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Results from the GeoERA MUSE shallow geothermal project – UK Cardiff pilot area

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ABSTRACT

Shallow geothermal energy systems deployment will play an important part in decarbonisation of heating and cooling of buildings. This trend will stimulate research into ground physical, thermal and hydraulic properties and impacts on urban aquifers and infrastructures. Moreover, subsurface heat extraction must be perceived as reliable, sustainable and equitable to create an environment for social acceptance and uptake of geothermal technologies. The EU H2020-funded GeoERA 'MUSE' project (2018-2021), involved 16 Geological Surveys, who shared methods and developed harmonised workflows for the evaluation of shallow geothermal resources in European urban areas (Götzl et al., EGC 2022). The project deployed and tested ground characterisation and geophysical monitoring techniques, monitored GSHP schemes, analysed the local market situation, produced fact sheets, made policy recommendations, and developed adaptive management strategies. The research included in-field monitoring studies in 14 urban pilot areas across Europe, including three UK urban pilot areas; Cardiff in south Wales, Glasgow in west Scotland and Colchester in east England. This paper summarises the result with a focus on the Cardiff area.

1. INTRODUCTION

Shallow geothermal energy systems are playing an ever-increasing role in electrification and decarbonisation of heating and cooling of buildings. The UK Government has set an interim target to reduce CO_2 emissions by 78% compared with 1990 levels by 2035, and effectively NetZero emissions by 2050. The UK Government aims to encourage the UK market to install 600,000 heat pumps per year by 2028 and a significant share of these, perhaps 10-20%, will be ground source/ water source heat pumps, marking a 20-fold increase in the 2020 UK installation rate. Most of the heat demand is in urban and residential areas and unregulated installation of a large number of GSHP schemes interfering with each other in urban aquifers is a likely future scenario. Therefore, for good planning and adaptive management it is vital that the needs and impacts of geothermal infrastructure are considered within the wider urban and transport master planning and heat network zoning. This paper aims to synthesise the key findings from the UK pilot areas for the international audience, and to sign-post the reader to the relevant outputs and new web resources.

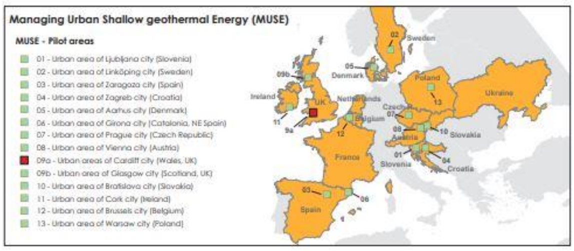

Figure 1: Location of Cardiff and Glasgow in relation to the other MUSE pilot areas. Colchester (UK) is not shown but location is shown on Figure 5.

2. METHODS

Activities in the Cardiff pilot area spanned a 2-year period between March 2019-2021. The tasks completed include:

Stakeholder workshop:

1. Early-stage stakeholder workshop in Cardiff in March 2019 to identify policy gaps and future research priorities and to share research methodologies and survey techniques with the 14 other geological survey organisations.

Field and lab work:

2. Continuous ground and river water temperature/ level monitoring for 24 months in 59 wells distributed across Cardiff, with annual down-well fluid temperature/conductivity profiling at 1m resolution. The majority of wells are installed in a typically 10 m thick shallow unconsolidated sand and gravel aquifer and/or Triassic Mercia Mudstone (marl) or older bedrock (Farr et al., 2017; Patton et al., 2020). A review and collation of available undisturbed ground temperature data was undertaken.
3. Long-term above- and below-ground monitoring at a shallow open loop groundwater source heat pump scheme (GWHP), including aquifer source temperature, water levels, heat pump system electrical consumption, air temperatures, enabled seasonal efficiency calculations (SPF). More detail is provided in Boon et al (2019).
4. Preliminary aquifer geochemical and microbiological studies: Microbial communities in groundwater can catalyse biogeochemical reactions with the potential to affect chemical speciation and redox along with other parameters. The diversity and activity of the groundwater microbial community will depend on multiple factors such as nutrient availability and temperature. An open-loop GSHP, such as the one installed in the study area, will change the biogeochemistry of the aquifer it utilises. Microbial activity has been implicated in clogging of GSHP systems, and although not observed here, understanding the effect of microbial activity is required as GSHP deployment is scaled-up and systems compete and circulate water through aquifers. The microbial community (16s rRNA) and activity of selected microbial groups (heterotroph, sulphate reducers and iron oxidisers) along with suite of geochemical analyses were analysed from groundwater collected from the GSHP system and compared to two control boreholes. Samples were collected at three time points and the GSHP system was sampled during operation and non-operational phases. Results and implications will be discussed further in Barnett et al (in prep).

