; Zebec Biogas, 2022) which represent a combined thermal resource of 14.4 MW$_{th}$.

4.3 Ground-truthing MiRAS

MiRAS output for locations of three recent mine water geothermal systems or research sites has been compared with empirical findings from those sites, to provide some quality assurance that MiRAS is indeed producing realistic output in mine void depth, mine water depth and geothermal potential.

Shettleston, Glasgow

The Shettleston Housing Association (SHA) mine water geothermal system operated for c. 20 years from 1999 in eastern Glasgow (4.1668 W, 55.8504° N) (Banks *et al.*, 2009, Walls *et al.*, 2021). It was a relatively small abstraction-injection doublet scheme operating between two different stratigraphic horizons. Although the Shettleston area has portions which meet all four MiRAS criteria, the exact location of the abstraction and reinjection boreholes does not meet all the criteria (Fig. 11, 12); specifically, it fails Criterion 1 (presence of overlapping seams). This conforms with the findings of Banks *et al.* (2009) and Banks *et al.*

(2019) who suggest that the abstraction borehole is likely completed into the workings of the Ell Coal Seam of Westmuir Pit (dating from 1845–1862), but speculate that the reinjection borehole may have been completed into unworked Coal Measures strata. It should be noted that the workings date from before the mandatory requirement to record mine workings (Younger and Adams, 1999), and thus some coal workings may be erroneously mapped or unmapped. The mine water head at Shettleston is predicted by MiRAS to be 0-10 m bgl. This is very close to the head of 12-13 m bgl recorded in 2016 beneath SHA (Walls *et al.*, 2020). This data point was not used to construct the MiRAS mine water head surface, due to its early date.

UKGEOS, Cuningar, Glasgow

The UK Geo-Energy Observatories (UKGEOS) Cuningar site is also located in eastern Glasgow (4.2008° W, 55.8383° N), and is a research facility for monitoring, testing and innovation of mine water geothermal energy systems (Monaghan *et al.*, 2021). It is extremely well documented and is underlain by seven worked coal seams from the Farme Colliery dating between 1805 and 1928 (Findlay, 2020). There are 5 boreholes which intersect mine workings of the Glasgow Upper and Glasgow Main coal seams (Monaghan *et al.*, 2019). The static mine water head (0.5 m to 3 m bgl) from UKGEOS was used as a datapoint to construct the MiRAS mine water head interpolation. There are no shallow worked coal seams (<30 m) at UKGEOS and the highest seam is c. 45 m bgl. MiRAS correctly identifies the Cuningar site as an optimal location for an abstraction-reinjection MWG system, although the shallow mine water head would need to be carefully managed to avoid mine water breakout during reinjection (Fig. 13).

Dollar, Clackmannanshire

The Dollar site (3.662° W, 56.165° N,) was researched by Walls *et al.* (2023) to evaluate whether ground stability investigations could be combined with data collection on mine water geothermal potential. The site has four seams worked during the last few centuries with the most recent workings forming part of the Dollar Colliery in 1950s and 60s. The depths range from surface outcrop to 50 m bgl, extending to greater depths north of the site in a small, isolated syncline. A mine water discharge from the colliery was used as a controlling data point for the mine water head interpolation (Criterion 3); thus, MiRAS represents the mine water head in Dollar Colliery with good accuracy. The terrain rises steeply north of Dollar colliery, and the mine water head thus becomes deep within a short distance of the discharge. Since much of the site is underlaid by shallow workings (<30 m bgl) or single worked coal seams (Fig. 14), MiRAS only shows a small fraction of the site with overlapping workings which satisfies all four criteria for optimal MWG exploitation (Fig. 15).

5. Discussion

The identification of optimal sites for mine water geothermal energy systems is a first step towards increasing uptake of the resource across Scotland. It is recognised that MiRAS is not a perfect interpretation of subsurface conditions, but it does provide an excellent tool for stakeholders and decision makers, allowing rapid screening of any site across the MVS for its mine water geothermal feasibility.

5.1 Future factors for consideration

The feasibility of a MWG site is influenced by more than the four criteria generated in this study, although these are seen as the principal factors. Other controlling "geofactors" were identified which could conceivably be added into a subsequent version with a multi-criteria evaluation technique are:

1. Mine water temperature. Farr *et al.* (2021) have demonstrated that mine water temperature, at least under static conditions, is related to depth. Thus, the "depth of working" information on which MiRAS is based could be used as a proxy to predict mine water temperature. Implementation of this would require careful consideration when dealing with multiple worked horizons as, given multiple worked seams, groundwater could be abstracted from a deeper seam and reinjected to a shallower (to maximise abstraction temperature) or vice versa (to minimise risk of uncontrolled mine water surface emergence). Temperature is thus a three-dimensional variable that would be challenging to represent in a two-dimensional tool such as MiRAS. Moreover, it must be recognised that mine water temperature could potentially change once an MWG scheme becomes operational and mine water actively starts to circulate within workings.
2. Mine water hydrochemistry. Walls *et al.* (2022) have compiled a thorough overview of mine water chemistry from a number of surface discharges of mine water throughout the MVS. Mine water chemistry can be highly influential in the

operational cost or long-term sustainability of an MWG scheme, High concentrations of dissolved iron can lead to clogging of wells, pipes or heat exchangers with ferric oxyhydroxide, while highly reducing, H_2S-rich saline waters can lead to corrosion risk, even of some stainless steels. Unfortunately, it is recognised that mine water hydrochemistry can be highly stratified, with both iron-rich, incrusting mine water and saline, reducing, corrosive mine water existing at a single site, within different mined horizons (Banks *et al.*, 2022). Such a complex three-dimensional variable, such as hydrochemistry cannot thus be readily represented in a two-dimensional tool such as MiRAS, and the hydrochemical data collated by Walls *et al.* (2022) may not be a good guide to hydrochemistry at depth.

3. Type of working. It is recognised that mine water geothermal exploitation requires different exploration strategies in different types of workings. For example, in old pillar and stall workings, the accuracy of old plans may not allow the reliable targeting of voids; rather, a statistical approach might be needed (e.g. 50% chance of success if the void to pillar ratio is around 1:1). In more modern longwall workings, it may be more appropriate to target either access roadways to longwall panels, or fractured / collapsed zones above longwall workings (Andrews *et al.*, 2020). Coal Authority data does contain information on dates of working of seam sections. Dates of working, possibly combined with an interpretation of working geometry, might conceivably used to estimate the likely method of working (pillar and stall, total extraction, longwall panels), although there was considerable overlap of working methods throughout time, and geometric interpretation would be time-consuming.
4. The plotting of existing open mine shafts, which might provide access to workings (for example, as one pole of a doublet) without the additional cost of drilling, or which might be used as “standing column” heat exchange systems, where water circulation takes place within a single shaft (as described by Burnside *et al.* 2016 at Markham, Derbyshire, UK). While the Coal Authority does possess knowledge of the state of backfill / openness of some shafts, the state of many others in not documented with certainty.
5. Annual rainfall and surface topographic gradient, could be incorporated into MiRAS as proxies for hydraulic gradients and throughflow rates in mine workings.
6. Regular updating of mine water head surface. Dataset 4 (monitored mine water head) was a “snapshot” of mine water head data held by the Coal Authority in

Autumn 2021. While post-abandonment mine water levels have largely recovered across the Midland Valley of Scotland, there are still some mines where recovery is in progress. There are other locations where head may be affected by variations in Coal Authority pumping regimes. Ideally, Dataset 4 within MiRAS should be updated every c. 5 years to reflect possible systematic temporal changes in head.

Moreover, the Coal Authority do possess other data sets which have not been incorporated into this version of MiRAS, but could be included in future versions. For example, the Coal Authority hosts:

- a more extensive polygon layer which shows "Probable shallow workings" – i.e., areas where coal was present at shallow depths and TCA believe that working was likely prior to mandatory plans. This could feasibly be used to supplement Dataset 2 (known "Shallow workings").
- an "In-seam contour" data set, derived from mine plans where seam elevations have been contoured. This could be used to supplement Dataset 3 ("In-seam level").

Uncertainties and Limitations

The results should be viewed in the light of some data source limitations and wider MWG considerations pertaining to the development of these resources. Some of these limitations and uncertainties are as follows:

1. **Data density.** In some areas, a low density of data points in some locations leads to inherent uncertainty in interpolated data, especially in the case of predicted mine water head.

2. **Number of overlapping seams.** MiRAS at present merely flags locations where multiple worked seams are present, it does not indicate whether two seams overlap, or a greater number.

3 **Areal size of mine water resource.** MiRAS indicates areas where four specific MWG criteria are satisfied. In some cases, these areas may be quite small and may give the impression of a very limited geothermal resource. In some cases, however, such limited areas may be hydraulically linked to much more extensive areas of mine workings where, for example, only two or three of the criteria are satisfied, but which

may for part of a larger mine water resource. Clearly, MiRAS should not be understood as a "resource map" *per se*, but as a map indicating locations where a resource can be optimally accessed via drilling. For example, in the case of Dollar only a small area meets all four MiRAS criteria (Fig. 15), but the extent of interconnected flooded workings forming the resource (Fig. 14) is considerably larger.

4. Exclusion of very shallow and very deep workings. The MiRAS concept might be criticised on the grounds that the "depth of workings" cut-offs for shallow (<30 m deep) and very deep (>250 m) are somewhat arbitrary. Indeed, the relatively shallow workings of Dollar colliery (Fig. 14 and 15) have been described in detail by Walls *et al.* (2023), who indicated that there might indeed be some potential for limited MWG development at the site, although that this should be in coordination with ground stability (and possible future ground stabilisation via grouting) assessments. Others (Farr *et al.* 2021) have pointed out that the highest mine water temperatures typically occur in the deepest workings and that these might be regarded as the most attractive prospects. In this paper, we have argued that exploration for and exploitation of such deep resources comes with significantly elevated exploration and drilling costs, and also with potentially undesirable (saline and highly reducing) mine water chemistry. The authors do, however, recognise that the "cut-off" at 250 m is arbitrary and might be revised in future iterations of MiRAS if drilling costs fall and if understanding the resources exploitation in deep workings improves.

5. Focus on newly drilled, single well doublet systems. It is acknowledged that MiRAS assumes that the most likely MWG exploitation methods will be via newly constructed borehole doublets drilled into different worked seams at a single location, or in close proximity. There are other methods of MWG exploitation, which MiRAS does not explicitly consider. Amongst these are: (i) single borehole(s) for abstraction only, followed by heat exchange, water treatment and disposal to a surface watercourse; while technically feasible, it is assumed that these will be unattractive on grounds of ongoing treatment cost. (ii) abstraction – injection doublets, but at widely spaced locations, as is implemented at Heerlen (Netherlands); such systems are undoubtedly attractive, but the ownership of widely spaced land parcels and access to a pipeline corridor between them is likely to require development by a regional authority (such as a Council or municipality). (iii) standing column solutions, where water is circulated only within a single mine shaft or borehole, of the type described by Burnside *et al.* (2016) at Markham, near Bolsover, Derbyshire.

MiRAS provides a valuable first-pass screening tool for interested individuals prior to, or at an early stage of project development. It cannot, however, replace the necessary expertise required for development of a MWG system. It contains little internal detail on mined areas it cannot be used to identify exact borehole locations, probable underground flow pathways or resource size. Successful project development requires integrating skills of hydrogeologists, mining engineers, chemists, HVAC and buildings services engineers, economists and planners (Walls *et al.*, 2021). Successful design and development of MWG requires a good understanding of underground flow pathways to ensure a sustainable system and to mitigate the risk of thermal "feedback" and depletion. The risk of thermal feedback is present in open loop doublet MWG systems that are heavily dominated by either heating or cooling provision (MacAskill *et al.*, 2015). Modelling techniques are available to identify and predict the rate and timing of thermal feedback (Ghoreishi Madiseh *et al.*, 2012; Loredo *et al.*, 2016, 2017a, 2018; van Hunen *et al.*, 2022). However, there is increasing recognition that development of mine water-coupled heating and cooling networks where there is a long-term balance between heat extraction and heat rejection, which use mines as a thermal buffer (Fraser-Harris *et al.*, 2022, Verhoeven *et al.*, 2014) or which use mines for underground thermal energy storage (UTES) would ultimately more likely to be sustainable. Specialist hydrochemical and water quality engineers are also required to design wells, pipe systems, heat exchangers and maintenance programs that minimise the risks of clogging and corrosion. While district heating and cooling networks will require a certain density of demand to be viable (which can be problematic in rural areas, James Hutton Institute, 2016; Harnmeijer et al., 2017), recent requirements for local authorities to consider Heat Network Zones can only encourage consideration of innovative regional environmental thermal resources (Scottish Government, 2023b; DESNZ, 2024).

