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The temperature of Britain's coalfields

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Abstract

Low temperature heat recovery, cooling and storage schemes, using abandoned flooded mine workings are a viable option for low carbon heating solutions within many abandoned British coalfields. The temperature of mine water is a useful parameter, coupled with depth to water, sustainable yield and recharge potential, to identify suitable locations and calculate the likely performance of heat recovery schemes. This paper aims to provide the first mapping and synthesis of the temperature of Britain's coalfields to support this emerging technology. Using the best available evidence, a median geothermal gradient of 24.1 ˚C/km was calculated for the British coalfields. However, geothermal gradients between separate coalfields can vary from 17.3 to 34.3 ˚C/km. The North East, Cumbria and Yorkshire coalfields all have mean geothermal gradients generally >30 ˚C/km, whilst geothermal gradients of generally <23 ˚C/km are measured in the Warwickshire, South Wales, Staffordshire, Douglas and Fife coalfields. Active dewatering schemes are shown to locally increase the apparent measured geothermal gradient by ingress and mixing of deeper water into the pumping shafts. This baseline spatial mapping and synthesis of coalfield temperatures offers significant benefit to those planning, designing and regulating heat recovery and storage in Britain's abandoned coalfields.

As the UK moves towards a low carbon, clean growth economy (BEIS 2017), it will need to significantly reduce its greenhouse gas emissions to meet an ambitious target of net zero for all greenhouse gasses by 2050 (CCC, 2019). Currently, heating in homes, businesses and industrial processes is responsible for a third of the UK's greenhouse gas emissions (BEIS, 2018). Despite this, progress to decarbonise heating has been 'too slow' (CCC, 2019) and remains a significant challenge across all types of building stock. It is thought that a mixture of renewable technologies could provide solutions for low carbon space heating and cooling; including electrification of heating using renewable sources, solar thermal, air- or water-source heat pumps, or ground source heat pumps (coupled either to closed loop heat exchangers or "open loop" groundwater circulation).
Following the closure of the majority of the British underground coal mines during the 1980s-1990s, the requirement to dewater ceased and many collieries were left to progressively flood (Fig. 1). The resulting mine water often has undesirable water chemistry and may be aggressive or acidic, with high iron and sulphate arising from oxidation of pyrite and associated precipitation of ochre (Banks & Banks, 2001). Most pre-treatment mine water is unusable for potable, industrial or agricultural uses, and can cause significant pollution events if allowed to enter surface waters or aquifers. Surface breakouts often occur along river valleys, where natural discharge points from mine water systems develop. Due to these challenges, mine water has historically been considered as a liability, requiring treatment to prevent environmental damage. In response to rising mine water levels and resulting outbreaks into surface water systems, mine water treatment schemes were constructed across Britain by the Coal Authority (National Rivers Authority, 1994; Environment Agency, 2008). However more recently, as the potential for heat recovery and storage is being revisited, mine water is increasingly being regarded as a potential geo-energy asset (Younger, 2014; 2016).
In Britain the majority of reported operational heat recovery schemes in coalfield areas are designed around open loop systems using an abstraction and return borehole or shaft (Banks *et al.* 2004, 2009, 2017; Burnside *et al*. 2016a; Farr *et al.* 2016; Al-Habaibeh *et al.* 2019; LoCAL, 2019; Townsend *et al.*, 2020). An open loop system at Dawdon, North East England, is supplied by mine water abstracted from a shaft before it is treated and discharged to the sea (Bailey *et al.,* 2013). Other operational heat recovery systems include a single shaft, or 'standing column' system (Anthresh et al., 2015; Al-Habaibeh *et al.* 2019; Burnside *et al.* 2016a; b) and also a closed loop heat exchanger in a surface treatment lagoon (Banks *et al.* 2017). The location of closed loop schemes are not available on an open register, so it is not possible to quantify how many are installed in Coal Measures strata. Reported examples of closed loop schemes include the Dunston Innovation Centre in Chesterfield (Banks, 2012) which includes 32 boreholes arranged in a 4 by 8 grid array and is used for both heating and cooling.

In the deepest parts of Coal Measures basins, below the worked coal seams, temperatures up to 80 ˚C (East Midlands), 60 ˚C (South Wales) and 100˚C (Cheshire) could be expected (Busby 2014), however low permeabilities make these targets less attractive for geothermal energy operations. In Britain wider deployment of open loop low temperature heat recovery from abandoned mine workings and upscaling to district systems, as demonstrated in Herleen, Netherlands (Verhoeven *et al.* 2014) still lags behind that of other countries (see global reviews e.g. Hall *et al.* 2011; Preene & Younger 2014; Ramos *et al.* 2015).

Throughout Britain there is increasing awareness of the potential for heat recovery, cooling and storage using low temperature water from abandoned coal mines. At the time of writing, eleven feasibility studies are in progress funded by HNDU (Heat Networks Delivery Unit) and several academic and commercial studies have been published both regionally and at a site scale (e.g. White Young Green, 2007; Gillespie *et al.* 2013; Harnmeijer *et al.* 2017; Bailey *et al.* 2016; Farr *et al.* 2016; Brabham *et al.* 2019; Todd *et al.* 2019). Many cities and towns in Britain are located upon disused coalfields, and could provide a significant potential customer base for renewable energy schemes utilising abandoned coal mines.

Heat recovery and storage in Britain's coal mines is still in its infancy and many challenges need to be addressed including: the ownership of heat (Abesser *et al.* 2018), identification of flooded workings, development of regulatory and licensing frameworks (Stephenson *et al.* 2019) and high initial CAPEX costs (Townsend *et al.* 2020). A bespoke 'geo-observatory' is being constructed in Glasgow as part of the UK Geoenergy Observatories (UKGEOS) programme to characterise the hydrogeology of abandoned coal mine workings and address scientific questions associated with sustainable low temperature heat recovery (Monaghan *et al.* 2018; Monaghan, 2019, Watson *et al.* 2019).

During the early stages of many mine water heat recovery projects one of the first questions to be asked is *'how warm is the mine water?'* as higher temperatures can improve efficiency and result in greater available ΔT values. In addition to temperature there are many other factors that must be considered including; depth to viable water filled targets, sustainable abstraction rates, discharge of used water and potential drilling challenges. These factors will influence the required drilling depth to targeted workings, energy required to pump mine water to the surface, heat lift required by a heat pump, capital cost and ultimately the viability of the overall scheme. This paper presents the first national scale map of mine water temperatures in the British coalfields using the best available evidence. These maps and information within should be used to support early stage scoping or feasibility studies for new proposed heat recovery or storage schemes in abandoned coal mines.

Methodology

As there is no single temperature dataset, measured using a consistent methodology that provides complete spatial coverage of Britain's coalfields, it was necessary to combine data from three sources. These include; 1) recent Coal Authority downhole temperature profiles, from boreholes and shafts that intercept flooded workings 2) the BGS UK Geothermal Catalogue (UKGC) including data from the National Coal Board, hydrocarbon boreholes, and other investigative boreholes, representing both mined and unmined areas of the coalfields, and 3) historic in-situ strata temperatures measured directly in coal seams within operational coal mines. The various methods of temperature measurements are described below, and illustrated in Figure 1.

The Coal Authority has delineated 174 'Mine Water Blocks' (MWB) for the majority of British coalfields. Most coalfields will consist of several MWB. MWB are based upon knowledge of hydrogeological connections (e.g. interconnected mine workings) or barriers (e.g. faults or unworked coal) and are delineated and updated by the Coal Authority. MWB are used in this study as they are the best currently available hydraulic units for the coalfields. Mine Water Blocks and the distribution of data points across the British coalfields are shown in Figure 2.

Downhole temperature profiles

The Coal Authority periodically undertake inspections, water sampling, and downhole geophysical surveys of their shafts and boreholes. One of the probes used during the geophysical survey is an electrical conductivity and temperature probe. Calibrated and lowered from the back of a bespoke vehicle (Fig. 1), the probe measures mine water temperature every 1 cm to the base of the borehole or shaft, recording the data in a digital file. In total 148 downhole temperature profiles, measured as part of the Coal Authority's monitoring programme between 2000 – 2019, were accessed for this study. In addition to the Coal Authority temperature profile data described above, other downhole temperature profiles were provided by Natural Resources Wales, UKGEOS-Glasgow, Environment Agency and Bridgend County Council.