Thermal property characterisation:

5. Collection of lithologically-representative bedrock cores from the Cardiff-Newport area and determination of key thermo-geological properties included natural moisture content, bulk/dry density, and effective porosity. Rock thermal conductivity (TC) and thermal effusivity was measured on saw-cut core samples in the lab using the Modified Transient Plane Source method (MTPS) using a C-THERM Trident (Canada) thermal analyser device. Calculated parameters include thermal diffusivity and specific and volumetric heat capacity. The work also included a review and comparison of data with previous conventional thermal response tests (TRT) (Van Gelder et al 2006).

Modelling:

6. Development of a groundwater model including urban infrastructure to provide a hydrogeological framework for subsequent heat flow models (e.g. Makasis et al 2021) and open loop GSHP potential mapping (Scheidegger et al. 2019).

Mapping, data and information

7. Creation of a geospatial database of existing shallow geothermal installations (open and vertical closed loop) to track deployment density and identify areas potentially susceptible to subsurface thermal interactions
8. Publication of shallow geothermal 'Fact Sheets', aimed at a wide range of technical and non-technical stakeholders, to inform them about the main thermo-geological characteristics and current GSHP market situation in Cardiff and Glasgow (Boon et al., 2021b).
9. Generation of new derived GIS raster map layers and 'Traffic-light' style open loop geothermal opportunity map for Cardiff with implementation of layers on the EuroGeoSurveys' European Geological Data Infrastructure (EGDI) platform (www.europe-geology.eu) and integration within the council's local GIS systems to aid their energy master planning and development of Sustainable Energy Action Plans (SEAPs). The project coincided with release of the BGS' open access Urban Interactive Models web tool hosted on the BGS GeoIndex that allows end-users to interact with the 1:50 000 scale 3D Quaternary geology model (Kendall et al., 2020) and allows the user to draw their own cross-sections and 'drill' virtual boreholes through the superficial deposits layers and into the top of the bedrock to support desk-top studies, developing conceptual 'geo-models', and planning of drilling works.

3. RESULTS AND DISCUSSION

The project held a full-project team workshop with invited local authority stakeholders at Cardiff Castle in late March 2019, Figure 3.

Figure 3: Photo of the MUSE project team during the 29th March 2019 stakeholder workshop at Cardiff Castle, Wales, UK.

Field work: Temperature monitoring

The plot in Figure 4 summarises shallow ground temperatures measured in Cardiff during the field work period between March 2019 and 2021.

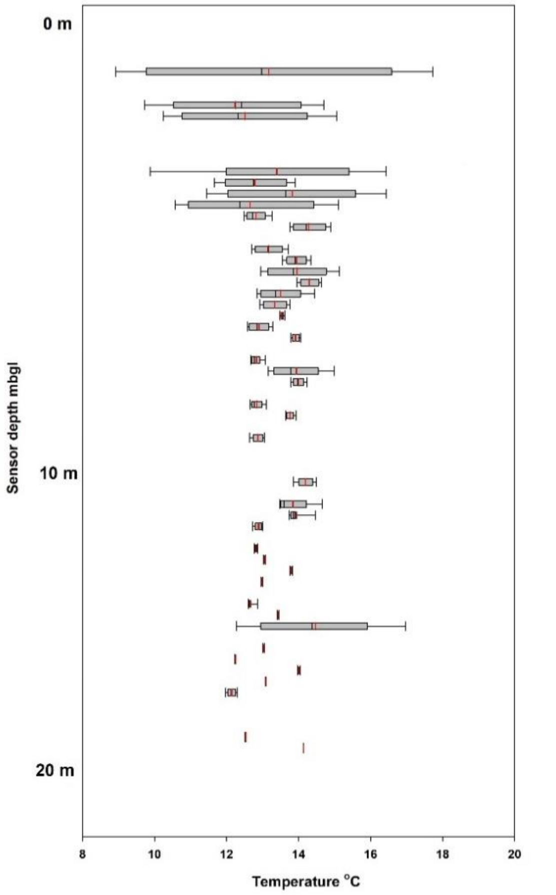

Figure 4: Summary plot of continuous (30 min) ground temperature monitoring data from 59 groundwater monitoring wells located across Cardiff (March 2019-2021). The Y axis of is relative and not to scale.

