Managing Urban Shallow Geothermal Energy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 4.2

Summary report about the outcomes in the pilot areas

Authors and affiliation:
Vaiva Cypaite[1], Ignasi Herms[1]
David Boon[2]
& the GeoERA-MUSE team

[1]ICGC, [2]BGS
E-mail of lead author:
Ignasi.Herms@icgc.cat

Version: 30-07-2021

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data		
Deliverable number	D4.2	
Dissemination level	Public	
Deliverable name	Summary report about the outcomes in the pilot areas	
Work package	WP4, Testing and implementation of developed methods and workflows in urban pilot areas across Europe	
Lead WP/Deliverable beneficiary	ICGC	
Deliverable status		
Submitted (Author(s))	30/07/2021	Ignasi Herms
Verified (Work package leader)	27/10/2021	Ignasi Herms
Approved (Project coordinator)	29/10/2021	Cornelia Steiner, Gregor Goetzl

EXECUTIVE SUMMARY

The summary report covers the WP4 fieldwork activities undertaken in 14 pilot areas and results achieved. Detailed description of activities undertaken in each pilot area (2019-2021), outcomes of performed field measurements and GIS datasets of each pilot area are available in chapter 2. Furthermore each pilot area also evaluated impact of achieved results on local management and energy strategies and lessons learned in each pilot area. Finally, an overall analysis of all activities and comparison between field measurements in different pilot areas is provided, as well as recommendations on geoscientific data assessment and mapping of shallow geothermal resources in urban areas.

Involved MUSE team

Project partner	Participants
Geološki zavod Slovenije, GeoZS	*Mitja Janža, Simona Adrinek, Dejan Šram*
Sveriges Geologiska Undersökning, SGU	*Mikael Erlström*
Instituto Geológico y Minero de España, IGME	*Eduardo Garrido, Alejandro García, Miguel Mejías, Carlos Baquedano, Cristina Pérez*
Hrvatski Geološki Institut, HGI-CGS	*Staša Borović, Kosta Urumović, Marco Pola, Mirja Pavić*
Geological Survey of Denmark and Greenland, GEUS, P16	*Claus Ditlefsen, Mette H. Mortensen, Anders J. Kallesøe, Thomas Vangkilde-Pedersen*
Institut Cartogràfic i Geològic de Catalunya, ICGC	*Ignasi Herms, Georgina Arnó, Vaiva Cypaite, Víctor Camps, Montse Colomer, Ariadna Conesa*
Česka Geologicka Služba – Czech Geological Survey	*Jan Holeček, Jaroslav Řihošek*
Geological Survey of Austria, GBA	*Cornelia Steiner, Gregor Goetzl*
British Geological Survey-Natural Environment Research Council, NERC-BGS	*David Boon, Gareth Farr, Ashley Patton, Corinna Abesser, Johanna Scheidegger, Jon Busby, Laura Williams, Alan Holden, Steve Thorpe, Andy Butcher, Barry Townsend, Mark Woods, Alison Monaghan, Kirsty Shorter*
State Geological Institute of Dionyz Stur, SGIDS	*Radovan Cernak, Jaromir Svasta*
Geological Survey Ireland, GSI	*Sarah Blake, Harrison Bishop, Taly Hunter Williams, Max Meakins, Alasdair Pilmer, Ross Mowbray*
Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium, RBINS-GSB	*Pierre-Yves Declercq, Estelle Petitclerc*
Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO	*Stefan Carpentier, Vincent Vandeweijer*
Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, PIG-PIB	*Maciej R. Kłonowski, Jacek Kocyła, Mateusz Żeruń*

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation, acronym	Full name
ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger
BTES	Borehole Thermal Energy Storage
CAPEX	Capital Expenditure (Investment costs)
CCS	CO_2 Capture and underground Storage
DAS	Distributed Acoustic Sensing
DTRT	Distributed Thermal Response Tests
DTS	Distributed Temperature Sensor
EGDI	European Geological Data Infrastructure (http://www.europe-geology.eu/)
FO	Fibre Optic
FO-DAS	Fibre Optic Distributed Acoustic Sensing
GIS	Geographical Information System
GSHP	Ground Source Heat Pump
GT	Geothermal
GWHE	Groundwater Heat Exchanger
GWHP	Groundwater Heat Pump (water-to-water heat pump)
HDD	Heating Degree Days
HT-ATES	High Temperature Aquifer Thermal Energy Storage
HTES	High Temperature Energy Storage
NMO	Normal Moveout
SGE	Shallow Geothermal Energy
TCS	Thermal Conductivity Scanner
TRT	Thermal Response Test
TWT	Two-Way Travel time
VLF	Very Low Frequency
VSP	Vertical Seismic Profile
WMS	Web Map Service
WSHP	Water-Source Heat Pump

1 INTRODUCTION

1.1 Description of the deliverable

This summary report covers the research activities undertaken in all 14 MUSE project urban pilot areas as well as the results achieved. It also contains comparative conclusions and lessons learned on the testing and implementation of methods and workflows developed in work packages WP2 and WP3.

1.2 Scope of the report

The summary reports focuses on the following activities performed in the GeoERA-MUSE pilot areas:

- Assessment of geoscientific field data including measurements, monitoring and modelling linked to GeoERA-MUSE,
- Preparation of GIS based datasets, which were integrated in the web based decision support and information tool on shallow geothermal energy use at EGDI platform.

The outcomes of the performed activities, including short explanatory notes, are described for each pilot area in chapter “Outcomes in the pilot areas”. This report also concludes on the lessons learned and impacts achieved in MUSE for each pilot area and for the project as whole with regard to WP3. This report furthermore provides a lessons chapter on the implementation of the ‘harmonized catalogue of workflows’ with regard to WP2. In the final chapter of this report, recommendations are provided as well as an outlook on possible follow-up activities of EuroGeoSurveys with regard to field data assessment as well as shallow geothermal resource mapping in urban areas.