Surface mine water (gravity or pumped) discharges, where no reinjection of "thermally spent" water is undertaken, are at little risk of thermal feedback and can thus be exploited in strongly heating- or cooling-dominated modes to satisfy potentially large heating and cooling demands (Coal Authority, 2020; Wood & Crooks, 2020). The water will usually require treatment prior to discharge to surface water (Banks et al. 2019), however, and consideration should be given to temperature changes (due to heat extraction or rejection) impacting the efficacy of treatment processes or the ecology of recipient water bodies (SEPA, 2016, 2022).

6 Conclusions

Data on abandoned mines in the Midland Valley of Scotland, and the waters they contain, has been compiled from The Coal Authority and Walls *et al.* (2022). These data have been combined with surface elevation data from the Ordnance Survey to create a Mine Water Geothermal Resource Atlas for Scotland (MiRAS). The data sets were processed in a GIS environment to produce interim GIS layers which show locations where:

1. there exist overlapping worked coal seams;
2. there are no shallow (<30 m bgl) workings which might adversely affect ground stability;
3. mine water head is within 60 m of the surface (as predicted by kriging mine water elevation points);
4. depth to mine workings is less than 250 m.

The four criteria were combined, and the resultant map indicates an area of 370.3 km^2 optimal for mine water geothermal development. These optimal areas can be found throughout the Midland Valley of Scotland, with the greatest footprint of potential sites in North Lanarkshire.

Ground-truthing of the MiRAS tool at three sites (Shettleston, Cuningar and Dollar), where mine water geothermal resources have been exploited or researched in great detail via intrusive ground investigation, indicates that MiRAS does indeed give a representative “first pass” indication of MWG potential, lending confidence in its utility as a screening tool.

The MiRAS allows areas to be screened for mine water geothermal (MWG) potential, speeding up project initiation and empowering potential “champions” of mine water geothermal energy. Areas which are denoted for residential, industrial or commercial development in local plans can be cross-referenced with the MiRAS, to understand whether or not MWG is a potential thermal supply. It is envisaged that this new means of rapid site appraisal will prove to be a useful tool for local authorities, landowners, and other stakeholders when exploring low-carbon heating opportunities and as a result, expand the awareness and increase the uptake of MWG resources. Future versions of the MiRAS could be expanded to include other factors, such as water chemistry or depth intervals, and have its impact improved by coupling to databases of regarding current and future heating and cooling demands. MiRAS cannot, however, replace the need for subsequent detailed technical specialist involvement in the design and development of MWG.

Acknowledgements

The authors would like to thank The Coal Authority for provision of datasets which were invaluable to this study. We extent our thanks to the Improvement Service for hosting the resultant Mine Water Geothermal Resource Atlas for Scotland online.

Funding

N.M.B is funded by a University of Strathclyde Chancellor's Fellowship. A.J.B is funded by the NERC National Environmental Isotope Facility award at SUERC (NEIF-SUERC, NE/S011587/1). Part of the analysis was funded by the John Mather's Rising Star Award.

References

Abbate, Z., 2016, User Guide For the Coal Authority Shallow Workings Dataset, p. 12,

Adams, C., Gordon, J. & Parker, K. (2023). The Gateshead mine water heat scheme. Presentation to the Society of Petroleum Engineers, Geothermal Seminar 2023 "Realising The Ambition", February 2023, Aberdeen, UK. https://www.spe-aberdeen.org/uploads/1115-SPE-Aberdeen-Feb23-Adams.pdf

Andrews, B. J., Cumberpatch, Z. A., Shipton, Z. K., and Lord, R., 2020, Collapse processes in abandoned pillar and stall coal mines: Implications for shallow mine geothermal energy: Geothermics, v. 88, p. 101904, https://doi.org/10.1016/j.geothermics.2020.101904.

Athresh, A. P., Al-Habaibeh, A., and Parker, K., 2015, Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System: Energy Procedia, v. 75, p. 1221-1228, https://doi.org/10.1016/j.egypro.2015.07.162.

Athresh, A. P., Al-Habaibeh, A., and Parker, K., 2016, The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment: International Journal of Coal Geology, v. 164, p. 69-76, 10.1016/j.coal.2016.04.015.

Bailey, M.T., Moorhouse, A.M.L. and Watson, I.A. (2013). Heat extraction from hypersaline mine water at the Dawdon MineWater Treatment Site. In "Mine Closure 2013", Proceedings of the Eighth International Seminar on Mine Closure, Cornwall, England, 18–20 September 2013; Australian Centre for Geomechanics: Perth, Australia, 2013; pp. 559–570. https://doi.org/10.36487/ACG_rep/1352_47_Bailey

Bailey, M. T., Gandy, C. J., Watson, I. A., Wyatt, L. M., and Jarvis, A. P., 2016, Heat recovery potential of mine water treatment systems in Great Britain: International Journal of Coal Geology, v. 164, p. 77-84, 10.1016/j.coal.2016.03.007.

Banks, D., 2012, An Introduction to Thermogeology: Ground Source Heating and Cooling. 2nd Edition. , Chichester, 526 p, 978-0-470-67034-7.

Banks, D., Making the red one green - renewable heat from abandoned flooded mines. , *in* Proceedings 36th Annual Groundwater Conference, International Association of Hydrogeologists, Irish Group. "Sustaining Ireland's Water Future: The Role of Groundwater", Tullamore, Co. Offaly, Ireland., 12th-13th April 2016 2016, Volume Session VI, p. 1-9, https://www.iah-ireland.org/conference-proceedings/2016.pdf.

Banks, D., 2023, Geothermal Heat: Status Quo or Deeper and Down?, Geoscientist: published online 18/4/23, https://geoscientist.online/sections/features/geothermal-heat-status-quo-or-deeper-and-down/.

Banks, D., Athresh, A., Al-Habaibeh, A., and Burnside, N., 2019, Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom: Sustainable Water Resources Management, v. 5, no. 1, p. 29-50, 10.1007/s40899-017-0094-7.

Banks, D., Fraga Pumar, A., and Watson, I., 2009, The operational performance of Scottish minewater-based ground source heat pump systems: Quarterly Journal of Engineering Geology and Hydrogeology, v. 42, no. 3, p. 347, 10.1144/1470-9236/08-081.

Banks, D., Skarphagen, H., Wiltshire, R., and Jessop, C., 2004, Heat pumps as a tool for energy recovery from mining wastes, Geological Society Special Publication, Volume 236, p. 499-513, 10.1144/GSL.SP.2004.236.01.27.

Banks, D., Steven, J., Black, A., and Naismith, J., 2022, Conceptual Modelling of Two Large-Scale Mine Water Geothermal Energy Schemes: Felling, Gateshead, UK: International Journal of Environmental Research and Public Health, v. 19, no. 3, p. 1643, https://www.mdpi.com/1660-4601/19/3/1643

Bell, F. G., 1986, Location of abandoned workings in coal seams: Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur, v. 33, no. 1, p. 123-132, 10.1007/BF02594714.

Bracke, R., and Bussmann, G., Heat-storage in deep hard coal mining infrastructures., *in* Proceedings World Geothermal Congress, Melbourne, Australia, 2015,

Burnside, N. M., Banks, D., Boyce, A. J., and Athresh, A., 2016, Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK: International Journal of Coal Geology, v. 165, p. 223-230, 10.1016/j.coal.2016.08.021.

Cameron, I.B. and Stephenson, D. (1985). *British regional geology: The Midland Valley of Scotland.* Third edition. Reprint 2014. British Geological Survey, Keyworth, Nottingham, UK.

Chen, M., Soulsby, C. and Younger, P.L. (1999). Modelling the evolution of minewater pollution at Polkemmet Colliery, Almond catchment, Scotland. Quarterly Journal of Engineering Geology 32 (4), 351–362. doi: 10.1144/GSL.QJEG.1999.032.P4.04.

Coal Authority (2020). Seaham Garden Village mine energy district heating scheme. Coal Authority Information Brochure: Mansfield, UK. Available online: https://www2.groundstability.com/wp-content/uploads/2020/01/CA_Seaham_Brochure.290120.pdf

DESNZ, 2024. Heat network zoning: overview. UK Government Department for Energy Security and Net Zero. January 2024, 9 pp. https://assets.publishing.service.gov.uk/media/65a1488b3308d2000d1fbf50/heat-network-zoning-overview.pdf

Diamond, J., 2022, Personal Communication - Drilling Cost Estimates, TownRock Energy,

Energy Saving Trust, 2021, Renewable Heat in Scotland 2020 report, p. 38, https://energysavingtrust.org.uk/wp-content/uploads/2021/10/Renewable-heat-in-Scotland-2020-report-version-2.pdf.

Farr, G. and Tucker, D., 2015. Mine water as an energy source for heat pumps: a case study from the South Wales Coalfield. Presentation to South West Regional Group of the Geological Society, Bristol, 21 April 2015. https://nora.nerc.ac.uk/id/eprint/510965/

Farr, G., Busby, J., Wyatt, L., Crooks, J., Schofield, D. I., and Holden, A., 2021, The temperature of Britain's coalfields: Quarterly Journal of Engineering Geology and Hydrogeology, v. 54, no. 3, p. qjegh2020-2109, 10.1144/qjegh2020-109.

Findlay, C., McDonald, B. and Cunningham, J., 2020, A History of Coal Mining in Rutherglen and Cambuslang. Rutherglen Heritage Society,

Fraser-Harris, A. P., McDermott, C. I., Receveur, M., Mouli-Castillo, J., Todd, F., Cartwright-Taylor, A., Gunning, A. P., and Parsons, M., 2022, The Geobattery Concept: A Geothermal Circular Heat Network for the Sustainable Development of Near Surface Low Enthalpy Geothermal Energy to Decarbonise Heating: Earth Science, Systems and Society, https://doi.org/10.3389/esss.2022.10047.

Ghoreishi Madiseh, S. A., Ghomshei, M. M., Hassani, F. P., and Abbasy, F., 2012, Sustainable heat extraction from abandoned mine tunnels: A numerical model: Journal of Renewable and Sustainable Energy, v. 4, no. 3, 10.1063/1.4712055.

Hall, A., Scott, J. A., and Shang, H., 2011, Geothermal energy recovery from underground mines: Renewable and Sustainable Energy Reviews, v. 15, no. 2, p. 916-924, 10.1016/j.rser.2010.11.007.

Harnmeijer, J., Schlicke, A., Barron, H., Banks, D., Townsend, D., Steen, P., Nikolakopoulou, V., Lu, H. and Zhengao, C., 2017. Fortissat minewater geothermal district heating project: case study. Engineering Technology and Reference. doi: 10.1049/etr.2016.0087

Healy, P. R., and Head, J. M., 1984, Construction over abandoned mine workings, London, 086017 218 X.

Jackson, L. (2022). Coal Authority plan for a treatment scheme on the South Esk. Midlothian View, 18th January 2022. https://www.midlothianview.com/news/coal-authority-plan-for-a-treatment-scheme-on-the-south-esk

James Hutton Institute, 2016, Feasibility Report of Fortissat Community Minewater Geothermal Energy District Heating Network, Edinburgh, The Scottish Government, 104 p, 978-1-78652-131-6

Jessop, A. M., 1995, Geothermal energy from old mines at Springhill, Nova Scotia, Canada., *in* Barbier, E., ed., World Geothermal Congress: Firenze, Italy., p. 463-468, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-jessop2.pdf

Jessop, A. M., MacDonald, J. K., and Spence, H., 1995, Clean energy from abandoned mines at Springhill, Nova Scotia: Energy Sources, v. 17, no. 1, p. 93-106, 10.1080/00908319508946072.