Subsoil temperatures vary seasonally between 9 °C and 18 °C, and the base of the Zone of Seasonal Fluctuation (ZSF) is around 11 m below ground surface where variation in groundwater temperature is ±2 °C, with a median value of 13 °C in the gravel aquifer.

The plot in Figure 5 includes selected temperature-depth profiles from Cardiff, Glasgow and Colchester, and provides a comparison of ground temperature variation across several UK urban areas that are all elevated <50 m above sea level but have distinctly different thermo-geological and hydrogeological regimes in the upper 100 m;

- Cardiff: ~5-20 m of variable lithology Quaternary/Holocene sediments with soft marine silts/clays and river alluvium with uncemented/unconsolidated cobbly sand and gravel aquifer resting on lower-permeability Triassic Mercia Mudstone bedrock (calcareous mudstone/marl and siltstone with thin sandstone, gypsum, conglomerate); matrix flow dominated groundwater system.
- Glasgow: ~30 m of variable lithology Quaternary/Holocene alluvium and glaciogenic deposits (till diamicton with sand and clay lenses) resting on variable permeability cyclic Carboniferous Coal Measures sedimentary rocks (sandstone, mudstone, siltstone, coal, limestone). Macro-porosity -dominated flow system;
- Colchester: ~5 m Quaternary cover sands resting on ~67 m of soft Paleogene sediments (lightly-overconsolidated clays, silts, sands) resting unconformably on Cretaceous Upper to Middle Chalk aquifer. Soft karstic limestone with duel/fracture-groundwater flow dominated.

The plots also show some distinctive features reflecting the different methods used to collect ground temperature data. The interpretation of the temperature profile data suggests Cardiff's subsurface is the warmest in the upper 100 m, while Colchester (chalk rock aquifer) is the coolest, despite their similar latitude of 51° N. The reasons the north Colchester site is cooler could be influenced by more rapid groundwater recharge (lower residence time). The site is also ~40 m higher in elevation than the other sites; Cardiff is a temperate coastal city with a strongly marine climate. Glasgow has a latitude of 55° N, and interestingly the temperature profile is intermediate, with extrapolated ground temperatures at 100 m depth estimated to be around 12 °C (Monaghan et al., 2022; Boon et al., 2021c). The ground temperature at the UKGEOS Glasgow research site was measured using a *Silixa* Fibre Optic XT-DTS hybrid cable grouted behind the casing and well screening (https://ukgeos.ac.uk/). The measurement separation is 0.25 m and stated resolution of ±0.01 °C. The relatively 'spiky' form of the DTS curve reflects the higher instrumental precision of the measurement system compared with the more standard manual temperature dip profiling approach used in Cardiff, which employed a *Solinst*® 107 TLC Meter with ±0.1°C stated accuracy and measurements recorded at 1m intervals below rest water level in the borehole. The difference between TRT-derived ground temperature profile measured in a closed loop U-tube and a profile measured in a nearby open well (Techniquest site) using a TLC Meter is around 0.5°C. The reason for this difference in ground temperature between nearby sites in the same city is not well understood; the sites are in the same bedrock geology and only 1 km apart. The surveys were taken 15 years apart using different methods with different resolution and accuracy and so further conclusions, such as the suggestion that the ground has cooled over the last 15 years by 0.5 °C, cannot be reliably made, but warrant further investigation. The continuous temperature profiling in the gravel aquifer in the Grangetown/Marl area of south Cardiff (using the same TLC Meter) has shown the undisturbed ground/aquifer temperature was consistently ~13.0 °C (±0.1 °C) at ~15 m below ground level between 2015-2021.

