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

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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

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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 km² 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/63cefed-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 GWth.

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 °C/km in Central Scotland, 26.8 °C/km in Ayrshire, 24.2 °C/km in Lothian, 22.2 °C/km in Douglas and 21.9 °C/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 MWth 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 observation 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, H₂S-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 ($\Delta T$) (Banks, 2012) and flow rate (Bailey et al., 2016). A higher minewater temperature would allow a greater ($\Delta T$) 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) × C3 (value of depth m BGL) × 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:

\[ G = Q \cdot \Delta T \cdot S_{Vwat} \]

Equation 2

\( G = \) heat available (kW), which is a function of
\( Q = \) water discharge rate (pumped or gravity) (L/s),
\( S_{Vwat} = \) volumetric heat capacity of water (kJ/L/°C)
\( T_{MW} = \) measured temperature of mine water discharge (°C),
∆T = 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 km² 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 km². 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/63cefed-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 $G = 6.9 \, \text{MW}_\text{th}$ 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 $14.4 \, \text{MW}_\text{th}$.

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, \( \text{H}_2\text{S} \)-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 chemical 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 km² 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 extend our thanks to the Improvement Service for hosting the resultant Mine Water Geothermal Resource Atlas for Scotland online.

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### Tables

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Summary</th>
<th>Quantity</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Underground workings</td>
<td>Polygons representing worked portions of mined seams. Converted to GIS format from mine abandonment plans.</td>
<td>33,651 polygons (104 MB)</td>
<td>The Coal Authority (Tipper, 2015b)</td>
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<td>2. Shallow workings</td>
<td>Derived from the ‘underground workings’ dataset by extracting all workings, or parts whose depth is 30 metres or less from the surface.</td>
<td>12,222 polygons (25 MB)</td>
<td>The Coal Authority (Abbate, 2016)</td>
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<td>3. In seam level</td>
<td>Point data representing the level of underground working at a specific point, in a specific seam, relative to Ordnance Datum (sea level)</td>
<td>82,794 points (39 MB)</td>
<td>The Coal Authority (Tipper, 2015a)</td>
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<td>4. Monitored mine water head</td>
<td>X and Y data of TCA monitored mine water head observation points from boreholes or shafts, with Z values relative to Ordnance Datum</td>
<td>48 locations</td>
<td>Contains data from © The Coal Authority. All rights reserved.</td>
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<td>5. Mine water discharge locations</td>
<td>X and Y data of unmonitored mine water discharges, Z values created by extraction from DTM</td>
<td>81 locations</td>
<td>Walls et al. (2022)</td>
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Table 1. Description of the input layers for GIS analysis.
<table>
<thead>
<tr>
<th>Local Authority</th>
<th>Area of optimal sites on MiRAS (km²)</th>
<th>Local Authority</th>
<th>Area of optimal sites on MiRAS (km²)</th>
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<tr>
<td>North Lanarkshire</td>
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<td>Midlothian</td>
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**Total = 370.3 km²**

Table 2. Coverage area by the MiRAS in each of the affected Scottish local authority areas.
<table>
<thead>
<tr>
<th>Local Authority</th>
<th>Area underlain by the MiRAS (km²)</th>
<th>Total heat available at surface (existing discharges) (kW)</th>
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<td><strong>Total</strong></td>
<td><strong>370.3</strong></td>
<td><strong>40,354</strong></td>
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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 Shetleston abstraction and reinjection boreholes, Glasgow. Source: data from The Coal Authority.

Fig. 12. Single and overlapping coal seam locations near Shetleston 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.
Figure 1
Figure 2

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.

Removal of overlapping polygons beneath shallow working shapefile

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 3
Figure 5
Figure 9
Figure 11
Figure 12
Figure 15