Jones, N. S., Holloway, S., Creedy, D. P., Garner, K., Smith, N. J. P., Browne, M. A. E., and Durucan, S., 2004, UK Coal Resource for New Exploitation Technologies. Final Report. British Geological Survey CR/04/015N,

Loredo, C., Banks, D., and Roqueñí, N., 2017a, Evaluation of analytical models for heat transfer in mine tunnels: Geothermics, v. 69, p. 153-164, 10.1016/j.geothermics.2017.06.001.

Loredo, C., Banks, D., and Roqueñí, N., 2018, Corrigendum to "Evaluation of analytical models for heat transfer in mine tunnels" [Geothermics 69C (2017) 153–164]: Geothermics, v. 71, p. 69, https://doi.org/10.1016/j.geothermics.2017.08.009.

Loredo, C., Roqueñí, N., and Ordóñez, A., 2016, Modelling flow and heat transfer in flooded mines for geothermal energy use: A review: International Journal of Coal Geology, v. 164, p. 115-122, 10.1016/j.coal.2016.04.013.

Loredo, C., Ordóñez, A., Garcia-Ordiales, E., Álvarez, R., Roqueñí, N., Cienfuegos, P., Peña, A. and Burnside, N.M., 2017b. Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Sci. Total Environ. 2017, 576, 59–69. doi: 10.1016/j.scitotenv.2016.10.084

MacAskill, D., Power, C., and Mkandawire, M., 2015, Researching the Geothermal Potential of the Former Springhill Mine: Report to the Cumberland Energy Authority,

Monaghan, A. A., 2014, The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation.: British Geological Survey for Department of Energy and Climate Change, London, UK.,

Monaghan, A. A., Starcher, V., Barron, H. F., Shorter, K., Walker-Verkuil, K., Elsome, J., Kearsey, T., Arkley, S., Hannis, S., and Callaghan, E., 2021, Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources: Quarterly Journal of Engineering Geology and Hydrogeology, p. qjegh2021-2033, 10.1144/qjegh2021-033.

Monaghan, A. A., Starcher, V., Ó Dochartaigh, B., Shorter, K., and Burkin, J., 2019, UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site; Science Infrastructure Version 2, *in* British Geological Survey, ed.: Keyworth, Nottingham., British Geological Survey, p. 49, UKGEOS Report G0100, BGS Open Report OR/19/032.

Nuttall, C.A. and Younger, P.L. (2004). Hydrochemical stratification in flooded underground mines: an overlooked pitfall. Journal of Contaminant Hydrology 69 (1), 101–114. doi: 10.1016/S0169-7722(03)00152-9.

Optimised Environments Ltd., 2020, ClimatEvolution: A vision for a place-based transition to climate resilience in East Lothian, p. 80, https://eastlothianconsultations.co.uk/housing-environment/climatevolution/supporting_documents/191381_Strategy%20and%20Action%20Plan%20Report%20v4_200514.pdf

Ordnance Survey, 2017, OS TERRAIN 5, User guide and technical specification, p. 31, https://www.ordnancesurvey.co.uk/documents/os-terrain-5-user-guide.pdf

Palumbo-Roe, B., Shorter, K. M., Fordyce, F. M., Walker-Verkuil, K., Ó Dochartaigh, B., Gooddy, D., and Darling, W. G., 2021, UKGEOS Glasgow Test Pumping Groundwater Chemistry Data Release, https://doi.org/10.5285/53ded3f2-a4e9-4f49-8084-2c8b3b485268

Ramos, E. P., Breede, K., and Falcone, G., 2015, Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects: Environmental Earth Sciences, v. 73, no. 11, p. 6783-6795, 10.1007/s12665-015-4285-y.

Scottish Government, 2020c, Annual Compendium of Scottish Energy Statistics 2020, p. 83, https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2019/05/annual-compendium-of-scottish-energy-statistics/documents/annual-compendium-december-2020/annual-compendium-december-2020/govscot%3Adocument/ACSES%2B2020%2B-%2BDecember.pdf

Scottish Government, 2023a. Scotland Heat Map - Interactive. Web-based service. https://heatmap.data.gov.scot/custom/heatmap/

Scottish Government, 2023b. Heat network zone (HNZ) guidance. Scottish Government, May 2023. https://www.gov.scot/publications/heat-network-zone-hnz-guidance/. Accessed 28/2/24.

SEPA, 2016, Supporting Guidance (WAT-SG-85): Application of Standards to Thermal Discharges, p. 12, https://www.sepa.org.uk/media/149827/wat_sg_85.pdf

SEPA, 2022, SEPA’s Requirements for Activities Related to Geothermal Energy v1.3, p. 11, https://www.sepa.org.uk/media/594535/geothermal-october-2022.pdf

The Coal Authority, 2017, Guidance for developers; Risk based approach to development management, Volume Version 4, p. 22, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/588157/Resources_for_Developers_Risk-Based_Approach_to_Development_Management_Version_4.pdf

The Coal Authority, 2022, Interactive Map, https://mapapps2.bgs.ac.uk/coalauthority/home.html, Date Accessed: 25/11/2021.

Tipper, L. J., 2015a, User Guide For the Coal Authority In Seam Levels Dataset, *in* The Coal Authority, ed., p. 11,

Tipper, L. J., 2015b, User Guide for the Coal Authority Underground Working Dataset, *in* The Coal Authority, ed., p. 12,

Todd, F., McDermott, C., Harris, A. F., Bond, A., and Gilfillan, S., 2019, Coupled hydraulic and mechanical model of surface uplift due to mine water rebound: implications for mine water heating and cooling schemes: Scottish Journal of Geology, v. 55, no. 2, p. 124-133, 10.1144/sjg2018-028.

Townsend, D., Naismith, J., Townsend, P., Milner, M., and Fraser, U., 2020, "On The Rocks" – Exploring Business Models for Geothermal Heat in the Land of Scotch, World Geothermal Congress: Reykjavik, Iceland, https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2020/08025.pdf

Triple Point Heat Networks (2023). Gateshead District Energy Scheme. Information brochure, https://tp-heatnetworks.org/wp-content/uploads/2023/08/gateshead-district-energy.pdf, accessed 24/1/24.

van Hunen, J., MacKenzie, M., Mouli-Castillo, J., Graham, S., and Adams, C., Modelling mine water flow and heat exchange in open-loop mine systems, *in* Proceedings 2022 Mine water geothermal energy symposium, https://iea-gia.org/workshop-presentations/2022-mine-water-geothermal-energy-symposium/, 2022,

Verhoeven, R., Willems, E., Harcouët-Menou, V., De Boever, E., Hiddes, L., Veld, P. O., and Demollin, E., 2014, Minewater 2.0 Project in Heerlen the Netherlands: Transformation of a Geothermal Mine Water Pilot Project into a Full Scale Hybrid Sustainable Energy Infrastructure for Heating and Cooling: Energy Procedia, v. 46, p. 58-67, 10.1016/j.egypro.2014.01.158.

Walls, D., Burnside, N. M., and Boyce, A. J., 2020, 'Old versus new': Comparing mine water geothermal systems in Glasgow, World Geothermal Congress: Reykjavik, Iceland., https://pure.strath.ac.uk/ws/portalfiles/portal/139102484/Walls_etal_WGC_2021_Old_versus_new_comparing_mine_water_geothermal_systems_in_Glasgow.pdf.

Walls, D. B., Banks, D., Boyce, A. J., and Burnside, N. M., 2021, A Review of the Performance of Minewater Heating and Cooling Systems: Energies, v. 14, no. 19, p. 6215, https://doi.org/10.3390/en14196215.

Walls, D. B., Banks, D., Boyce, A. J., Townsend, D. H., and Burnside, N. M., 2023, Combining ground stability investigation with exploratory drilling for mine water geothermal energy development. Lessons from exploration and monitoring: Scottish Journal of Geology, 10.1144/sjg2022-011.

Walls, D. B., Banks, D., Peshkur, T., Boyce, A. J., and Burnside, N. M., 2022, Heat Recovery Potential and Hydrochemistry of Mine Water Discharges From Scotland's Coalfields: Earth Science, Systems and Society, v. 2, 10.3389/esss.2022.10056.

Wood, J. and Crooks, J. (2020).Mine energy at Seaham Garden Village, 2020. Presented at the Seaham Garden Village Supply Chain Engagement Day. 29 January 2020. Available online: https://www2.groundstability.com/wp-content/uploads/2020/02/02-03-Tolent-and-Coal-Authority.pdf (accessed on 10 Jan 2024).

Wyatt, L.M., Moorhouse, A.M.L. and Watson, I.A. (2014). Evolution in tidal related hydrogeochemistry at a long-term coal mine water pumping and treatment scheme, former Frances Colliery, Scotland. *In:* Proc. IMWA 2014 "An Interdisciplinary Response to Mine Water Challenges". https://www.imwa.info/docs/imwa_2014/IMWA2014_Wyatt_9.pdf

Younger, P. L., 2012, Crouching enemy, hidden ally: the decisive role of groundwater discharge features in two major British battles, Flodden 1513 and Prestonpans 1745: Geological Society, London, Special Publications, v. 362, no. 1, p. 19-33, doi:10.1144/SP362.2.

Younger, P. L., 2016, Abandoned coal mines: From environmental liabilities to low-carbon energy assets: International Journal of Coal Geology, v. 164, p. 1-2, 10.1016/j.coal.2016.08.006.

Younger, P. L., and Adams, R., 1999, Predicting Mine Water Rebound R&D Technical Report W179 Environment Agency, 1857050509.

Zebec Biogas (2022). Craighall Energy: Frances Colliery Minewater Heat Recovery Scheme. Zebec Biogas, Glasgow, UK.

https://www.evaluationsonline.org.uk/evaluations/Documents.do?action=download&id=1050&ui=basic.

(1)

Tables

Dataset	Summary	Quantity	Source
1. Underground workings	Polygons representing worked portions of mined seams. Converted to GIS format from mine abandonment plans.	33,651 polygons (104 MB)	The Coal Authority (Tipper, 2015b)
2. Shallow workings	Derived from the 'underground workings' dataset by extracting all workings, or parts whose depth is 30 metres or less from the surface.	12,222 polygons (25 MB)	The Coal Authority (Abbate, 2016)
3. In seam level	Point data representing the level of underground working at a specific point, in a specific seam, relative to Ordnance Datum (sea level)	82,794 points (39 MB)	The Coal Authority (Tipper, 2015a)
4. Monitored mine water head	X and Y data of TCA monitored mine water head observation points from boreholes or shafts, with Z values relative to Ordnance Datum	48 locations	Contains data from © The Coal Authority. All rights reserved.
5. Mine water discharge locations	X and Y data of unmonitored mine water discharges, Z values created by extraction from DTM	81 locations	Walls et al. (2022)
6. Digital terrain model (DTM)	Raster layer of surface elevation for 5m grid squares	2.8 GB	Crown copyright and database rights 2022 Ordnance Survey.

Table 1. Description of the input layers for GIS analysis.

Local Authority	Area of optimal sites on MiRAS (km^2)	Local Authority	Area of optimal sites on MiRAS (km^2)
North Lanarkshire	90.9	Midlothian	10.7
South Lanarkshire	52.2	Stirling	8.2
Fife	46.4	East Dunbartonshire	7.6
East Ayrshire	30.3	East Lothian	6.3
West Lothian	28.9	Dumfries and Galloway	5.6
Glasgow City	23.3	Renfrewshire	1.4
Falkirk	17.9	City of Edinburgh	1.2
North Ayrshire	16.9	East Renfrewshire	0.4
Clackmannanshire	11.1	Perth and Kinross	0.2
South Ayrshire	10.7		
Total = 370.3 km^2			

Table 2. Coverage area by the MiRAS in each of the affected Scottish local authority areas.

Local Authority	**Area underlain by the MiRAS (km^2)**	**Total heat available at surface (existing discharges) (kW) (from Walls *et al.* (2022))**
North Lanarkshire	90.9	4489
South Lanarkshire	52.2	3018
Fife	46.4	8903
East Ayrshire	30.3	2395
West Lothian	28.9	6572
Glasgow City	23.3	5.3
Falkirk	17.9	1103
North Ayrshire	16.9	372
Clackmannanshire	11.1	261
South Ayrshire	10.7	795
Midlothian	10.7	3279
Stirling	8.2	N/A
East Dunbartonshire	7.6	6.1
East Lothian	6.3	7758
Dumfries and Galloway	5.6	470
Renfrewshire	1.4	N/A
City of Edinburgh	1.2	752
East Renfrewshire	0.4	N/A
Perth and Kinross	0.2	176
Total	**370.3**	**40,354**

Table 3. Coverage area of the MiRAS and heat available from surface mine water resources, broken down into local authority areas.