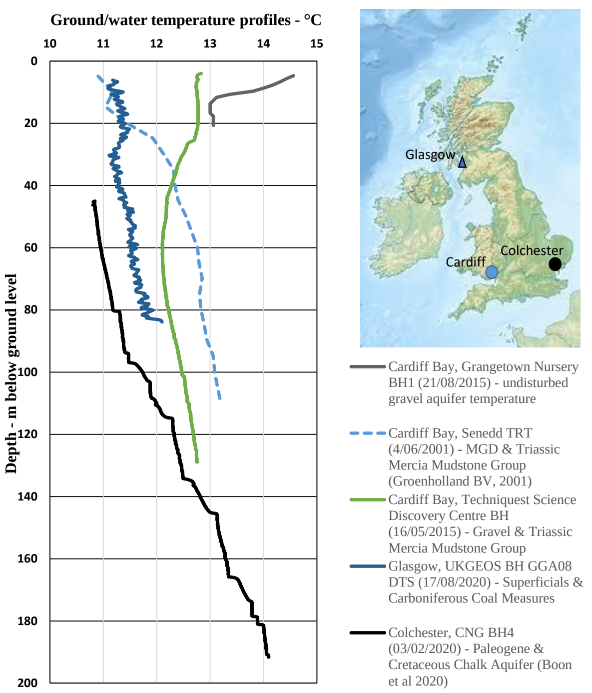

Figure 5: Plot of measured undisturbed ground temperature profiles from three UK urban areas: Cardiff, Glasgow (Monaghan et al., 2022) and Colchester (Boon et al., 2020).

The measured/estimated temperatures at 100 m depth (Fig 5) are slightly lower than the UK average mean value of 13.6 °C but close to the median value of 12.5 °C (Busby et al., 2011, n=497), with the exception of Colchester which is around 1 degree cooler than the UK median. The temperatures measured at 100 m depth in Cardiff are not quite as warm as the 14-16 °C range suggested in (Busby et al., 2011 Fig. 2), whose GIS-based map interpolation is heavily influenced by thermal springs in nearby Bristol (Hotwells), illustrating the importance of even spatial data coverage and representation of each geological structural domain for fair comparisons of thermal potential to be made between urban areas.

Lab work: Soil and Rock Thermal Properties

Typical range of thermal conductivity for the main units are summarised in Table 1. Results of thermal property analysis are detailed more fully in Boon et al., (2021a). Fresh wax-preserved mudstone samples yielded higher TC values than equivalent partially re-saturated core material. Poorly-preserved Triassic mudstone materials (naturally dried-out core) were more difficult to test, and results less reliable, due to slaking of the clay-rich materials when re-saturated under low confining stress. Thickness-averaged (harmonic mean) ground thermal conductivity estimations were calculated using fresh-core-based values and were found to be similar to TRT-derived values from the same geological profile.

Table 1: Typical thermal properties of the geological units encountered in south Cardiff. Compiled from soil and rock core analysis (Boon et al., 2021a), BGS unpublished data, and literature values.

	Unit Name (BGS Map Code)	Estimated Thermal Conductivity (saturated) (W/mK)
Artificial Deposits	Made Ground (MGR). Variable composition.	Variable. 1.0-2.0
Superficial Deposits	Tidal Flat Deposits (TFD). Soft to firm organic clay, silt, sand (mud), with thin peat lenes	1.0-1.2
	Alluvium (ALV). Riverine clay, silt, sand and gravel.	2.0-2.5
	Glacio-fluvial sheet deposits (GFSD). Sand and gravel. Aquifer.	2.0-2.5
Triassic Bedrock	Mercia Mudstone Group – argillaceous facies; silty mudstone, with thin gypsum and sandstone beds (MMG)	1.9-2.1
	Marginal Facies coarse-grained sediments; sandstone and dolomitic conglomerates (MMG-MMF)	2.1-2.9

Mapping and modelling

The GIS data layers derived from the 3D superficial geology model (Kendall et al., 2020) were resampled as 50 m grids in the EPSG:3034 map projection. Geothermal themed layers include:

- extent and thickness of glacio-fluvial sheet deposits (GFSD) that constitute the bulk of the gravel aquifer
- elevation of geological bedrock (m above OD)
- average groundwater temperature below ZSF
- piezometric heads in the shallow gravel aquifer (Fig. 6)
- point locations for existing (known) GSHP systems.