The BGS UK Geothermal Catalogue

The BGS UK Geothermal Catalogue (UKGC) is managed by the British Geological Survey. It originated as an output from a series of reports as part of the 'Investigation of the geothermal potential of the UK' programme, UK Department of Energy and the European Commission 1976 to 1988 (Burley & Gale, 1981; BGS, 1984; 1985, Browne 1987, Holliday, 1986; Thomas *et al.* 1983). The catalogue was originally published in 1978 (Burley & Edmunds 1978) and followed by three revisions (Burley & Gale

1982; Burley *et al*. 1984; Rollin 1987). Data from this catalogue was also used in earlier national scale mapping of subsurface temperature across Britain (Busby *et al.* 2011). The UKGC also contains more recent data from sites including the 'Newcastle Science Central borehole' (Younger *et al.* 2016). The data in the BGS UKGC contains both data from boreholes in unmined and mined sections of the coalfields.

Coal strata temperatures

Between 1848 and 1924 various committees were established to gain a better scientific and practical understanding of 'human endurance of high temperatures, and upon the possibility of reducing temperature of the air in contact with the heated strata' (HMSO, 1871). Three main phases of investigation were undertaken and strata temperature measurements were made in coal seams or small boreholes drilled within operational mines (Fig. 1). The strata temperature measurements have been collated for this study. We acknowledge that many of the collieries were actively dewatered and many were cooled with air and the impact of this upon the measured rock strata temperatures is unknown. First 'The Royal Coal Commission- 'Possible Depth of Workings' 1866-1871, reported a total of 179 in-situ strata temperature measurements from 15 operational collieries in England and Wales (HMSO, 1871). Between 1867 and 1881 the 'Underground Temperature Committee', funded by the Department of Scientific and Industrial Research, undertook 23 in-situ bedrock temperature measurements from 10 operational collieries in England. (Everett 1870 a, b; 1871, 1872. 1873, 1877, 1879, 1880, 1881, 1882a, b; Lebour, 1881). Separately Prestwich (1887) reported strata temperatures from British coal mines; however it is likely some data from previous studies had been summarised in this report. During the late 19th and early 20th Centuries, as coal mines became deeper, more evidence was required on the variability and controls of heat in mines and the impact on miners. Between 1910-1925 the 'Committee for the control of atmospheric conditions in hot and deep mines' was formed. In total 201 in situ strata temperature measurements at 45 operational collieries in England, Scotland and Wales were reported. (Anon 1919-20; Rees, 1920-21; Graham, 1921-22; Jones 1924; 1926).

Mine water blocks and depth to workings

For each MWB the shallowest and deepest recorded mine workings were calculated and rounded to the nearest 100 m, to provide a minimum and maximum worked depth within each MWB. The maximum worked depth for each MWB is used to create a lower boundary for the mapping. However it should be noted that the maximum depths do not mean that workings occur continually across the MWB at this depth.

Method for calculating temperatures

For the mapping exercise it was necessary to distinguish between temperatures which we believed to be more representative of wider equilibrium conditions across the MWB and localised temperature gradients measured at actively pumped boreholes and shafts.

Equilibrium temperatures are measured in unpumped monitoring boreholes in both recovered and recovering coalfields, hydrocarbon exploration wells and historic coal strata measurements made in active collieries. Equilibrium temperatures are considered to be a reasonable reflection of the temperature of the coalfield. Equilibrium temperatures were recorded in all three data sets.

Pumped temperatures are only measured in actively pumped boreholes and shafts, used mostly for the purpose of mine water management and pollution prevention. Pumped temperatures were only recorded in the Coal Authority temperature log dataset. The measured temperatures, often elevated compared to equilibrium temperatures, were considered to reflect localised changes due to pumping.

A few MWB are data rich enabling an average and range of equilibrium temperatures to be calculated at 100 m depth intervals. For other MWB there were only a few UKGC and coal strata temperature data which were combined with the mean surface annual air temperature to calculate a geothermal gradient from which 'equilibrium' temperatures at 100 m intervals were predicted. Mean annual air temperatures (from MetOffice HadUK-Grid District data 1980-2019) were assigned at a depth of 15m below ground to each coalfield area to improve the calculation of the geothermal gradient. For 'equilibrium' temperatures, where individual MWB have no data but there was data for other MWBs within the same coalfield an average value from the entire coalfield was applied to the MWB with no data. It was not possible to assign temperature values where there were no data for an entire coalfield, e.g. Shropshire and The Forest of Dean.

Mine water temperature maps

A series of maps have been drawn to illustrate temperatures in 100 m depth intervals across British coalfields, with maps produced for depths between 100-1000 m. The Coal Authority's 174 MWB (Fig. 2) have been used as boundaries and have been populated with attributes. Of the 174 MWB; 79 have measured mine water or strata temperature data and 82 were assigned average temperatures from adjacent MWB within the same coalfield. 13 MWB have no temperature data and no adjacent blocks within the coalfield from which to apply average values and thus remain unknown. Each MWB was assigned temperature data at 100 m intervals based upon the depths of known mine workings

(Table 1). Mapped coal mine workings in British coalfields occur from the surface, to 1785 mbgl (meters below ground level) and measured temperature data was available to a maximum depth of 1300 mbgl, although we only show maps upto 1000m depth. Using a GIS (geographical information system) each MWB polygon was assigned with its associated attributes (Table 1). Maps of 'equilibrium' temperatures from 100-1000 m and pumped temperatures at 100 and 200 m are generated from the data.

Results

Firstly, comparisons between historic in-situ strata temperatures and modern borehole data (BGS UKGC) are discussed (Fig. 3), followed by summary of all equilibrium data at a national scale with 100 m increments of depth (Table 2) and finally the temperature data are summarised for each individual British coalfield (Table 3). Two examples of the impacts of pumping, from a 'pumped coalfield' are provided from active pumping schemes (Fig. 4 a & b). The data are presented in a series of maps covering the main British Coalfields (Fig. 5 -8).

Comparison of BGS UKGC and historic in-situ strata temperature data

Data from the BGS UKGC and historic in-situ strata measurements (1848 -1924) are compared in Figure 3. The historic strata temperature data were measured in operational coal mines and thus the depth of measurements is limited by the depth of the coal mining activity. The BSG UKGC data are derived from measurements in boreholes which can be drilled to depths greater than the active coal workings and also in areas of unworked coal measures. Broadly, there is a good correlation of mean temperatures derived from the older in-situ strata measurements from dry operational mines and the more recent BGS UKGC data measured from boreholes and shafts with both data sets displaying the same general trend of increasing temperatures with depth. This broad correlation between the two datasets implies that the post closure flooded temperature of coal mine workings has reached an approximate temperature equilibrium with the surrounding strata.

The historic in-situ strata temperature data (Fig. 3) report that between 1000 and 1200 mbgl the mean temperature of the mined Coal Measured strata is 37.8 °C. This correlates very well with the BGS UKGC data (38.2 °C) at the same depth range, and the predicted mean temperature at a UK scale of 37°C at 1km depth (Busby *et al.* 2011). Minimum measured temperatures were 9.7 °C (between 100-200 mbgl) and 9.0 °C (between 0-100 mbgl) for the BGS UKGC data and in-situ strata data respectively. Maximum reported temperatures were 57.8 °C (between 1600 and 1700 mbgl) and 40.8 °C (between 1100 and 1200 mbgl) for the BGS UKGC data and in-situ strata data respectively. Temperature variations within each 100 m depth slice are generally greater in the BGS

UKGC data (with a maximum range of 32.8 °C) and smaller in the historic strata temperature data (with a maximum of 13.9 °C).

One explanation for the larger range in temperatures observed in the BGS UKGC data is that this dataset comprises of measurements from both mined and unmined sections of coalfield. However, it is also possible that some of the data contained within the BGS UKGC had not reached thermal equilibrium at the time of measurement. Despite this the broad similarity in mean values between the BGS UKGC data and the older in-situ strata temperature data suggests that the older in-situ data could, with caution, be used to predict mean post closure modern flooded temperatures in coal mines. This could be especially useful where older strata temperature data exists but where there are no existing boreholes or shafts to measure modern day temperatures within a coalfield.

Temperatures in equilibrium British coalfields at 100 m depth intervals

Initially all the coalfield data were collated and presented in 100 m depth intervals, from 100 -1200 mbgl, across all of the coalfields in Britain (Table 2), combining data from the Coal Authority downhole temperature profiles, BGS UKGC and historic in-situ strata temperatures. The minimum temperature is 9.5 ˚C (100 mbgl) and the maximum temperature is 52.8 ˚C (1100 mbgl). Using a mean annual UK air temperature of 9 ˚C, calculated geothermal gradients at each 100 m depth interval (from 100-1100 m) produce relatively similar gradients varying only slightly from 23.2-26.9 ˚C/km. Despite the similarity of the mean geothermal gradients at each 100 m interval there can also be significant differences between the maximum and minimum measured temperatures at the same depth which can be as much as 29.4 ˚C/km (at 1100 mbgl). Most boreholes for heat recovery, cooling and storage schemes will not be drilled to such depths, due to increasing cost and risk, although access to deeper mine water may be possible via existing shafts. Even at relatively shallow depths, where drilling is most likely to occur, significant differences between the maximum and minimum measured temperatures are also reported in Britain's coalfields e.g. 11.7 ˚C (100 mbgl), 14.2 ˚C (200 mbgl) and 10.8 ˚C (300 mbgl) and thus a more refined analysis by coalfield is required.