Figures

Fig. 1. Map of the central belt of Scotland depicting the principal Scottish Coalfields within the extent of The Coal Authority's Coal Mining Areas. Source: data from The Coal Authority.

Fig. 2. Flow diagram showing the overall GIS processing of the 6 input datasets to create the criteria for the MiRAS. The 4 criteria are indicated, or abbreviated to C.

Fig. 3. (Top) Flow diagram showing specific ArcGIS processing methodology of "underground workings" and "shallow workings" datasets to reach Criteria 1 and 2 "overlapping mined seams without mines shallower than 30 m". (Bottom) Schematic representation of conversion from "underground workings" and "shallow workings" (left), to "overlapping mined seams without mines shallower than 30 m" (right).

Fig. 4. Map of central Scotland showing areas of overlapping coal seams, without shallow seams (<30 m bgl), derived from Datasets 1 and 2. Source: data from The Coal Authority.

Fig. 5. Map of predicted mine water piezometric surface (m OD), derived from Datasets 4, 5 and 6. UKGEOS: UK Geoenergy Observatory. Source: data from The Coal Authority.

Fig. 6. Map of predicted depth to mine water level (head) (m bgl), derived from combining Fig. 5 with a digital terrain model (Dataset 6). Source: data from The Coal Authority and Ordnance Survey. Background map ©OpenStreetMap.

Fig. 7. Map of worked seam (mine void) elevation points, derived from Dataset 3, coloured to reflect depth relative to the 250 m bgl cut-off. Source: data from The Coal Authority and Ordnance Survey. Background map ©OpenStreetMap.

Fig. 8. Mine Water Geothermal Resource Atlas for Scotland with optimal areas coloured corresponding to the depth to mine water (m bgl). Pink shaded areas reflect shallower depth to mine water head (0 – 20 m bgl), and blue shaded areas reflect 20 – 60 m bgl. Source: data from The Coal Authority. and Ordnance Survey. Background map ©OpenStreetMap.

Fig. 9. Enlarged portion of Fig. 8 for Lanarkshire area, with optimal areas coloured corresponding to the depth to mine water (m bgl). Source: data from The Coal Authority and Ordnance Survey. Background map ©OpenStreetMap.

Fig. 10. The western portion of the East Lothian Local Authority area which hosts the Mine Water Geothermal Resource Atlas for Scotland, with surface thermal resources included. Source: data from The Coal Authority and Ordnance Survey. Background map ©OpenStreetMap.

Fig. 11. The Mine Water Geothermal Resource Atlas for Scotland applied to Shettleston abstraction and reinjection boreholes, Glasgow. Source: data from The Coal Authority.

Fig. 12. Single and overlapping coal seam locations near Shettleston abstraction and reinjection boreholes, Glasgow. Source: data from The Coal Authority.

Fig. 13. The Mine Water Geothermal Resource Atlas for Scotland applied to the UKGEOS Cuningar Site, Glasgow. The 5 boreholes which are completed into coal mines are shown in black. Source: data from The Coal Authority and NERC.

Fig. 14. Areas of shallow (<30 m), overlapping and single coal seams beneath the Dollar Site, Clackmannanshire. The study area for Walls *et al.* (2023) is shown by the black polygon. Shallow workings are shown as seen on TCA's interactive map viewer (The Coal Authority, 2022). Source: data from The Coal Authority.

Fig. 15. The Mine Water Geothermal Resource Atlas for Scotland applied to the Dollar Site, Clackmannanshire. The study area for Walls *et al*. (2023) is shown by the black polygon. Source: data from The Coal Authority.

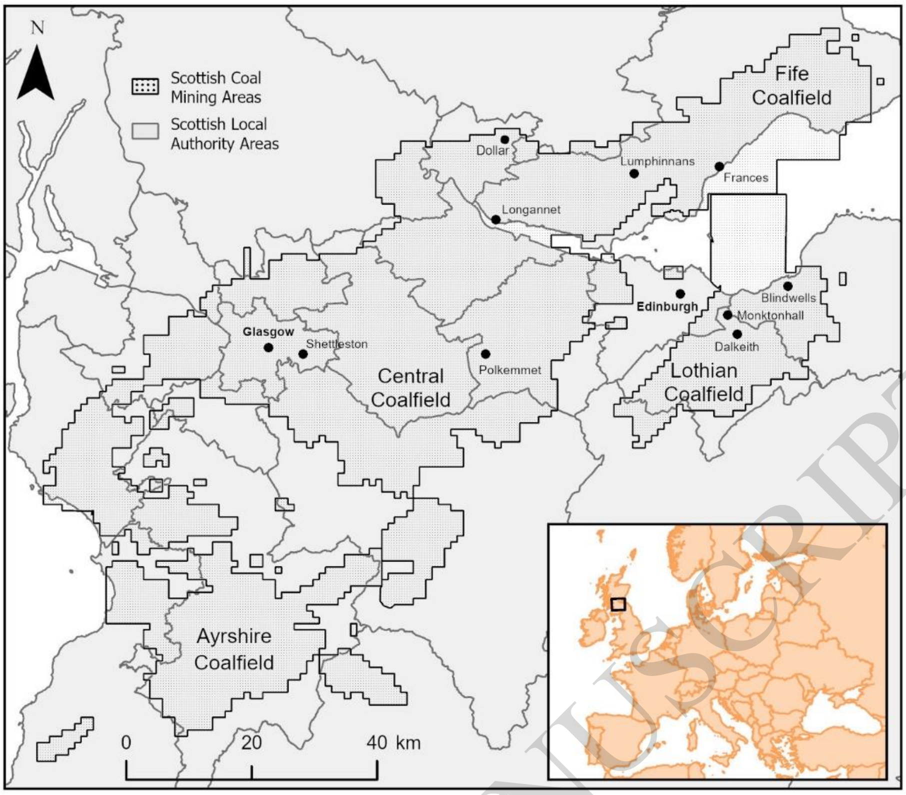

N
Scottish Coal Mining Areas
Scottish Local Authority Areas
Fife Coalfield
Dollar
Lumphinnans
Frances
Longannet
Edinburgh
Blindwells
Monktonhall
Dalkeith
Glasgow
Shettleston
Polkemmet
Central Coalfield
Lothian Coalfield
Ayrshire Coalfield
0
20
40 km

Figure 1

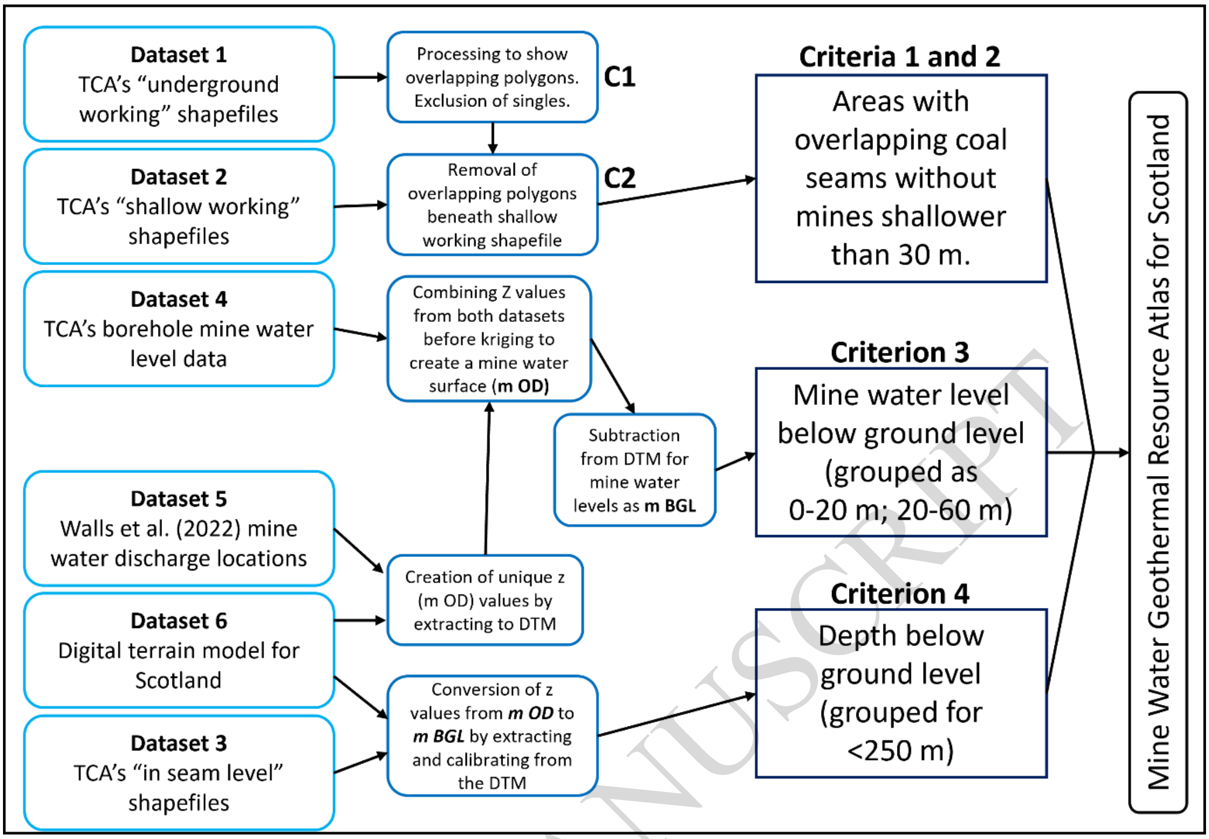

Dataset 1
TCA's "underground working" shapefiles
Dataset 2
TCA's "shallow working" shapefiles
Dataset 4
TCA's borehole mine water level data
Dataset 5
Walls et al. (2022) mine water discharge locations
Dataset 6
Digital terrain model for Scotland
Dataset 3
TCA's "in seam level" shapefiles
Processing to show overlapping polygons. Exclusion of singles.
C1
Removal of overlapping polygons beneath shallow working shapefile
C2
Combining Z values from both datasets before kriging to create a mine water surface (m OD)
Subtraction from DTM for mine water levels as m BGL
Creation of unique z (m OD) values by extracting to DTM
Conversion of z values from m OD to m BGL by extracting and calibrating from the DTM
Criteria 1 and 2
Areas with overlapping coal seams without mines shallower than 30 m.
Criterion 3
Mine water level below ground level (grouped as 0-20 m; 20-60 m)
Criterion 4
Depth below ground level (grouped for <250 m)
Mine Water Geothermal Resource Atlas for Scotland