The map in Figure 7 depicts the surface geology and thickness of the gravel aquifer unit and location of the monitored open loop GSHP system (Boon et al., 2019). The green and blue areas have an aquifer thickness of >5 m and are considered to have favourable open loop GSHP potential. Other data layers include estimated drilling depth to rockhead - which also reflects minimum drilling and casing depth through superficial deposits, and elevation of top bedrock surface. Geological cross section can be freely drawn through the 3D geology model using the BGS GeoIndex tools. These can support site specific conceptualisation of the shallow geology; for example Figure 8 shows the ground conditions around the open loop GSHP in the Grangetown area. Summary geological cross-sections are also provided through the wider study area - generated from the 3D urban geology model (Kendall et al., 2020). These GIS-based map layers are viewable and downloadable on the EGDI platform (www.europe-geology.eu), and via the MUSE project website https://geoera.eu/projects/muse3. Supplementary data and reports relevant to urban geology and geothermal research in Cardiff are also accessible on NERC Open Research Archive (NORA) and the UK GeoEnergy Observatories project website (www.ukgeos.ac.uk).

Groundwater model

Comparing simulated hydraulic heads to 194 groundwater monitoring points, we we find that the model better represents observed hydraulic heads by including leakage into the sewer network. We represented this as drains in the numerical model and losses from mains water. Model calibration using Monte Carlo analysis has shown the non-uniqueness of fluxes in interaction with the sewer network, docks, the sea, and the rivers for a similar goodness of fit with the observed water levels. Consistently however, we find that the groundwater system is strongly influenced by the sewer network.

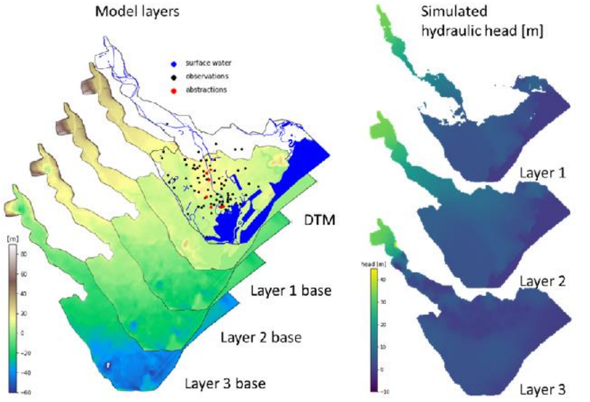

Figure 6: Groundwater model layers and simulated hydraulic head model for the gavel aquifer. The modelled aquifer layers (left) and simulated hydraulic heads (right). The layers correspond to 1) the Tidal Flat Deposits, river alluvium or glacio-fluvial deposits, 2) the glacio-fluvial deposits and 3) the Triassic Mercia Mudstone bedrock.

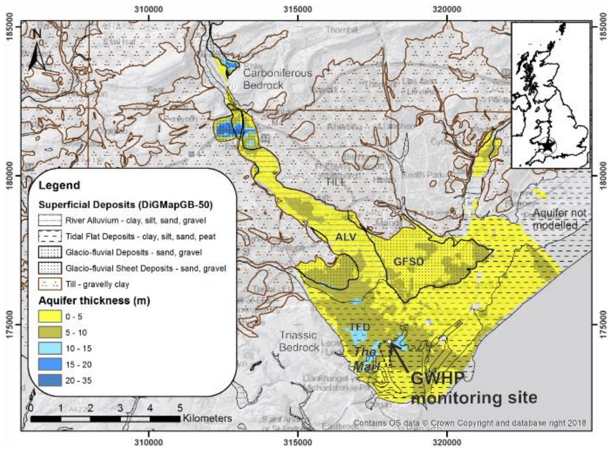

Figure 7: Surface geology map of Cardiff depicting modelled thickness of shallow glacial gravel aquifer [GFSD] and location of monitored open loop GSHP system (after Boon et al., 2019). Green and blue areas have good shallow open loop GSHP potential. Map contains BGS-UKRI map data. Grid is UK National Grid OSGB.