Geothermal gradients of the British Coalfields

To better understand the variability of temperature at each 100 m depth interval the data have been ranked by mean geothermal gradient for each of the British coalfields (Table 3). It was not possible to rank the North Wales or Leicestershire coalfields as they both had only one data point, Forest of Dean and Shropshire coalfields have no data and were not included in the ranking. The data were sorted using the mean geothermal gradients for the entire coalfield at all depths. Using this approach the median geothermal gradient is calculated at 24.1 ˚C/km for all of the British coalfields. The coalfields with the highest mean geothermal gradients include; the North East (34.4 ˚C/km), Cumbria (32.5 ˚C/km) and Yorkshire (32.3 ˚C/km). The lowest mean geothermal gradients are reported from Warwickshire (17.3 ˚C/km), South Wales (19.5 ˚C/km), Fife (21.9 ˚C/km), Douglas (22.2 ˚C/km) and Staffordshire (22.5 ˚C/km). A series of maps (Fig. 5 - 8) have been drawn to illustrate the spatial and lateral variability of average equilibrium temperatures from between 100 and 1000 mbgl and pumped temperatures at 100 and 200 mbgl across the British coalfields.

Effect of pumping on mine water temperature in a shaft

Whilst the majority of data discussed represent equilibrium temperatures of mine water or coal strata, the localised effect of pumping (or where mine water rebound forces water vertically up disused shafts to the surface) can significantly alter the locally calculated geothermal gradient.

Two examples are provided from pumping shafts at Dawdon and Horden collieries in the North East Coalfield where pumps are installed at 100 mbgl. Prior to commencement of pumping, in 2010 at Dawdon Theresa Shaft (Easting 443580, Northing 547810) (Fig. 4 a), four temperature profiles were measured between 2000 and 2008, which were broadly similar. However after a period of pumping, which commenced in 2010 at ~100 l/s, the measured temperature profile within the shaft significantly increased, possibly as deeper water is drawn into and mixes with or replaces cooler water in the shaft. A similar pattern is observed at Horden South Shaft (Easting 444225, Northing 541858) (Fig. 4 b), where pumping commenced in 2004 at ~40 l/s. Despite there only being one pre-pumping temperature profile in 2003, the data show an overall increase of water temperature along the length of the shaft. There is some fluctuation in the post pumping measurements at Horden South Shaft (Fig. 4 b) and this could be related to variations in the pumping rate which were increased to ~120 l/s up to 2008, and after 2008 returned to ~40 l/s.

Although an increase in temperature may be perceived as a benefit, it can also be coupled with mine water with less favourable chemistry, which could create challenges for the infrastructure of heating and cooling schemes. The effects of pumping at Dawdon resulted in an increase of electrical conductivity, measured at the pump depth of 100m below ground, from 10,296 µs/cm (Pre pumping 1.9.2003) to 58,630 µs/cm (during pumping 28.7.2010). Electrical conductivity also increased at Horden from 1,169 µs/cm (Pre pumping 31.10.2003) to 18,069 µs/cm (during pumping 28.7.2010).

Data from pumped shafts and boreholes (Table 2) were compared with equilibrium temperatures to a depth of 500 m. The pumped data shows that a higher mean temperature and geothermal gradient is measured at 100 and 200 m depth intervals, however the deeper data between 300 and 500 m in pumped coalfields shows a cooler temperature than the equilibrium coalfields. The mechanism for this is not fully understood and could simply be a factor of the number of data points available for analysis which is significantly less in pumped coalfields.

It is not yet clear if these observed warming effects are experienced in all pumping scenarios, and it is quite likely that it is driven by the temperature and or depth of the most productive workings that are intercepted. It is possible that in some settings cooler shallower groundwater could be induced into the shaft or borehole during pumping producing cooler temperatures under pumping regimes. There is no evidence to indicate if these effects are localised (i.e. within the shaft or borehole) or if temperature changes are experienced within the wider – hydraulically connected parts of the mine water block (e.g. within the cone of influence of the shaft or borehole). During the quality assessment and mapping process measured temperatures from MWB that were considered to be pumped (e.g. pumping and or actively rising mine water systems) were separated from MWB that were considered to be in thermal equilibrium. The reason for this decision was to avoid 'hot spots' created by possibly localised effects of pumping in shafts and boreholes as described above and illustrated in Figs. 4(a) & (b). In locations where warmer mine water is already at surface (e.g. pumped or by gravity), there is an exciting potential opportunity to harness this heat energy without significant additional drilling or pumping costs.

Discussion

A national monitoring network for mine water temperature?

The authors acknowledge that the data used in this study, whilst being the best available evidence, has been compiled from a range of sources, using varying methodologies and from both operational mines (in-situ strata temperatures) and from post closure flooded mines. The data set spans a period of 170 years (1848-2018). There are also many geographic gaps in the data coverage with nearly half of the mine water blocks having no temperature data or being assigned an average value from a surrounding coalfield. If we are to sustainably licence, regulate and model the impacts of heat recovery and storage in abandoned coal mines then systematic monitoring and mapping, utilising the existing Coal Authority infrastructure, could be undertaken to better characterise and measure the temperature of British coalfields both spatially and over time. The BGS UKGC is an ideal place to which new data could be stored, and monitoring locations should be identified and instrumented with permanent sensors to quantify temperature change over time. Monitoring near operational heat recovery and storage systems would also provide information on wider impacts of these systems against an established baseline. Permits to investigate heat from coalfields should also have the requirement that temperature data and borehole logs be submitted and added to the BGS borehole and BGS UKGC database.

Pumped v equilibrium temperatures

The equilibrium temperatures demonstrate that shallow mine water temperatures are broadly in agreement with predicted geothermal gradients for the UK. It has also been demonstrated that geothermal gradients vary between coalfields, with higher geothermal gradients in the North East, Cumbria and Yorkshire. Abstraction of mine waters in warmer coalfields could potentially result in higher temperature water occurring at shallow depths within pumped shafts and boreholes, however this is likely to be a localised effect. Each colliery or connected colliery network is likely to be different and it cannot be assumed that pumping will always result in increased near surface mine water temperature. However for a large abstraction, as may be the case for a district heating network, the possibility of higher groundwater temperatures occurring at shallower depths following pumping, should be considered in the planning phase as it may result in greater ΔT values for the heat pump system. Although the possibility of warmer temperature mine water occurring at shallow depths, due to the localised effects of pumping, may be perceived as an advantage it could also be coupled with poorer mine water chemistry, which could provide challenges including; fouling or corrosion of pipework.

Controls on mine water temperatures

This study illustrates the variability in measured mine water and strata temperatures across the British coalfields and highlights the need for a better understanding of the controls on mine water temperature, especially if we are to sustainably regulate the recovery, cooling and storage of heat. Although the regional geothermal gradients probably exert most influence over mine water temperatures, other potential drivers need to be better understood.

Characterisation of the thermal properties of surrounding and overlying strata may help assess if certain types of cover provides a 'thermal blanketing' effect, where by the thermal properties of the overlying strata help to retain heat in the mine workings. Abstraction can locally increase temperatures (Fig 4a;b) in shafts but could also potentially induce cooler recharge into the workings, although a cooling effect has not been seen in the data in this study. The effect of mine water pumping and recharge on temperature, especially where multiple schemes occur, or are planned, may require hydrogeological modelling of groundwater and heat flow if they are to operate sustainably and without negative feedback loops. Improved hydrogeological and heat flow models may be required that illustrate recharge pathways, temperature and depth of mine waters, type of workings (e.g. pillar and stall or longwall) and fault and fracture networks. Temperatures could be influenced by the residence time of mine water, and indirectly by the permeability of open and collapsed mine workings. Andrews et al (2020) suggests then when pillar and stall mine workings collapse low permeability clay rich material and mud can be added to the system potentially reducing permeability in collapsed workings, this is significant both locally when designing mine water heating and cooling schemes but also needs to be considered for future resource assessments at a coalfield/country scale. Energy from exothermic chemical reactions (e.g. oxygen and pyrite) in mine water, are considered to be relatively low where oxygen is limited e.g. below the waters surface (Banks et al 2014). However many mine workings may receive oxygenated water, for example from reinjection from heating or cooling schemes, or where oxygenated surface water rapidly recharges into mine workings (e.g. via shafts or from losing rivers). Spatiotemporal characterisation of bacterial communities in mine water discharges in the south Wales coalfield suggests that microbiomes are dominated by Fe and S oxidisers (Soares, 2019). Quantification of heat generated by these microbiomes is currently unknown and future work should consider how these microbiomes operate under different temperature regimes, especially where heat is removed or stored in coalfields. Potential ‘knock-on’ effects from heat storage in abandoned mines need to be better understood, for example what is the impact on microbial communities and chemical reactions under increasing temperature scenarios, and could this result in more clogging or precipitation in either the boreholes or mine workings?