Figure 2

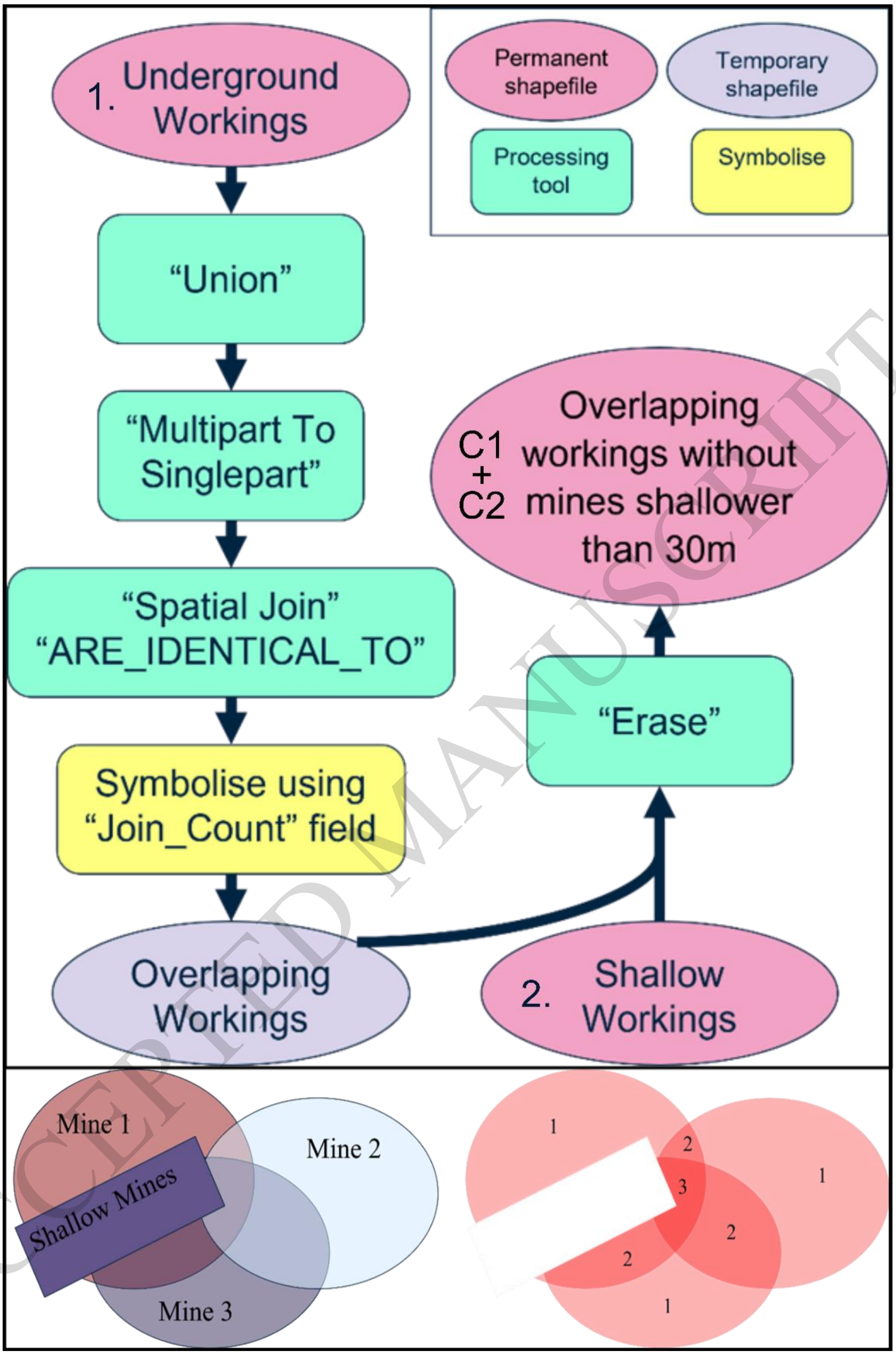

Permanent shapefile
Temporary shapefile
Processing tool
Symbolise
1. Underground Workings
"Union"
"Multipart To Singlepart"
"Spatial Join" "ARE_IDENTICAL_TO"
Symbolise using "Join_Count" field
Overlapping Workings
2. Shallow Workings
"Erase"
C1 + C2
Overlapping workings without mines shallower than 30m
Mine 1
Mine 2
Mine 3
Shallow Mines
1
2
3
2
1
2
1

Figure 3

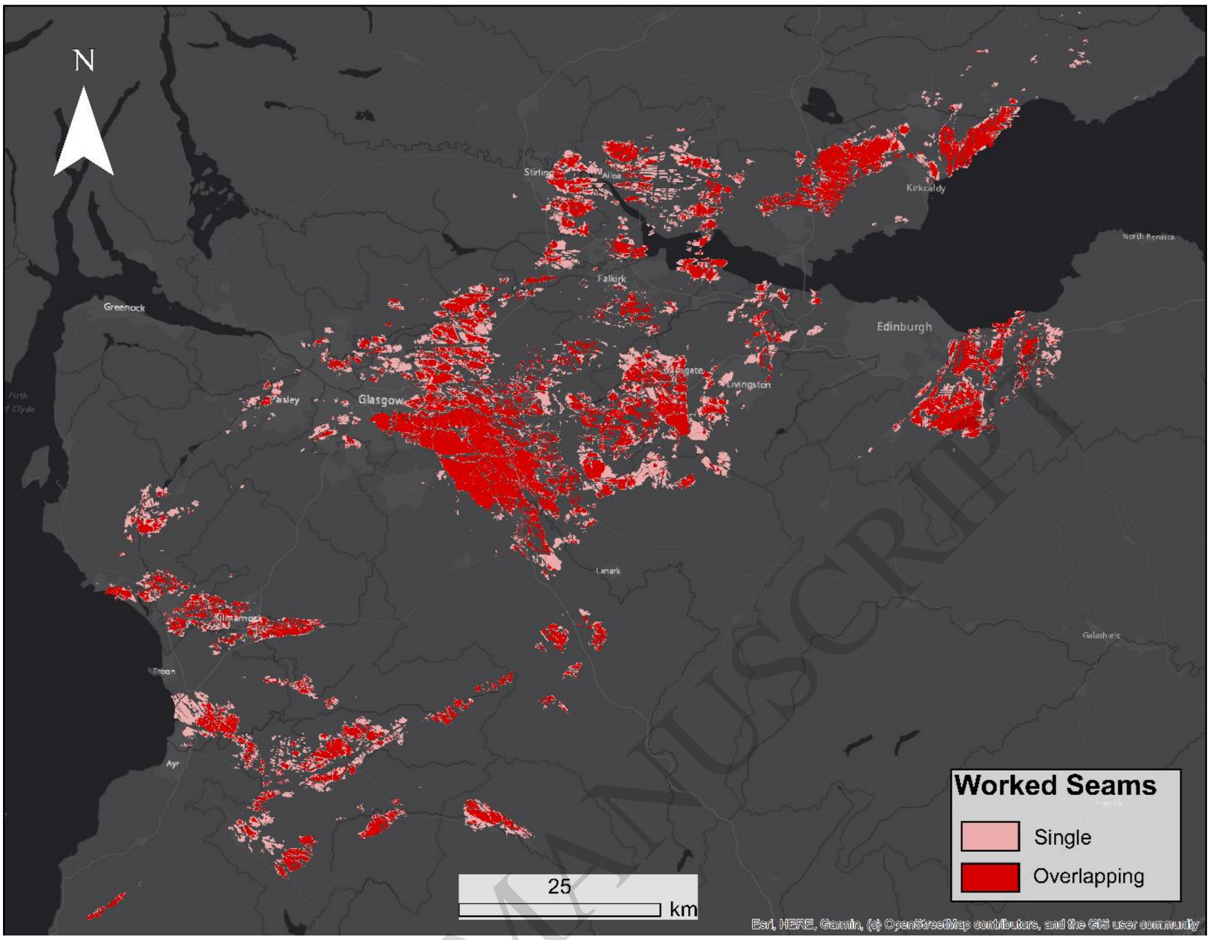
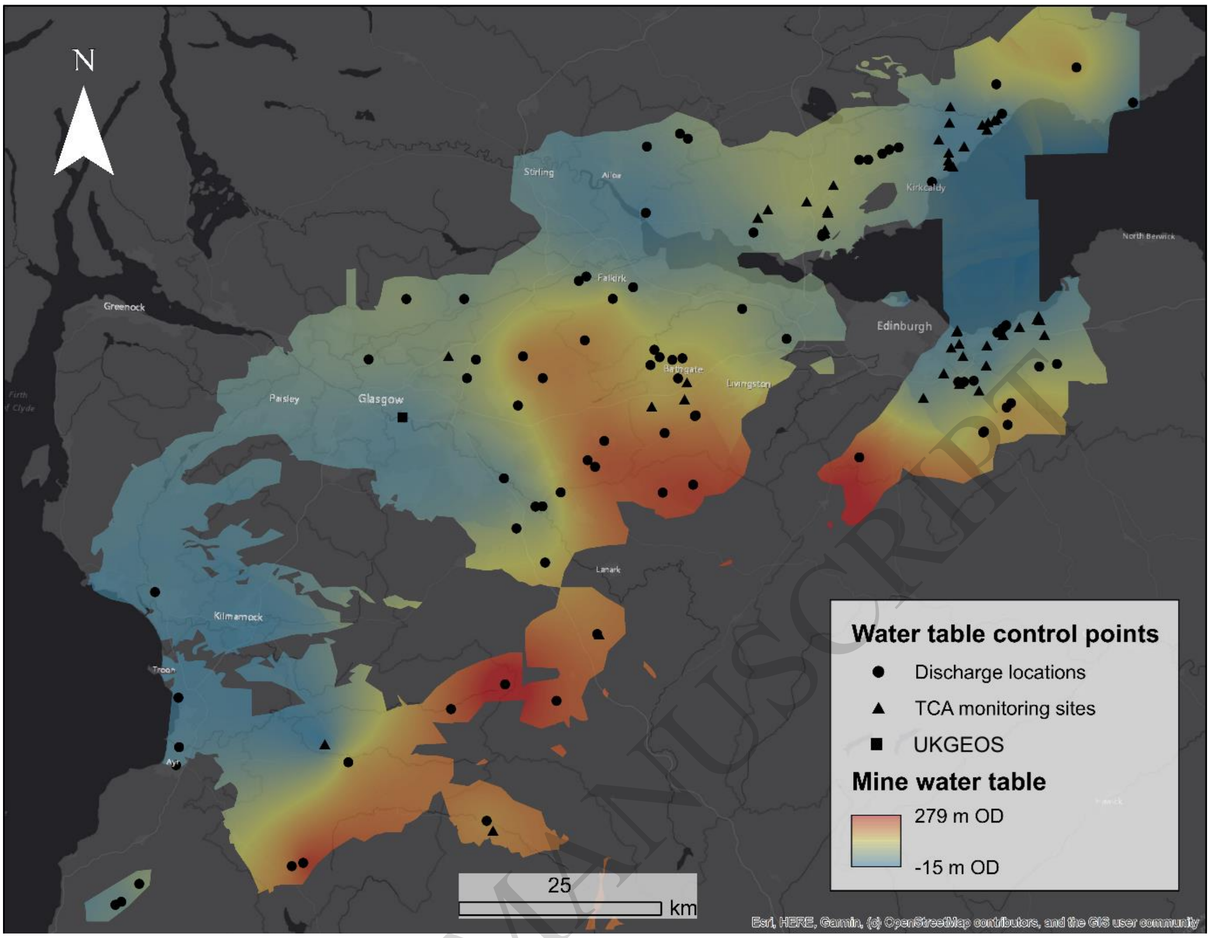

N
Stirling
Alloa
Kirkcaldy
North Berwick
Falkirk
Greenock
Edinburgh
Glasgow
Paisley
Livingston
Firth of Clyde
Lanark
Kilmarnock
Troon
Ayr
Galashiels
Worked Seams
Single
Overlapping
25
km
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 4