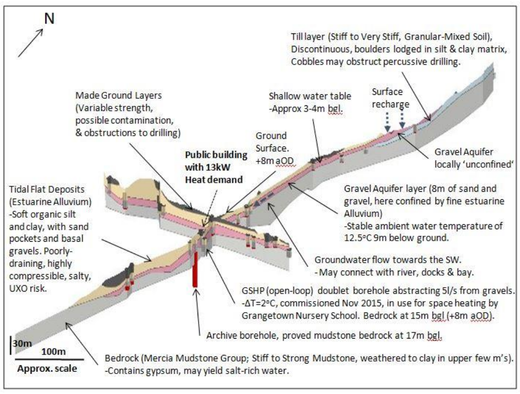

Figure 8. Example of annotated cross section using the 3D urban geology model data.

3. CONCLUSIONS

From the technical perspective, the work done in the MUSE Cardiff pilot area suggests the shallow glacial gravel aquifer is a good target for small to medium sized (20-500kW) open loop ground source heat pump systems, and the shallow drilling depths of <20m required make this option particularly cost effective for GSHP systems located on the thicker parts of this aquifer, in the west of the city. The thermal productivity of a single well doublet is likely to be limited by the sustainable yield and re-injection capacity, which has not been sufficiently pump-tested to derisk larger schemes wanting to abstract >10l/s. One small (22kWt) open loop groundwater heat pump scheme has been operating successfully in a school since 2015 with average Seasonal Performance Factor (H4) of around 4.5 (GW13/W50). Vertical closed loop schemes will also be viable almost everywhere, and there are approximately five closed loop GSHP schemes already in operation in public and multi-residential buildings. Estimated effective ground thermal conductivities in 100 m deep borehole heat exchangers installed in c.20 m of superficial deposits and c.80 m of Triassic marl bedrock will typically fall in the range of 2-3W/mK. Average undisturbed ground temperatures of 12.5°C are anticipated between 0-100 m, with ground temperatures locally enhanced by sewer network losses and underground Urban Heat Island effect. Artesian water is generally not an issue when drilling in the superficial deposits or bedrock in central Cardiff. There is one 21°C 'thermal spring' fed by upwelling water from Carboniferous Limestone aquifer at nearby Taffs Well, located on the northern boundary of the city, which is currently being repurposed for a community low carbon heating scheme. GSHP deployment in the city is under-saturated, and there is ample underground space in Cardiff for many more geothermal boreholes and geo-exchange infrastructure. GSHP schemes constructed through the aquifer are most likely to thermally interact and open loop wells spaced <30m part are likely to experience recirculation. There is also untapped potential for open loop schemes in the Ely and Taff rivers, docks, lakes, Cardiff Bay and Bristol Channel. Comparisons of urban ground temperatures in three UK cities, Cardiff, Glasgow and Colchester show some variation, but generally range between 11-13°C with Cardiff (south Wales) being the 'warmest' and Colchester (Essex, England) the 'coolest'.

From a policy perspective, the urban geothermal characterisation studies undertaken within the MUSE project have added to a growing body of information and evidence that is helping to de-risk the concept and increase confidence for investment in using shallow geothermal heating and cooling technologies (heat pumps) in the city for retrofit and new builds. The project observed that local case studies seem to have more impact on consumer confidence than overseas case studies for reducing the perceived risk of transitioning from gas to heat pumps in the UK context. On the other hand, sharing of experiences and data with European and international projects brings significant benefits for improving research and engineering capability, and seems to have high influence when it comes to inspiring local actors to consider heat pumps and low carbon district heating, equitable underground planning, and deployment and regulation of future GSHP schemes. The outcomes of the EU Horizon2020 funded activities, such as GeoERA MUSE project, have already begun to inform and support development of Local Area Action Plans, energy system decarbonisation strategies, and their legacy data (e.g. EGDI) play a small but important role in achieving the UK's Net Zero 2050 and interim targets. The project provided an opportunity to interface with local authority stakeholders and regulators in three UK urban areas, and demonstrated the value of urban geology data and high-quality environmental baseline surveys for supporting future climate change adaption measures, energy security challenges, and for creating knowledge and training resources to support the emerging geothermal energy system services supply chain in the UK.

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