Conclusions

This paper presents the best available dataset on the temperature of Britain’s Coalfields, despite the data being measured using various methods, in both operational mines and flooded post closure mines. Analysis of the temperature data show that;

- The median geothermal gradient in Britain’s equilibrium (not actively pumped) coalfields is calculated at 24.1˚C/km, however mean geothermal gradients in separate coalfields can vary from 17.3-34.3 ˚C/km;
- The coalfields with the highest mean geothermal gradients include; North East, Cumbria and Yorkshire all of which have mean geothermal gradients generally >30 ˚C/km, whilst geothermal gradients generally <23 ˚C/km are found in Warwickshire, South Wales, Staffordshire, and the Douglas and Fife Coalfields in Scotland.
- Comparison of mean temperatures from historic in-situ strata measurements with modern boreholes and shaft temperatures at similar depths show broad agreement, thus it is possible that older in-situ strata temperature measurements can be used to estimate post closure temperatures in coal mines;
- Two examples from active dewatering shafts show that abstraction of mine water can, in some cases, locally influence the measured geothermal gradient in shafts as deeper warmer water is drawn into the shaft, bringing warmer water closer to the surface.

Despite this study using the best available evidence there is significant potential to expand the baseline characterisation of mine water temperature in Britain's coalfield, to both better understand and regulate heat recovery, cooling and storage schemes as we move towards a low carbon economy.

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Table 1. Example of attributes used to create mine water temperature maps

Table 2. Summary of coal mine temperatures from Mine Water Blocks at 100 m depth intervals across the British coalfields. Equilibrium temperatures are in black whilst data from pumped mine water bodies are in red. Data compiled from a combination of downhole temperature profiles, bottom hole temperatures and historic strata temperatures. Data © Copyright the Coal Authority all rights reserved; © British Geological Survey, UKRI.

Table 3. Britain's coalfields ranked by order of their average geothermal gradient at 100 m depth intervals (does not include pumped data). The following coalfields are not included as they have ≤1 data point; North Wales, Leicestershire, Forest of Dean and Shropshire. Data compiled from a combination of downhole temperature profiles, bottom hole temperatures and historic strata temperatures. Data © Copyright the Coal Authority; © British Geological Survey, UKRI.

Fig. 1. Methods of temperature measurements in coalfields; 1-2, geophysical downhole logging of water filled boreholes and shafts and 3- in situ coal seam measurements in operational 'dry' mines. Diagram is not to scale and is for illustrative purpose only. Amended by Craig Woodward, BGS after Ben Gilliand © BGS UKRI.

Fig. 2. Location of coalfield 'mine water blocks' and data points used in this study. Contains Ordnance Survey data © Crown Copyright and database rights 2020. Contains Mine Water Blocks © Copyright Coal Authority (2020) all rights reserved and BGS, UKGC locations © BGS, UKRI.

Fig. 3 Box Plot of BGS UKGC (blue) and historic in-situ coal strata temperature (grey) from coalfields in equilibrium (does not include pumped data)

BGS UKGC (blue) Borehole temperature data from the BGS UKGC from all coalfields plus a 500 m radius. Data © BGS, UKRI. **'STRATA' are historic in-situ strata temperatures (grey)** from operational British coalfields (1866-1924). Box plot shows; box is upper and lower quartile; whiskers are maximum and minimum, red line mean, black line median, outlier dots are 95th and 5th percentiles. Data from HMSO, 1871; Everett 1870a, b; 1871, 1872. 1873, 1877, 1879, 1880, 1881, 1882a; Prestwich, 1887; Anon 1919-20; Davies, 1919-1920; Rees, 1920-21; Graham, 1921-22; Jones 1924; 26.

Fig. 4 A & B. **A**) Down shaft temperature profiles measured at 'Dawdon Thersea Shaft' North East England where pumping (P) started in 2010 at 100 l/s and **B**) Down shaft temperature profiles measured at 'Horden South Shaft' where pumping (P) started in 2004 at 40 l/s was increased up to

~120 l/s in 2008, and after 2008 returned to ~40 l/s. At both sites the pump inlet depth was approximately 100 mbgl. Black arrows indicate general trends of increasing temperature. Data copyright Coal Authority (2020) all rights reserved.

Fig. 5. Temperature for average (arithmetic mean) equilibrium and pumped temperatures at 100 mbgl. Dots indicate where MWB temperature has been estimated by applying average values from adjoining Mine Water Blocks within the same coalfield. Contains 1:50,000 BGS DiGMap ©BGS UKRI and Ordnance Survey data © Crown Copyright and database rights 2020. Contains Mine Water Blocks and data © Copyright Coal Authority (2020) all rights reserved.

Fig. 6. Temperature for average (arithmetic mean) equilibrium and pumped temperatures at 200 mbgl. Dots indicate where MWB temperature has been estimated by applying average values from adjoining Mine Water Blocks in the same coalfield. Contains 1:50,000 BGS DiGMap ©BGS UKRI and Ordnance Survey data © Crown Copyright and database rights 2020. Contains Mine Water Blocks and data © Copyright Coal Authority (2020) all rights reserved.

Fig. 7. Average (arithmetic mean) estimated temperature in mine water blocks in equilibrium from 300 to 600 mbgl. Dots indicate where MWB temperature has been estimated by applying average values from adjoining Mine Water Blocks in the same coalfield. Contains 1:50,000 BGS DiGMap ©BGS UKRI and Ordnance Survey data © Crown Copyright and database rights 2020. Contains Mine Water Blocks and data © Copyright Coal Authority (2020) all rights reserved.

Fig. 8. Average (arithmetic mean) estimated temperature in undisturbed mine water blocks in equilibrium from 700 to 1000 mbgl. Dots indicate where MWB temperature has been estimated by applying average values from adjoining Mine Water Blocks in the same coalfield. Contains 1:50,000 BGS DiGMap ©BGS UKRI and Ordnance Survey data © Crown Copyright and database rights 2020. Contains Mine Water Blocks and data © Copyright Coal Authority (2020) all rights reserved.

Attribute field		Example
Mine Water Body name		Nottingham South
Coalfield		Nottinghamshire
Measured Temperature Data		Yes
Minimum depth of recorded workings mbgl		0
Maximum depth of recording workings mbgl		746
100 m depth*	Average (mean) Temperature °C	11.9
	Maximum Temperature °C	12.3
	Minimum Temperature °C	11.6

*average, maximum and minimum values are entered every 100 m until the maximum depth of recorded working (rounded to the nearest 100 mbgl).