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 5

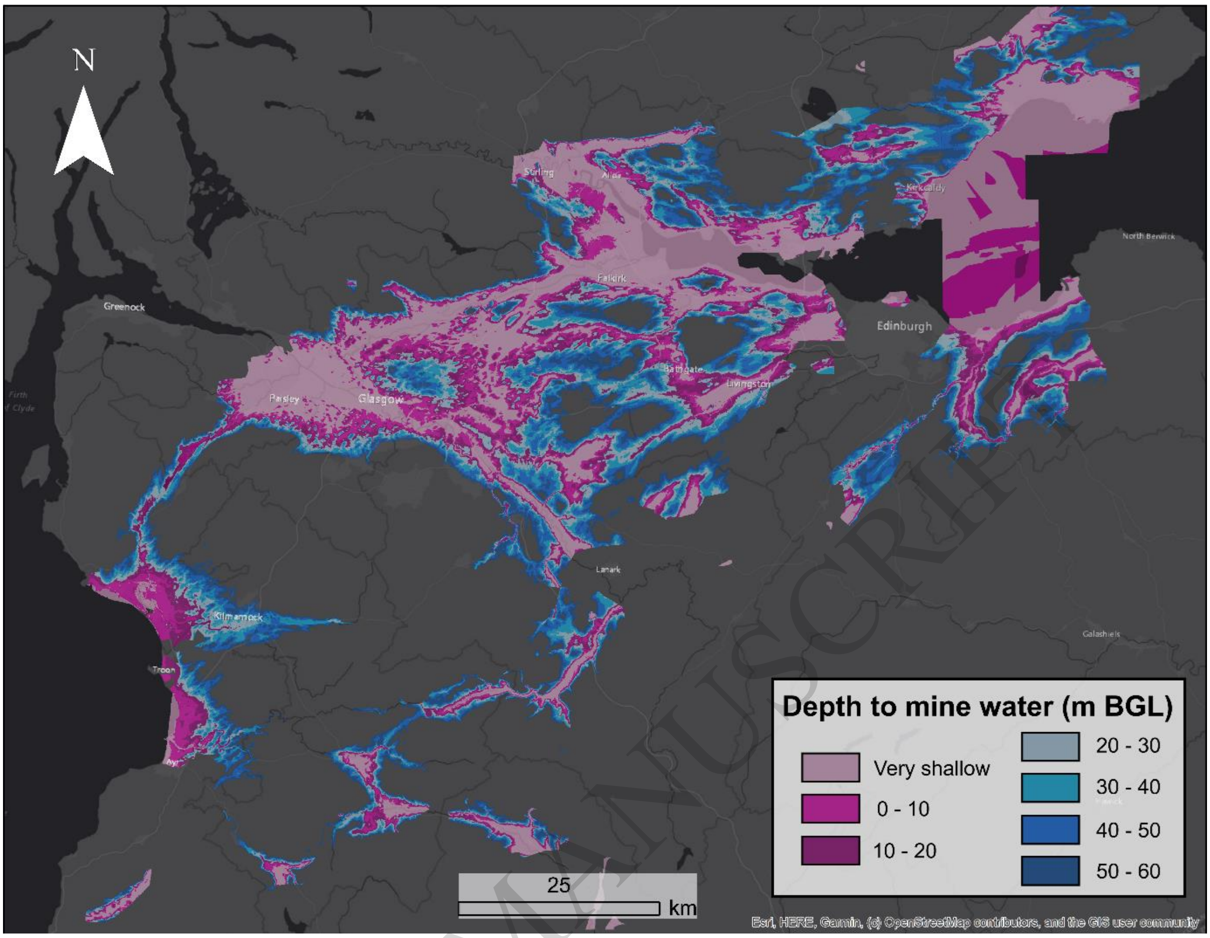

N
Stirling
Alloa
Kirkcaldy
North Berwick
Falkirk
Greenock
Edinburgh
Bathgate
Livingston
Paisley
Glasgow
Firth of Clyde
Lanark
Kilmarnock
Troon
Ayr
Galashiels
Depth to mine water (m BGL)
Very shallow
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
25
km
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 6

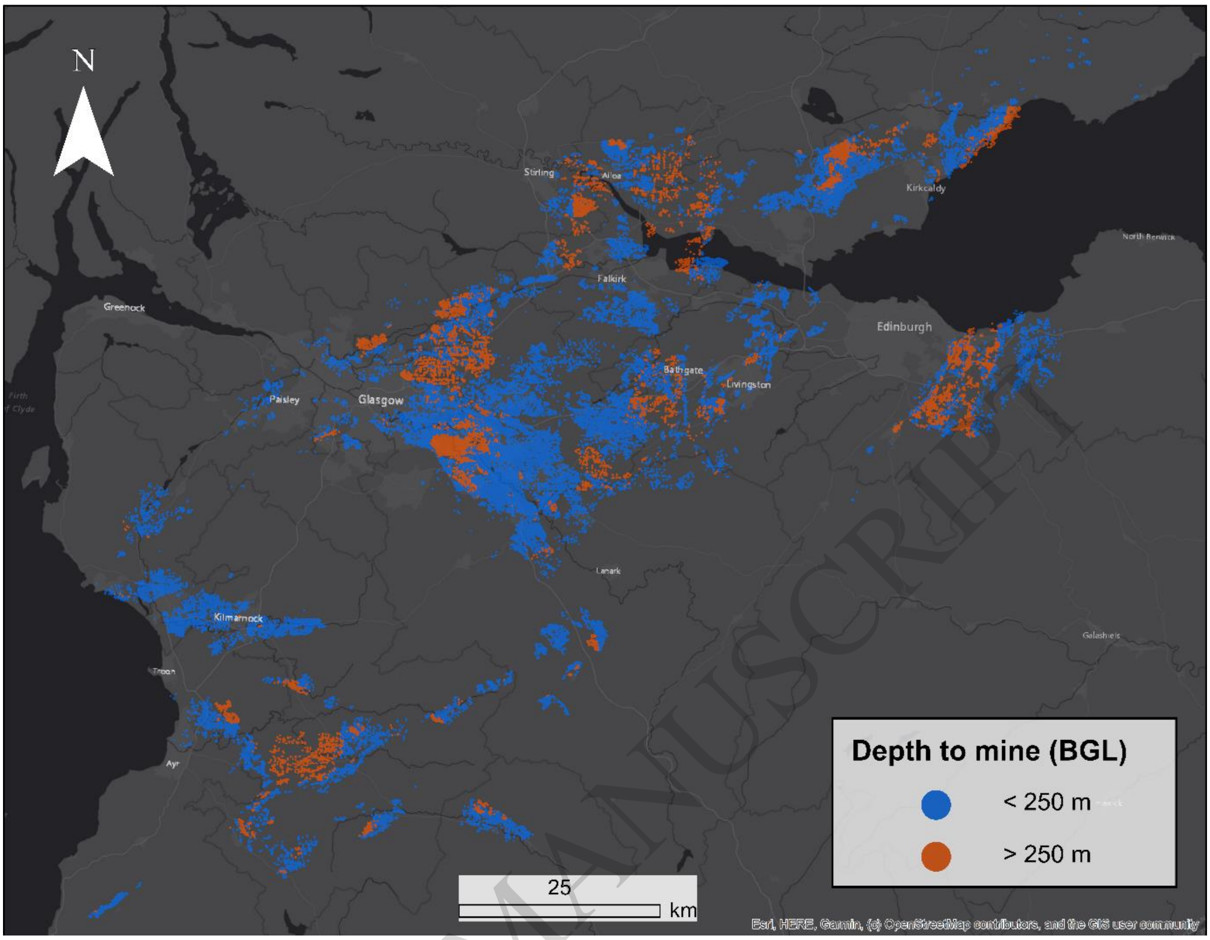

N
Stirling
Alloa
Kirkcaldy
North Berwick
Falkirk
Greenock
Edinburgh
Bathgate
Livingston
Paisley
Glasgow
Firth of Clyde
Lanark
Kilmarnock
Galashiels
Troon
Ayr
Depth to mine (BGL)
● < 250 m
● > 250 m
25
km
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 7

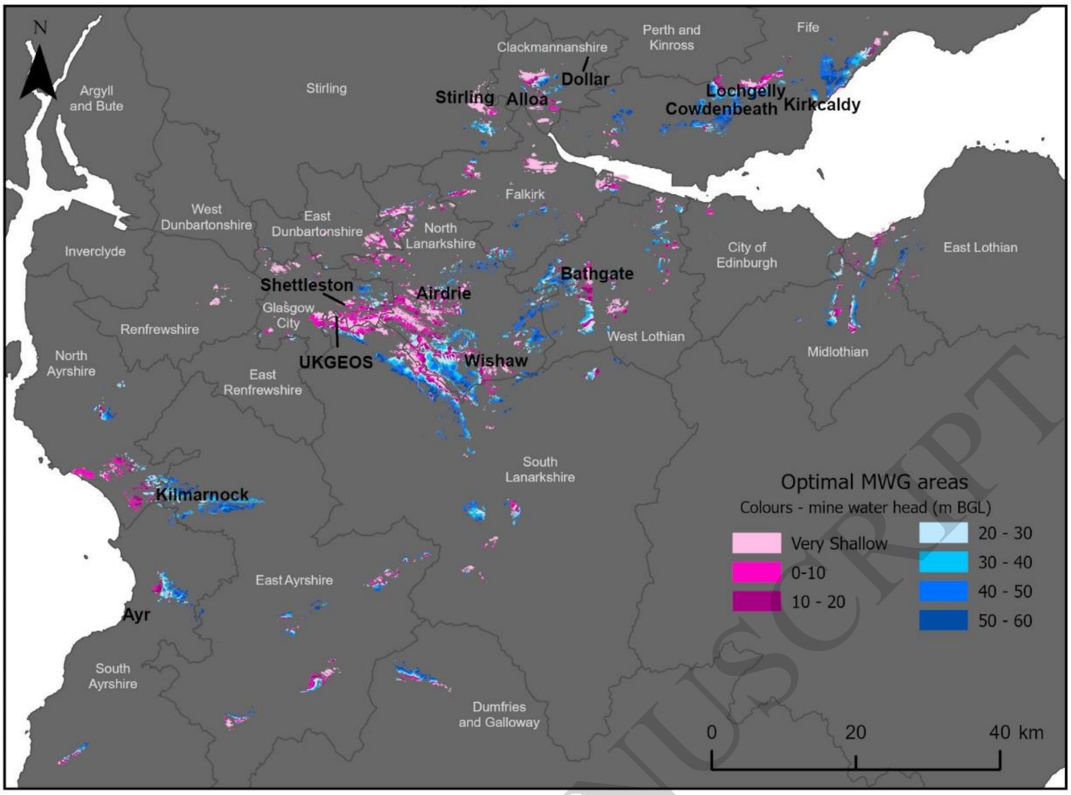

N
Argyll and Bute
Stirling
Clackmannanshire
Perth and Kinross
Fife
Dollar
Stirling
Alloa
Lochgelly
Cowdenbeath
Kirkcaldy
Falkirk
West Dunbartonshire
East Dunbartonshire
North Lanarkshire
Inverclyde
City of Edinburgh
East Lothian
Bathgate
Shettleston
Airdrie
Glasgow City
Renfrewshire
West Lothian
UKGEOS
Wishaw
Midlothian
North Ayrshire
East Renfrewshire
South Lanarkshire
Optimal MWG areas
Colours - mine water head (m BGL)
Very Shallow
0-10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
Kilmarnock
East Ayrshire
Ayr
South Ayrshire
Dumfries and Galloway
0
20
40 km

Figure 8

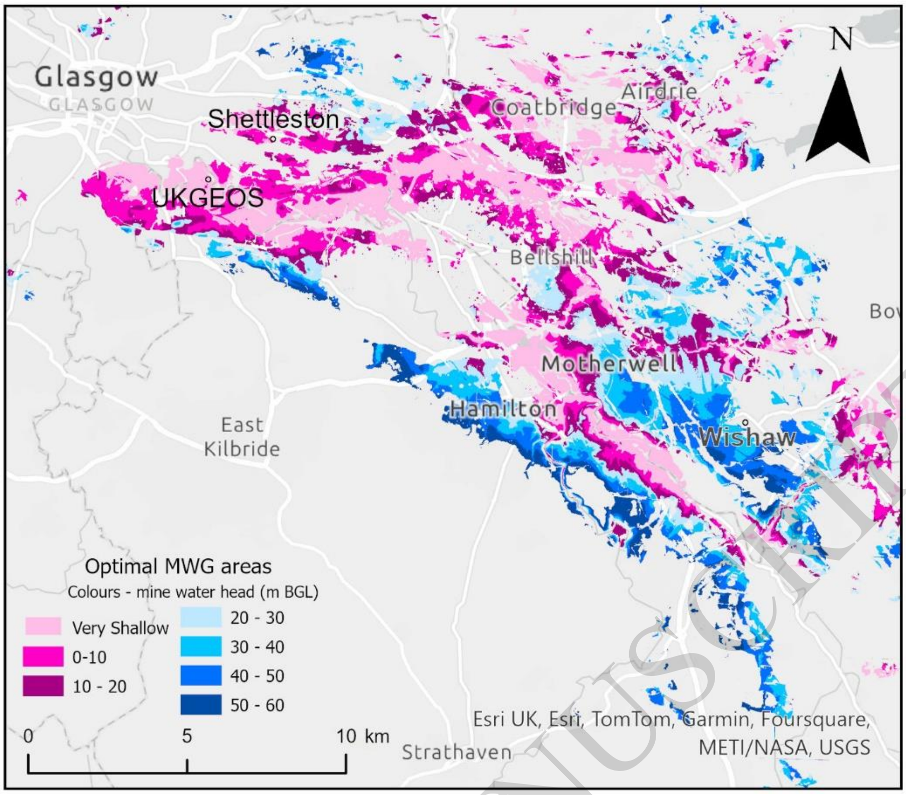

Glasgow
GLASGOW
Shettleston
UKGEOS
Coatbridge
Airdrie
Bellshill
Motherwell
Hamilton
Wishaw
East Kilbride
Strathaven
Bo
N
Optimal MWG areas
Colours - mine water head (m BGL)
Very Shallow
0-10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
0
5
10 km
Esri UK, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS

Figure 9

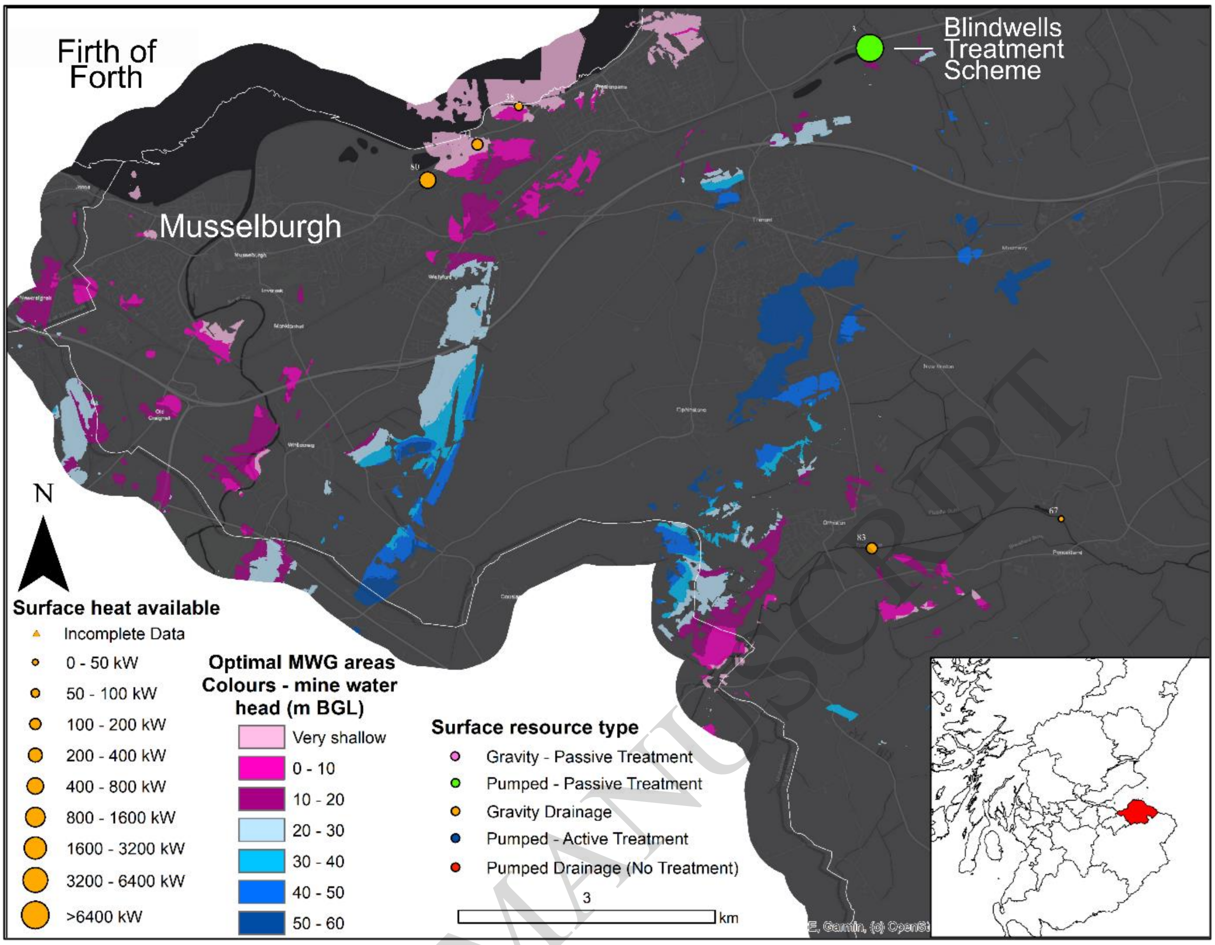
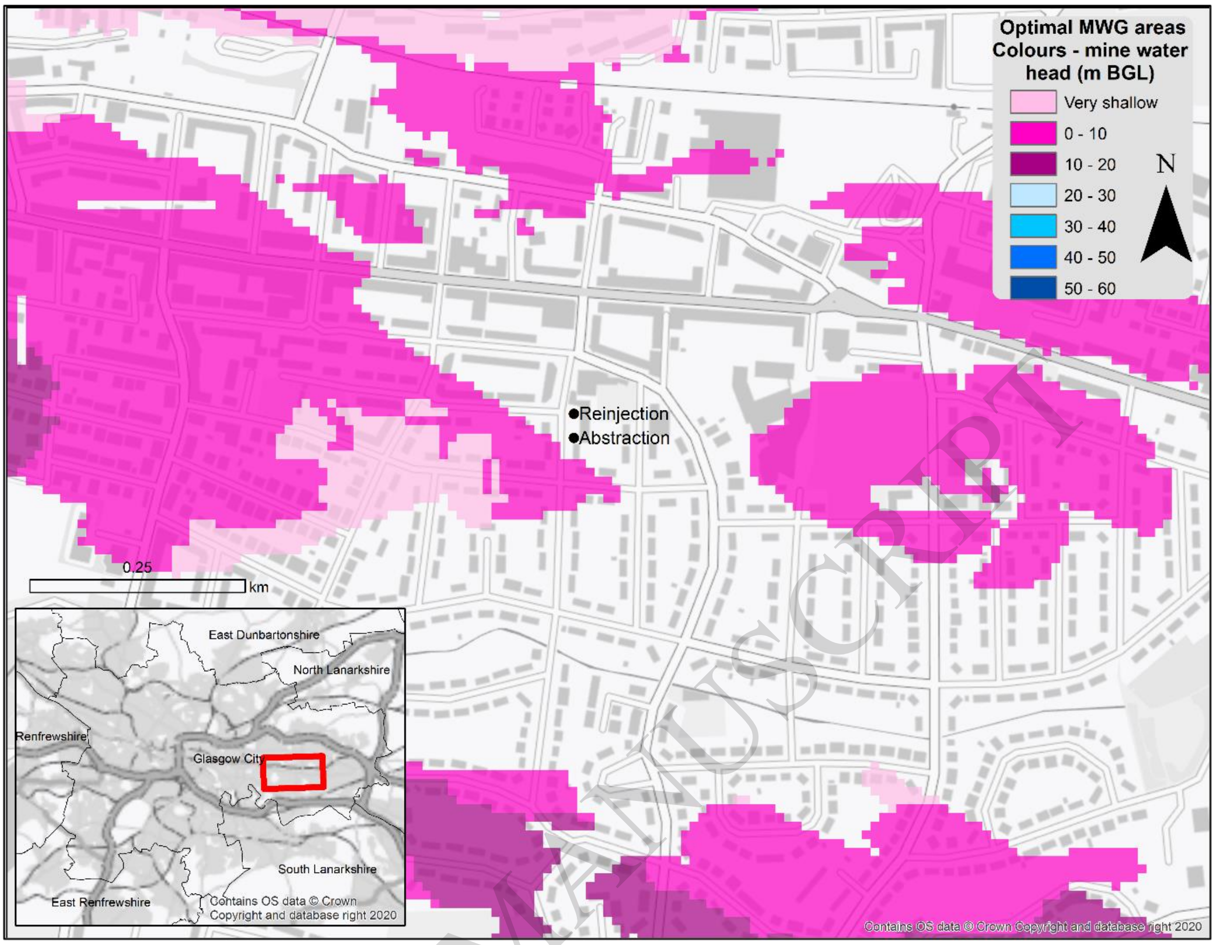

Firth of Forth
Musselburgh
Blindwells Treatment Scheme
N
Surface heat available
Incomplete Data
0 - 50 kW
50 - 100 kW
100 - 200 kW
200 - 400 kW
400 - 800 kW
800 - 1600 kW
1600 - 3200 kW
3200 - 6400 kW
>6400 kW
Optimal MWG areas
Colours - mine water head (m BGL)
Very shallow
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
Surface resource type
Gravity - Passive Treatment
Pumped - Passive Treatment
Gravity Drainage
Pumped - Active Treatment
Pumped Drainage (No Treatment)
3
km
18
80
83
67

Figure 10



Contains OS data © Crown Copyright and database right 2020

Contains OS data © Crown Copyright and database right 2020

Figure 11

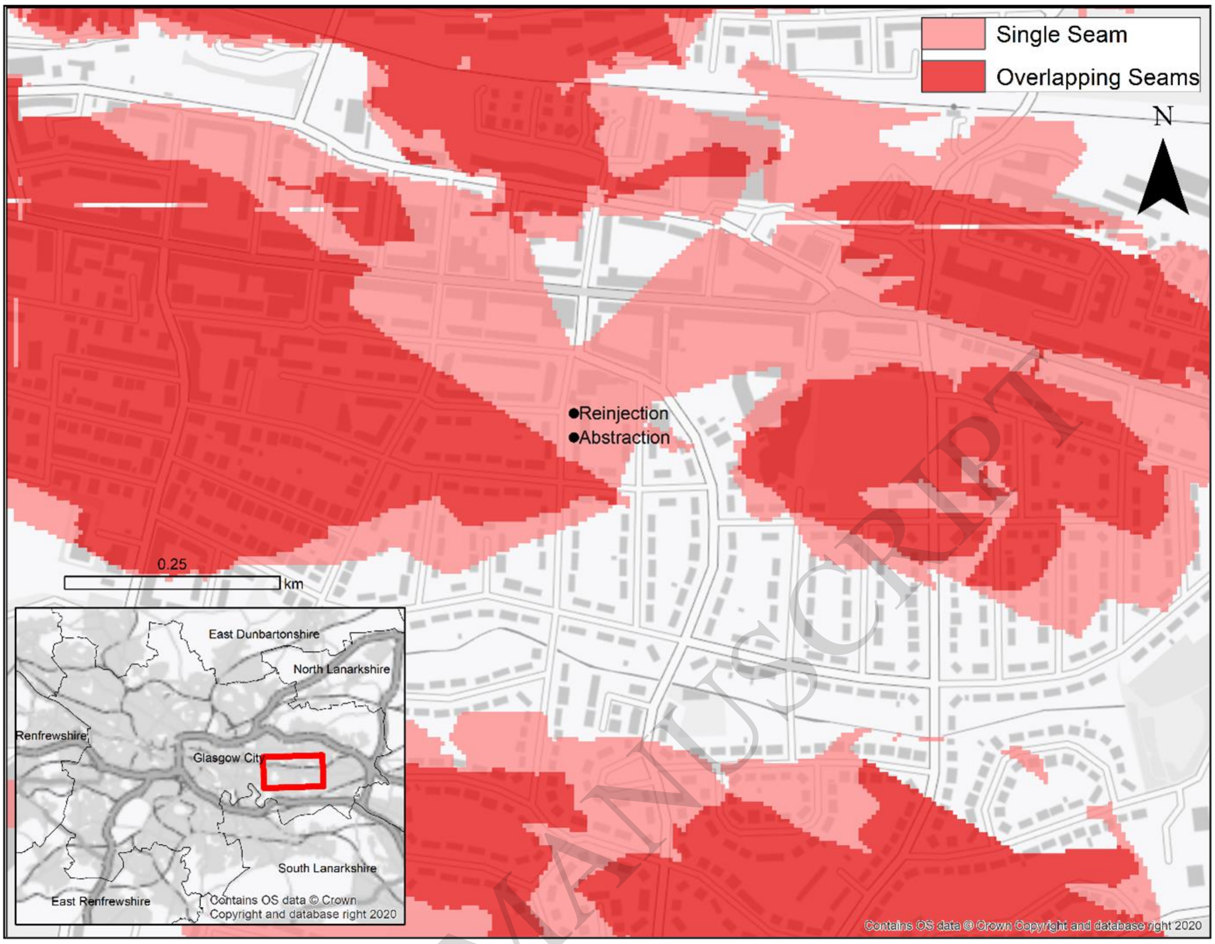

Single Seam
Overlapping Seams
N
Reinjection
Abstraction
0.25
km
East Dunbartonshire
North Lanarkshire
Renfrewshire
Glasgow City
South Lanarkshire
East Renfrewshire
Contains OS data © Crown Copyright and database right 2020
Contains OS data © Crown Copyright and database right 2020