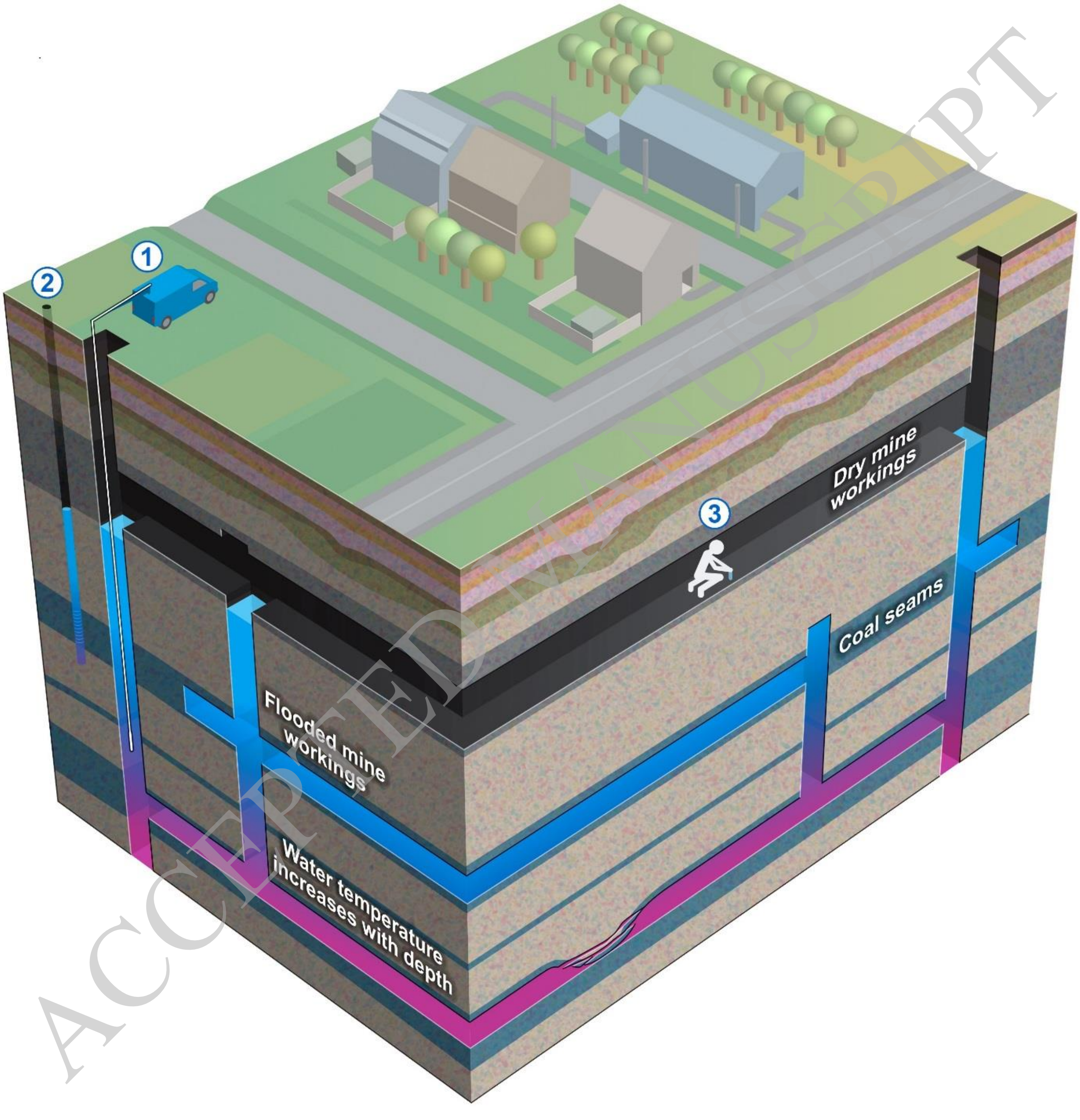
Depth mbgl	***n***	**Min T ˚C**	**Max T ˚C**	**Range T ˚C**	**Mean T ˚C**	**Median T ˚C**	**Mean Geothermal Gradient ˚C /km ⁺**
100	76	9.5	15.6	6.1	11.7	11.6	26.6
100	20	9.2	19.8	10.6	13.3	13.3	
200	76	10.7	17.8	7.0	14.2	14.3	25.9
200	16	11.8	21.5	9.7	15.1	15.1	
300	69	12.9	23.7	10.8	16.7	17.0	25.6
300	10	13.4	23.0	9.6	16.6	16.6	
400	70	14.2	25.6	11.4	19.2	19.4	25.4
400	7	13.7	21.8	8.1	16.8	16.8	
500	66	15.5	29.6	14.1	21.8	22.3	25.5
500	5	14.1	23.3	9.2	17.7	17.7	
600	53	16.8	33.6	16.8	23.7	24.4	24.5
700	51	18.1	37.6	19.5	26.2	27.0	24.6
800	44	19.5	41.6	22.2	28.2	27.9	24.0
900	34	20.8	45.6	24.9	30.8	30.1	24.2
1000	27	22.1	49.6	27.5	33.4	35.8	24.4
1100	9	23.4	52.8	29.4	37.4	34.6	25.8
1200	2	32.8	40.9	8.1	36.9	36.9	23.2

Geothermal gradients not calculated for disturbed data

n=number of Mine Water Blocks with measured data – note some MWB can have both equilibrium and pumped data

⁺ calculated using 9 ˚C as average UK surface temperature and mean temperature

				Depth below ground level m													
Coalfield	**Mean air temp ˚C 1980-2019**	**MWB total**	**MWB with data**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**	**1100**	**1200**	**1300**	**Mean Geothermal gradient ˚C/km**
North East	9.0	29	9	31.9	32.1	35.7	35.7	36.1									34.3
Cumbria	9.0	9	3	32.7	32.5	32.4	32.4	32.4									32.5
Yorkshire	9.0	10	5	32.9	31.9	31.3	30.6	31.7	31.6	32.4	32.4	32.3	32.1	36.4			32.3
Central -Scotland	8.1	2	2	35.0	30.0	28.0	28.2	27.9	27.6	29.1	29.0	29.0	29.6	34.5			29.8
Nottinghamshire	9.6	18	10	24.8	27.7	28.5	28.9	29.1	29.3	29.4	29.2	29.2					28.5
Ayrshire	7.4	5	1	27.0	26.5												26.8
Kent	10.4	4	3			25.2	25.4	25.6	24.6	26.4	26.4	26.5	26.5				25.8
Lothian	7.4	1	1	40.0	25.0	24.0	22.9	22.3	21.9	21.7	21.4	21.3	21.1				24.2
Lancashire	9.0	18	7	30.1	26.7	25.6	25.0	24.7	23.8	23.6	23.5	21.8	22.9	21.6	23.2	19.8	24.0
Bristol and Somerset	9.9	8	3	20.7	23.5	24.4	25.0	25.2	25.5	25.6	22.9	23.0					24.0
South Derbyshire	9.6	2	2	23.0	24.3												23.6
Staffordshire	9.6	11	8	17.1	19.3	20.1	21.6	22.8	23.0	23.1	23.1	23.2	23.3	30.5			22.5
Douglas	8.1	1	1	23.0	22.5	22.3	22.2	22.1	22.0	22.0	22.0	21.9	21.9				22.2
Fife	7.4	3	3	28.3	24.2	23.1	21.1	20.5	20.2	19.9	19.8	19.6	21.8				21.9
South Wales	9.9	22	17	13.5	17.6	19.0	19.3	20.2	20.5	20.7	20.9	22.3	18.4	22.5			19.5
Warwickshire	9.6	15	2	16.5	17.0	17.3	17.4	17.5	17.5	17.5	17.5	17.4					17.3
							Median geothermal gradient of British coalfields										24.1