Figure 12

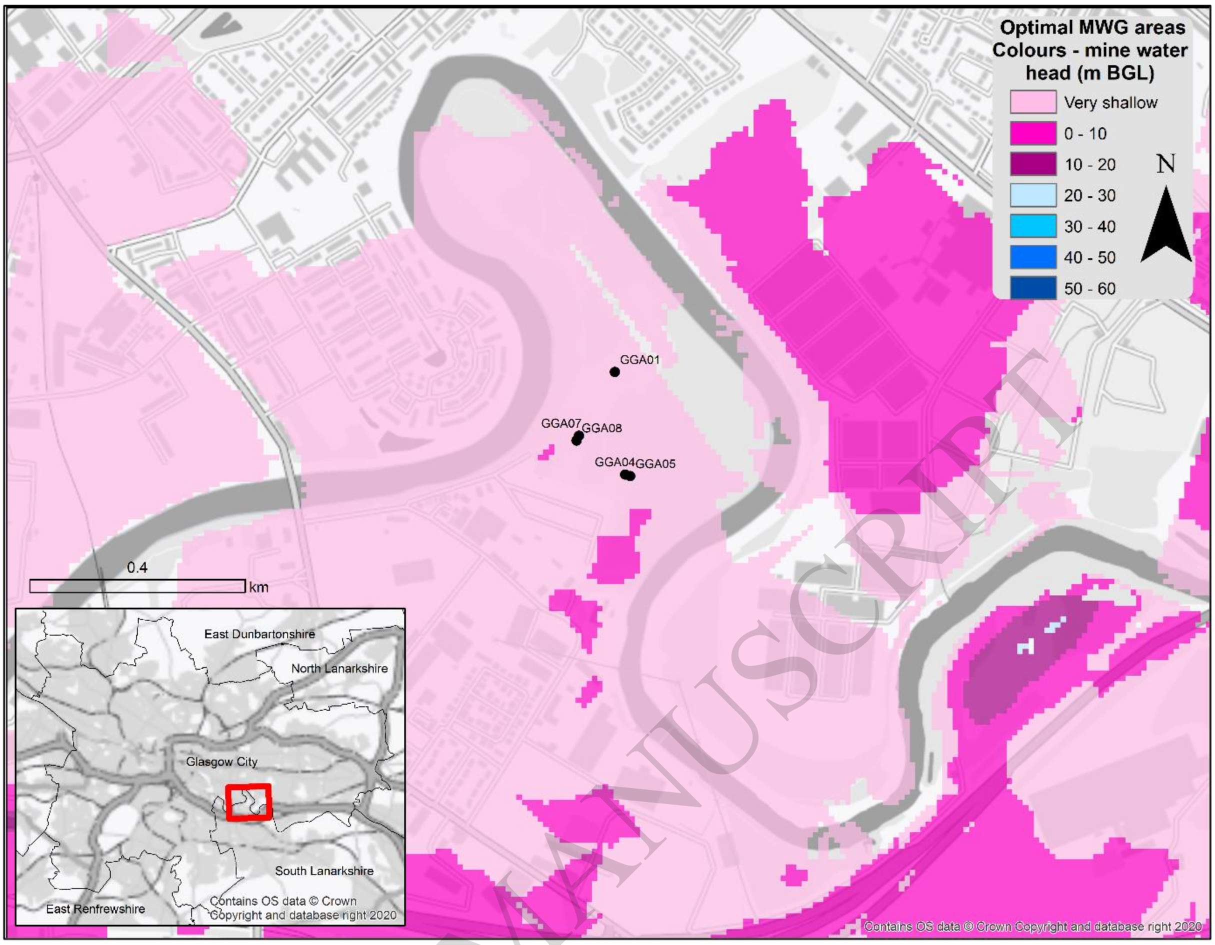
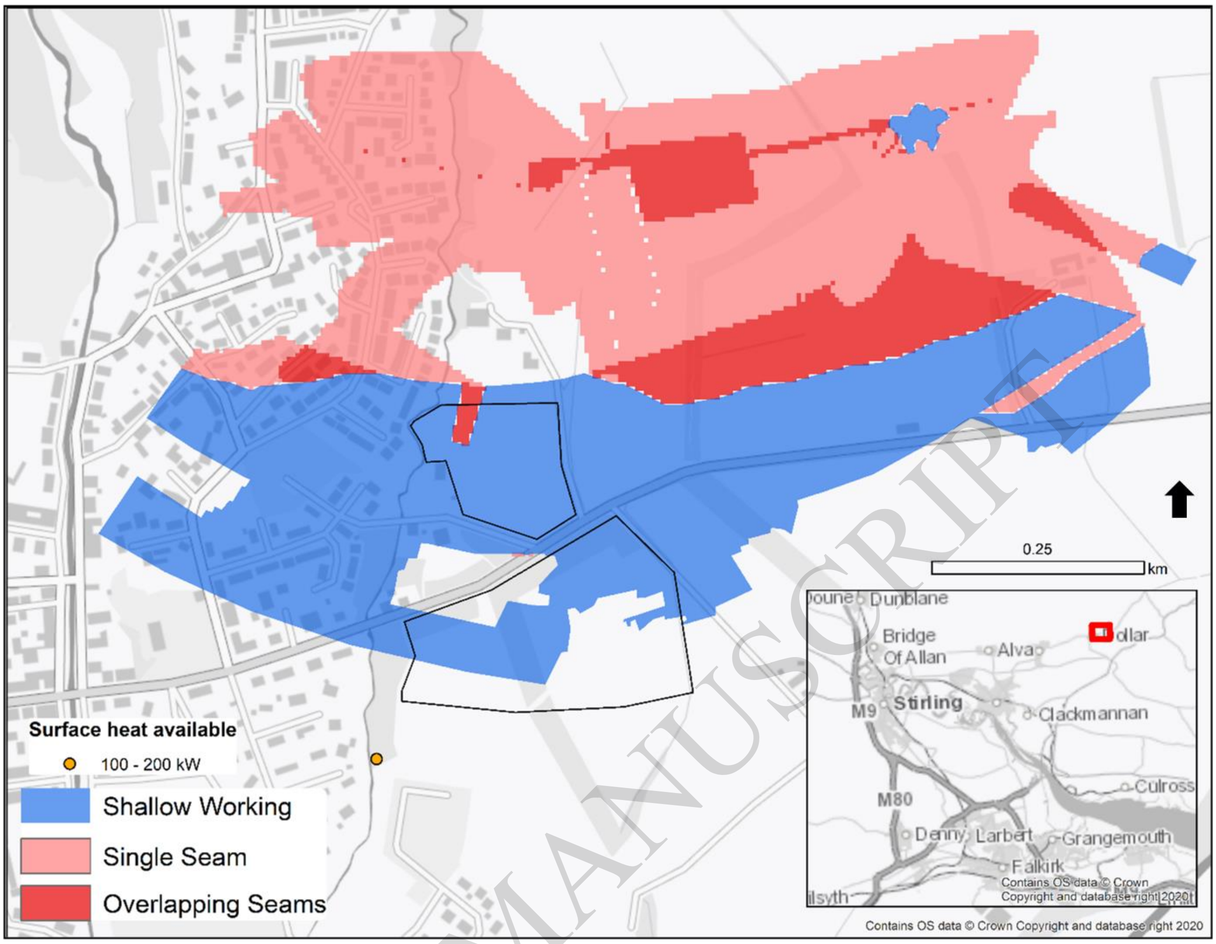

Optimal MWG areas
Colours - mine water head (m BGL)
Very shallow
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
N
GGA01
GGA07
GGA08
GGA04
GGA05
0.4
km
East Dunbartonshire
North Lanarkshire
Glasgow City
South Lanarkshire
East Renfrewshire
Contains OS data © Crown Copyright and database right 2020
Contains OS data © Crown Copyright and database right 2020

Figure 13



Contains OS data © Crown Copyright and database right 2020

Contains OS data © Crown Copyright and database right 2020

Figure 14

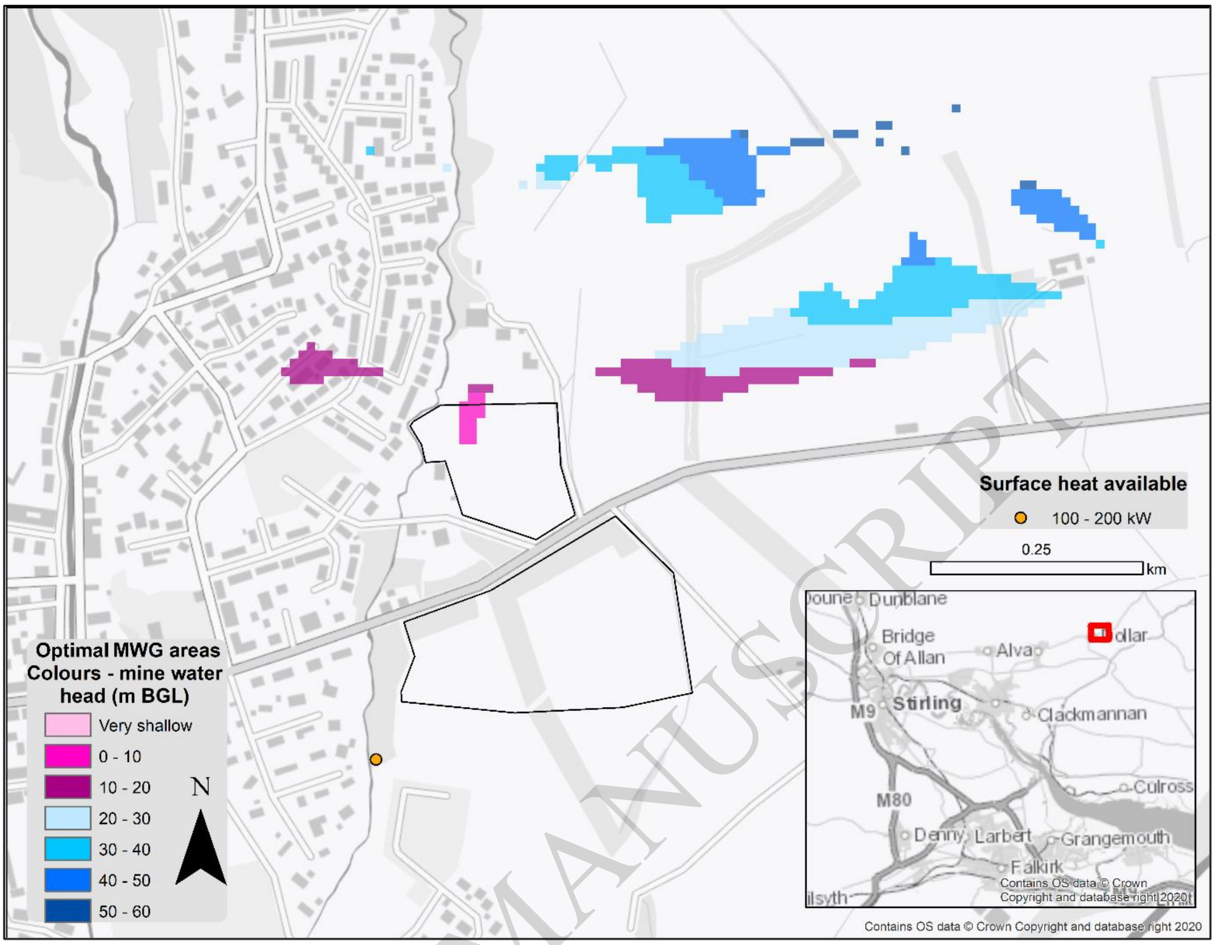

Optimal MWG areas
Colours - mine water head (m BGL)
Very shallow
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
N
Surface heat available
100 - 200 kW
0.25
km
Doune
Dunblane
Bridge Of Allan
Alva
Dollar
M9
Stirling
Clackmannan
Culross
M80
Denny
Larbert
Grangemouth
Falkirk
Kilsyth
Contains OS data © Crown Copyright and database right 2020
Contains OS data © Crown Copyright and database right 2020

Figure 15