②
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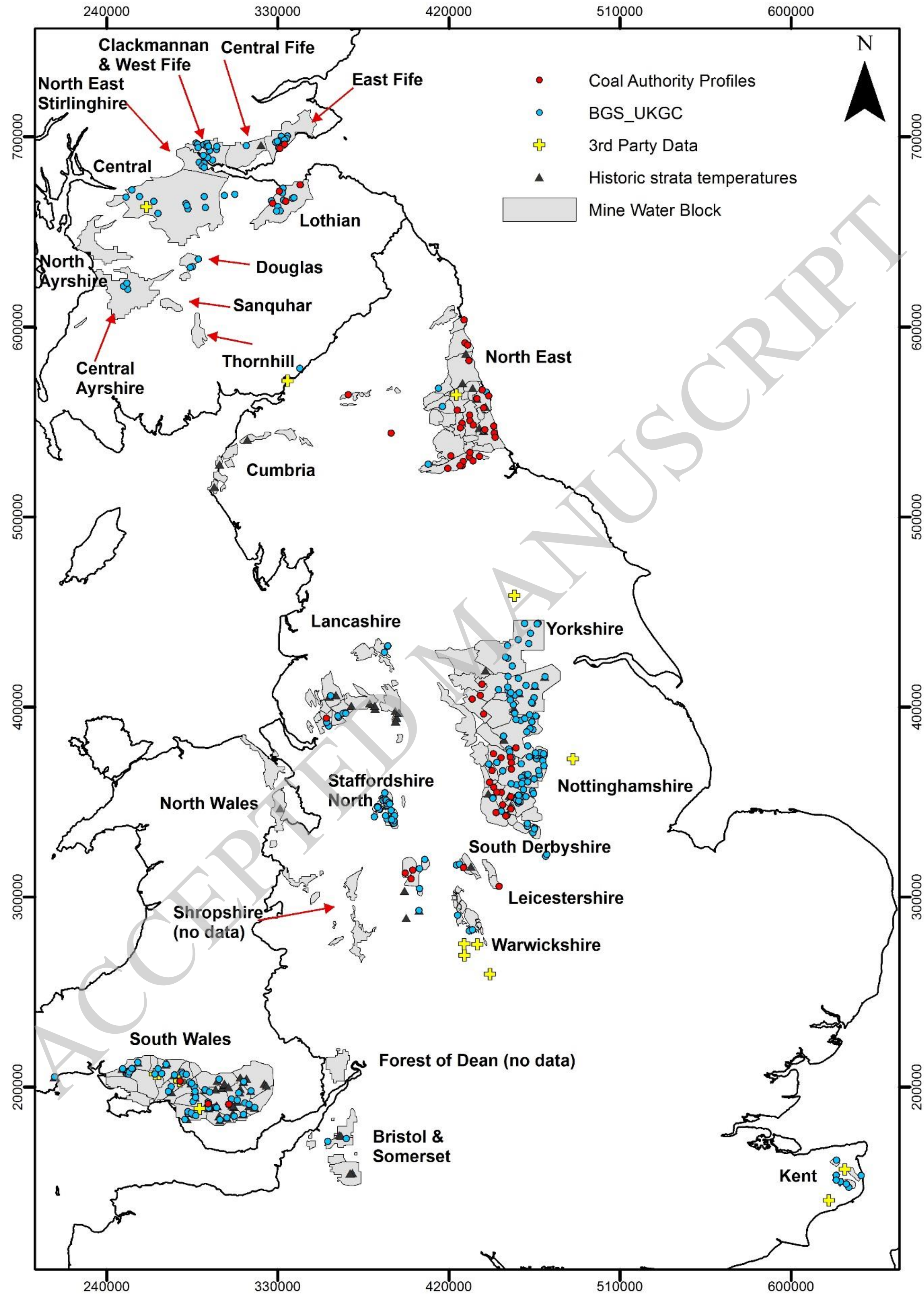
③
Dry mine workings
Coal seams
Flooded mine workings
Water temperature increases with depth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Historic strata temperatures
Mine Water Block
Clackmannan & West Fife
Central Fife
North East Stirlinghire
East Fife
Central
Lothian
North Ayrshire
Douglas
Sanquhar
Central Ayrshire
Thornhill
North East
Cumbria
Lancashire
Yorkshire
North Wales
Staffordshire North
Nottinghamshire
South Derbyshire
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Warwickshire
South Wales
Forest of Dean (no data)
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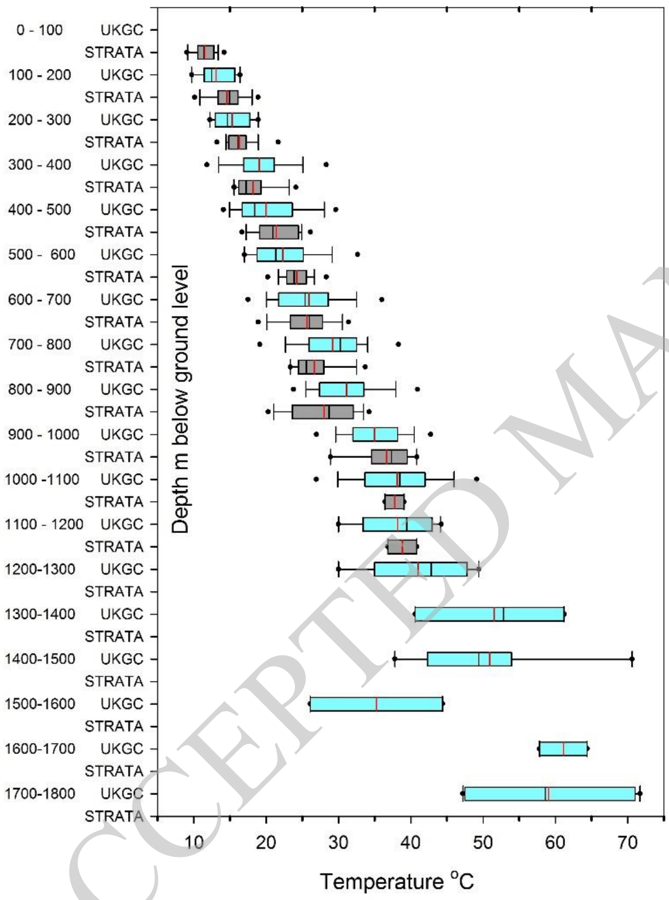
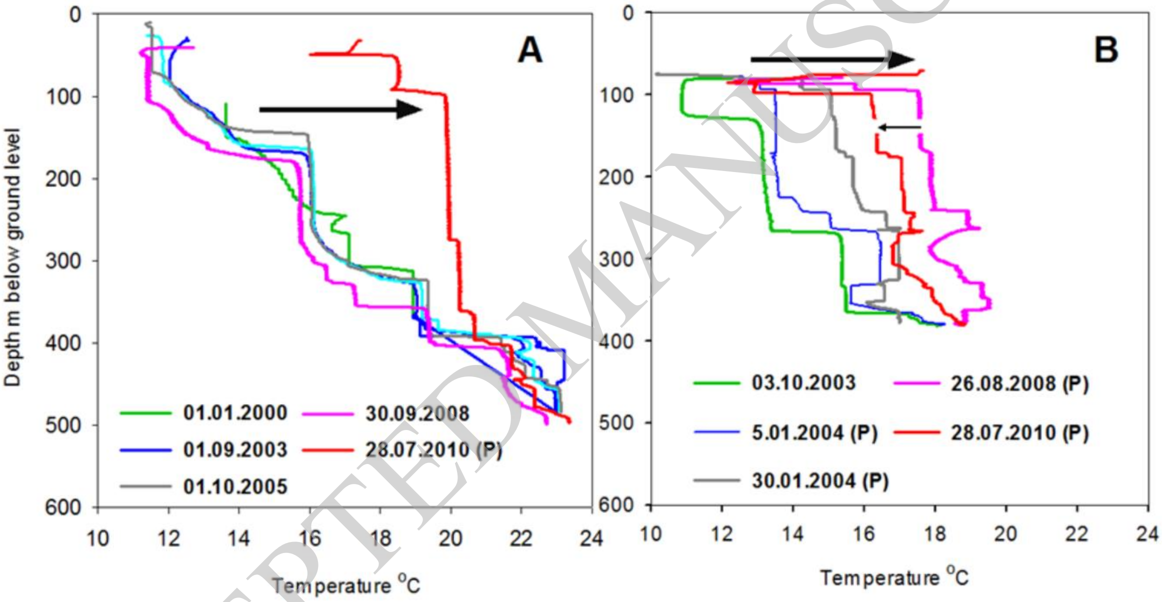
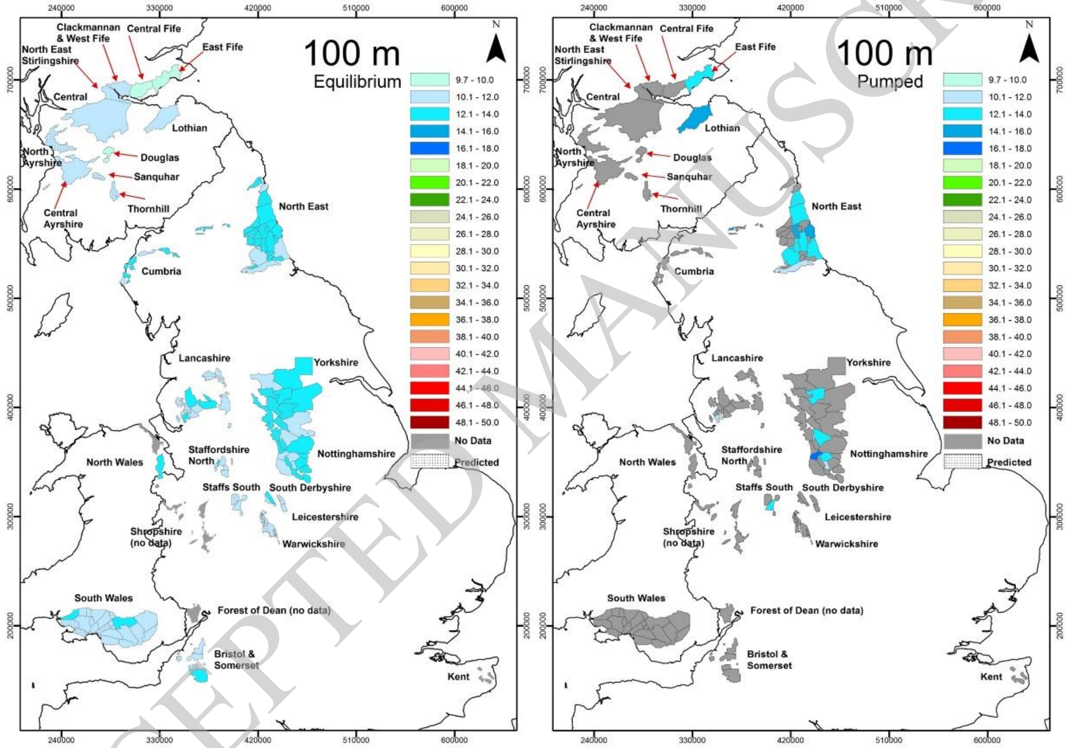
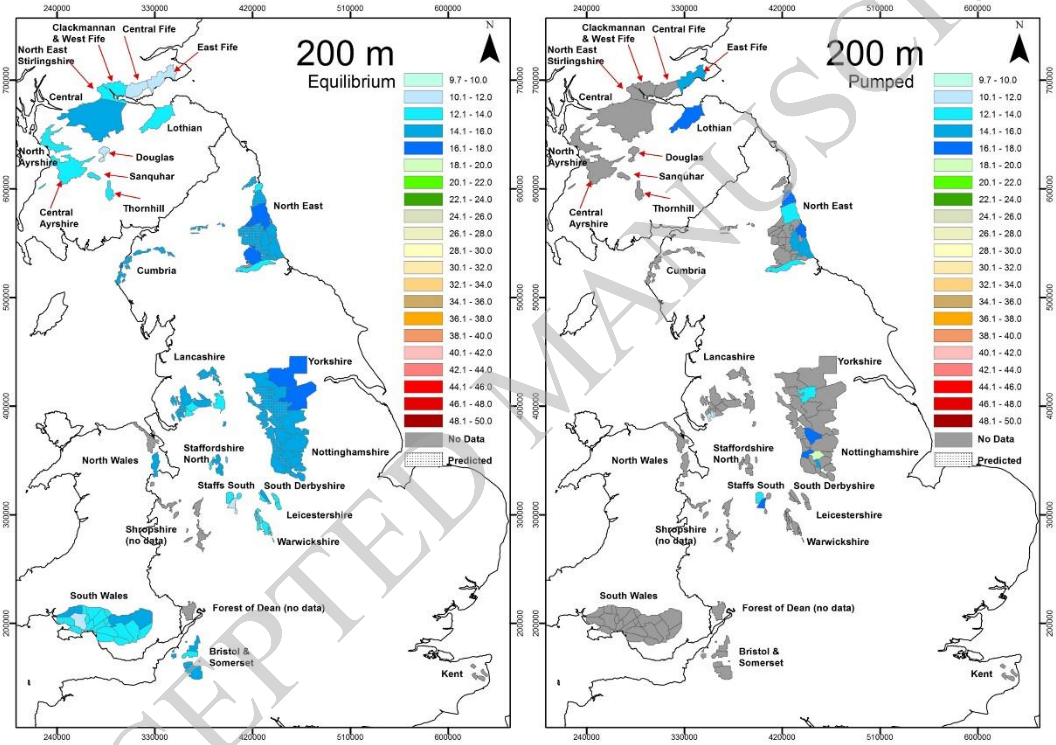
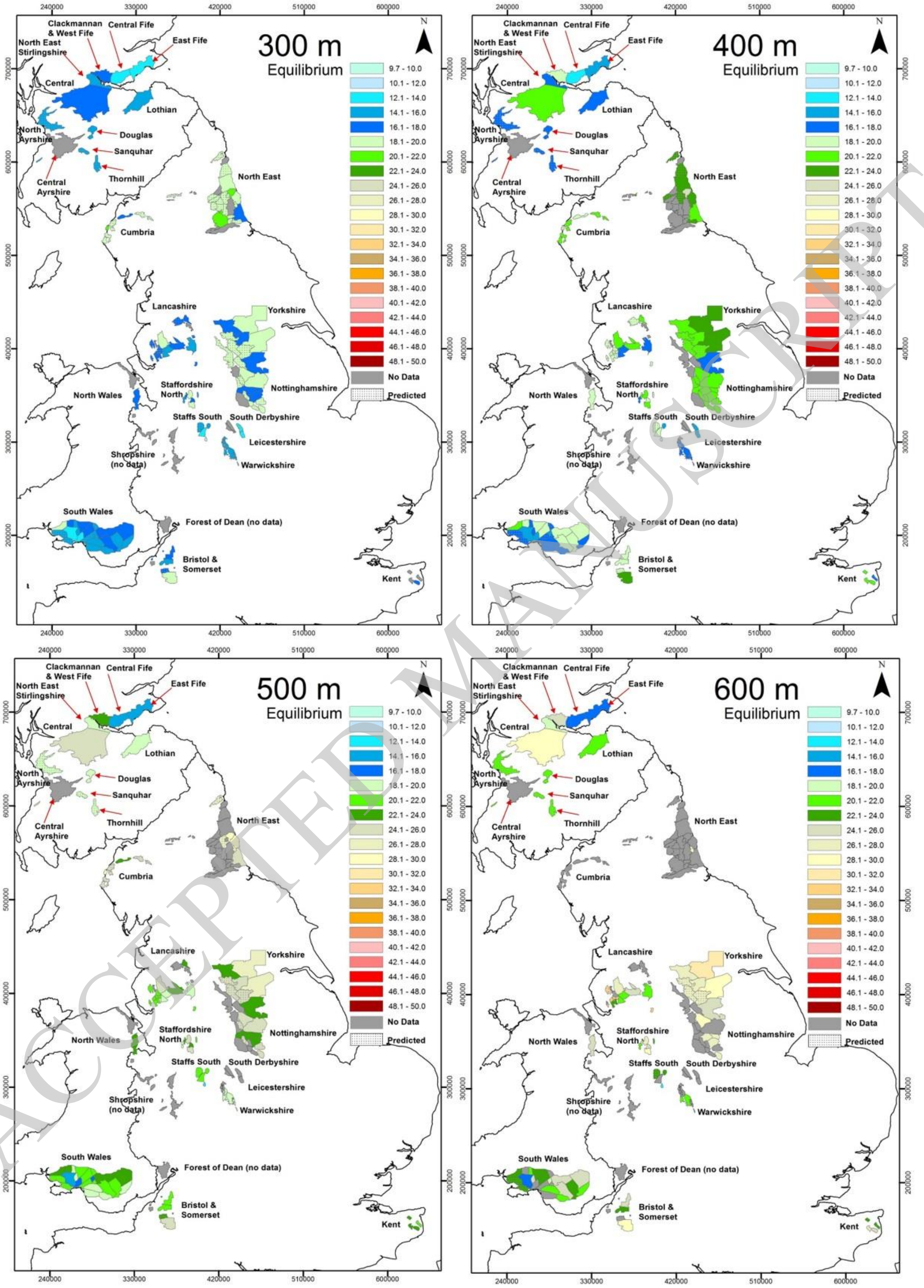


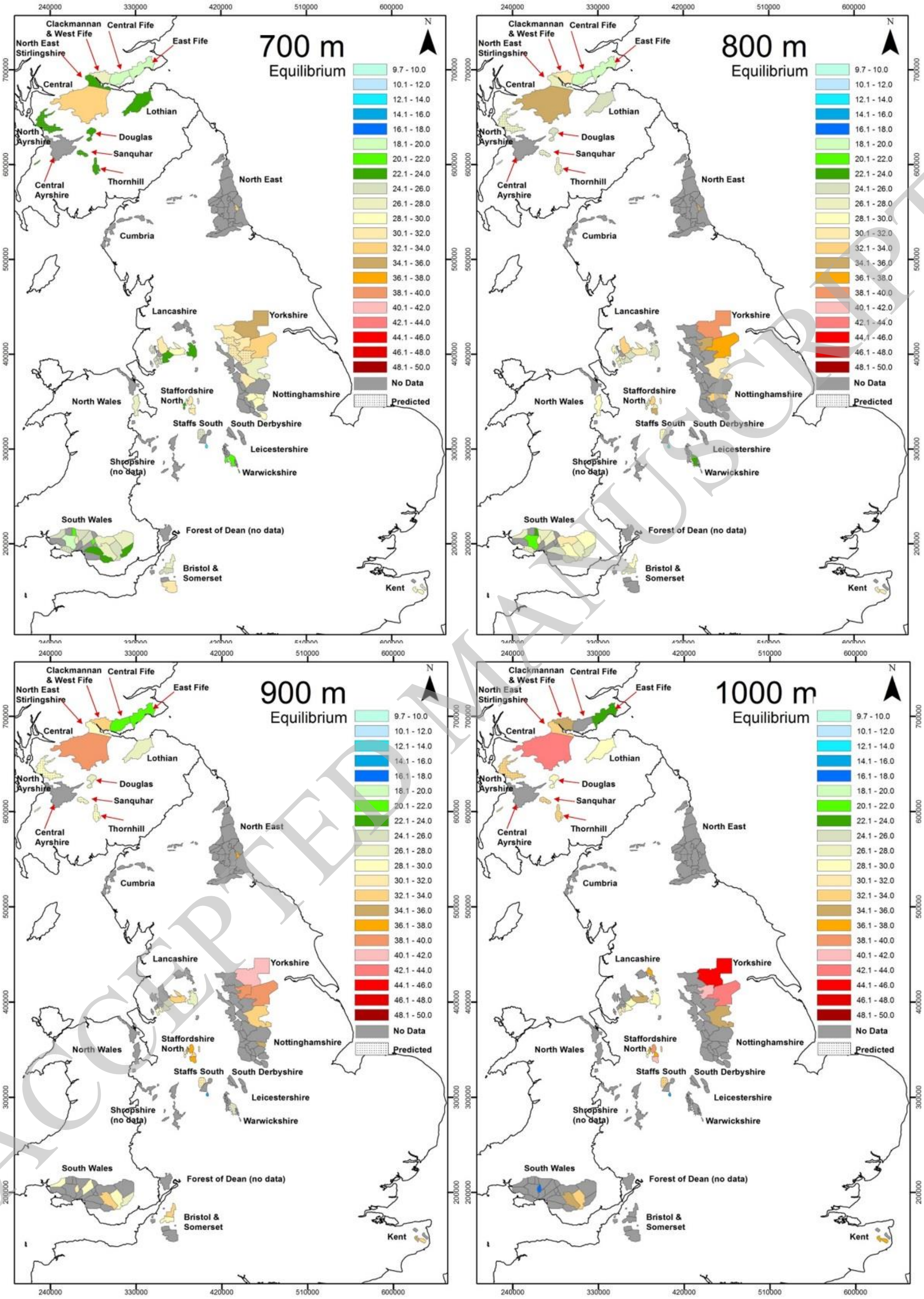
Depth mbg	Source	*n*	Max T°C	Min T°C	Mean T°C	SD	Range T°C
0 - 100	UKGC	*0*	n.a	n.a	n.a	n.a	n.a
	STRATA	*28*	14.4	9	11.5	1.5	5.4
100 - 200	UKGC	*6*	16.4	9.7	13.1	2.2	6.7
	STRATA	*39*	18.9	5.6	14.6	2.6	13.3
200 - 300	UKGC	*10*	18.9	12.2	15.3	2.5	6.7
	STRATA	*29*	23.3	12.2	16.2	2.1	11.1
300 - 400	UKGC	*19*	28.3	11.8	19.1	3.8	16.5
	STRATA	*72*	25.6	14.7	18.2	2.7	10.8
400 - 500	UKGC	*23*	29.7	14.0	20.0	4.3	15.7
	STRATA	*91*	27.2	16.4	21.4	2.8	10.8
500 - 600	UKGC	*26*	34.4	17.0	22.3	4.5	17.4
	STRATA	*53*	28.3	19.4	24.2	2.1	8.9
600 - 700	UKGC	*44*	44.4	15.0	25.9	5.4	29.4
	STRATA	*78*	32.5	18.6	25.7	3.6	13.9
700 - 800	UKGC	*28*	41.5	18.0	29.2	4.8	23.5
	STRATA	*66*	34.4	22.9	26.7	3.2	11.5
800 - 900	UKGC	*45*	41.7	21.4	31.1	4.7	20.3
	STRATA	*16*	34.2	20.3	28	4.5	13.9
900 - 1000	UKGC	*41*	43.3	26.7	35.0	4.0	16.6
	STRATA	*1*	28.9	28.9	28.9	n.a	n.a
1000 - 1100	UKGC	*24*	50.0	26.0	38.1	5.8	24.0
	STRATA	*3*	39.1	36.4	37.8	1.3	2.6
1100 - 1200	UKGC	*14*	44.2	30.0	38.2	5.0	14.2
	STRATA	*2*	40.8	36.8	38.8	2.8	4
1200-1300	UKGC	*7*	49.4	30.0	41.0	6.4	19.4
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a
1300-1400	UKGC	*3*	61.2	40.6	51.5	8.5	20.6
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a
1400-1500	UKGC	*7*	70.6	37.8	50.9	9.7	32.8
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a
1500-1600	UKGC	*2*	44.4	26.1	35.3	9.1	18.3
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a
1600-1700	UKGC	*2*	64.4	57.8	61.1	3.3	6.7
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a
1700-1800	UKGC	*4*	71.7	47.2	59.0	11.3	24.5
	STRATA	*0*	n.a	n.a	n.a	n.a	n.a


A
B
Depth m below ground level
0
100
200
300
400
500
600
10
12
14
16
18
20
22
24
Temperature °C
01.01.2000
30.09.2008
01.09.2003
28.07.2010 (P)
01.10.2005
03.10.2003
26.08.2008 (P)
5.01.2004 (P)
28.07.2010 (P)
30.01.2004 (P)


100 m
Equilibrium
100 m
Pumped
N
240000
330000
420000
510000
600000
700000
600000
500000
400000
300000
200000
Clackmannan & West Fife
Central Fife
East Fife
North East Stirlingshire
Central
Lothian
North Ayrshire
Douglas
Sanquhar
Central Ayrshire
Thornhill
North East
Cumbria
Lancashire
Yorkshire
North Wales
Staffordshire North
Nottinghamshire
Staffs South
South Derbyshire
Leicestershire
Shropshire (no data)
Warwickshire
South Wales
Forest of Dean (no data)
Bristol & Somerset
Kent
9.7 - 10.0
10.1 - 12.0
12.1 - 14.0
14.1 - 16.0
16.1 - 18.0
18.1 - 20.0
20.1 - 22.0
22.1 - 24.0
24.1 - 26.0
26.1 - 28.0
28.1 - 30.0
30.1 - 32.0
32.1 - 34.0
34.1 - 36.0
36.1 - 38.0
38.1 - 40.0
40.1 - 42.0
42.1 - 44.0
44.1 - 46.0
46.1 - 48.0
48.1 - 50.0
No Data
Predicted


200 m
Equilibrium
200 m
Pumped
N
240000
330000
420000
510000
600000
700000
600000
500000
400000
300000
200000
Clackmannan & West Fife
Central Fife
East Fife
North East Stirlingshire
Central
Lothian
North Ayrshire
Douglas
Sanquhar
Central Ayrshire
Thornhill
North East
Cumbria
Lancashire
Yorkshire
Staffordshire North
Nottinghamshire
North Wales
Staffs South
South Derbyshire
Leicestershire
Shropshire (no data)
Warwickshire
South Wales
Forest of Dean (no data)
Bristol & Somerset
Kent
9.7 - 10.0
10.1 - 12.0
12.1 - 14.0
14.1 - 16.0
16.1 - 18.0
18.1 - 20.0
20.1 - 22.0
22.1 - 24.0
24.1 - 26.0
26.1 - 28.0
28.1 - 30.0
30.1 - 32.0
32.1 - 34.0
34.1 - 36.0
36.1 - 38.0
38.1 - 40.0
40.1 - 42.0
42.1 - 44.0
44.1 - 46.0
46.1 - 48.0
48.1 - 50.0
No Data
Predicted


300 m
Equilibrium
400 m
Equilibrium
500 m
Equilibrium
600 m
Equilibrium
N
240000
330000
420000
510000
600000
700000
600000
500000
400000
300000
200000
Clackmannan & West Fife
Central Fife
East Fife
North East Stirlingshire
Central
Lothian
Douglas
North Ayrshire
Sanquhar
Thornhill
Central Ayrshire
North East
Cumbria
Lancashire
Yorkshire
Staffordshire North
Nottinghamshire
North Wales
Staffs South
South Derbyshire
Leicestershire
Shropshire (no data)
Warwickshire
South Wales
Forest of Dean (no data)
Bristol & Somerset
Kent
9.7 - 10.0
10.1 - 12.0
12.1 - 14.0
14.1 - 16.0
16.1 - 18.0
18.1 - 20.0
20.1 - 22.0
22.1 - 24.0
24.1 - 26.0
26.1 - 28.0
28.1 - 30.0
30.1 - 32.0
32.1 - 34.0
34.1 - 36.0
36.1 - 38.0
38.1 - 40.0
40.1 - 42.0
42.1 - 44.0
44.1 - 46.0
46.1 - 48.0
48.1 - 50.0
No Data
Predicted


700 m
Equilibrium
800 m
Equilibrium
900 m
Equilibrium
1000 m
Equilibrium
N
240000
330000
420000
510000
600000
700000
600000
500000
400000
300000
200000
9.7 - 10.0
10.1 - 12.0
12.1 - 14.0
14.1 - 16.0
16.1 - 18.0
18.1 - 20.0
20.1 - 22.0
22.1 - 24.0
24.1 - 26.0
26.1 - 28.0
28.1 - 30.0
30.1 - 32.0
32.1 - 34.0
34.1 - 36.0
36.1 - 38.0
38.1 - 40.0
40.1 - 42.0
42.1 - 44.0
44.1 - 46.0
46.1 - 48.0
48.1 - 50.0
No Data
Predicted
Clackmannan & West Fife
Central Fife
North East Stirlingshire
East Fife
Central
Lothian
North Ayrshire
Douglas
Sanquhar
Thornhill
Central Ayrshire
North East
Cumbria
Lancashire
Yorkshire
Staffordshire North
Nottinghamshire
North Wales
Staffs South
South Derbyshire
Leicestershire
Shropshire (no data)
Warwickshire
South Wales
Forest of Dean (no data)
Bristol & Somerset
Kent