1.3 Overview of the MUSE pilot areas

Between 2019 and 2021 14 urban areas across Europe with different geological, hydrogeological and climatic conditions have been working towards better management of urban geothermal energy. This chapter briefly introduces and describes each pilot area. This information is complimented by a series of digestible Factsheets (v1) which were prepared by partners in the early stage of the MUSE project and published on the MUSE webpages.

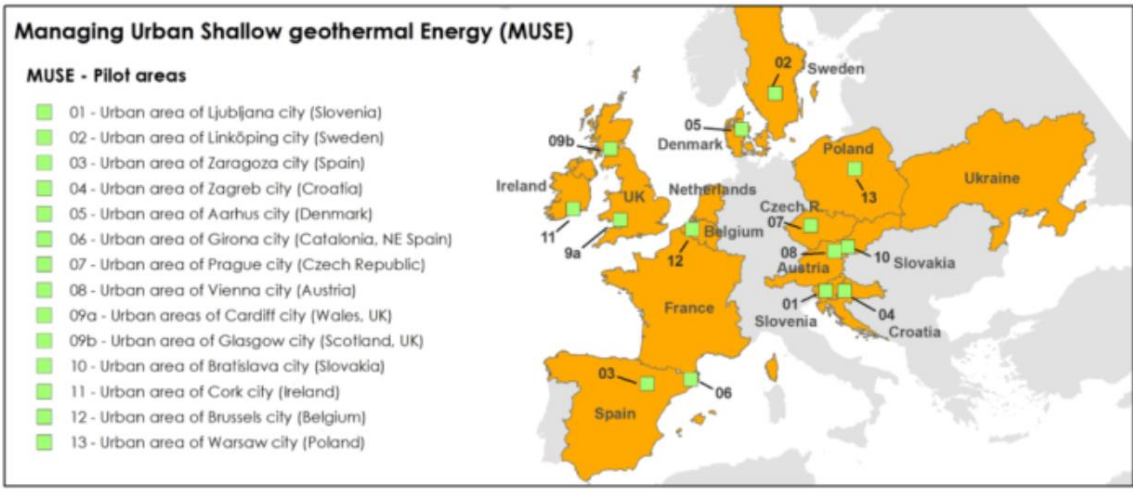

Figure 1. Map highlighting location of MUSE- Pilot areas.

MUSE pilot areas (Figure 1):

1. Ljubljana pilot area (Slovenia)

Population:	289 500 (2018)
Area:	65 km^2
Mean annual temperature:	10.9°C
Elevation:	265 - 320 m a.s.l.
Study focus:	Analyzing potential hazards and interferences and integration of these aspects into strategies and actions for integrated groundwater management

2. Linköping pilot area (Sweden)

Population:	158 841 (2018)
Area:	11.1 km^2
Mean annual temperature:	6.1°C
Elevation:	35 to 45 m a.s.l.
Study focus:	Investigation of possible installation of Borehole Thermal Energy Storage schemes, to shift 100 GWh heat from summer to winter

3. Zaragoza pilot area (SE Spain)

Population:	697 895 (2018)
Area:	106.03 km^2
Mean annual temperature:	15.3°C
Elevation:	184-265 m a.s.l.
Study focus:	Assessment of SGE resources and possible conflicts of use, groundwater monitoring, and development of tailored management strategies

4. Zagreb pilot area (Croatia)

Population:	802 338 (2018)
Area:	641 km^2
Mean annual temperature:	10.9°C
Elevation:	120 - 1,033 (majority 120 - 300) m a.s.l.
Study focus:	Influence of open loop groundwater heat pump systems at two locations

5. Aarhus pilot area (Denmark)

Population:	336 411 (2017)
Area:	469 km^2
Mean annual temperature:	8.9°C
Elevation:	0 -128 (1-100 populated) m a.s.l.
Study focus:	Investigation of the possible integration of SGE and energy storage in a mature central heating system

6. Girona pilot area (Catalonia, NE Spain)

Population:	138 702 (2016)
Area:	48 km^2
Mean annual temperature:	14.7°C
Elevation:	65 - 186 m a.s.l.
Study focus:	Data collection, ground characterization, 3D modelling and mapping of SGE resources

7. Prague pilot area (Czech Republic)

Population:	1 294 513 (2018)
Area:	496 km^2
Mean annual temperature:	11.2°C
Elevation:	177 – 399 m a.s.l.
Study focus:	Assessment of SGE resources and possible conflicts of use due to overexploitation

8. Vienna pilot area (Austria)

Population:	242 000 (2017)
Area:	43.5 km^2
Mean annual temperature:	11.8°C
Elevation:	150-170 m a.s.l.
Study focus:	The assessment of SGE resources and possible conflicts of use due to overexploitation.

9. Cardiff pilot area (Wales, UK)

Population:	346 000 (2012)
Area:	140 km^2
Mean annual temperature:	10.8°C
Elevation:	0-30 m a.s.l.
Study focus:	Aquifer characterization, groundwater and thermal monitoring and modelling, resource and conflict maps as a basis for future planning, management and evidence-based clean energy policy development.

10. Glasgow pilot area (Scotland, UK)

Population:	621 020 (2017)
Area:	45.7 km^2
Mean annual temperature:	8.3°C
Elevation:	0-196 m a.s.l.
Study focus:	Analyzing the feasibility of exploiting a network of abandoned flooded coal mines for seasonal cavern thermal energy storage (CTES)

11. Bratislava pilot area (Slovakia)

Population:	429 564 (2017)
Area:	367 km^2
Mean annual temperature:	10.5°C
Elevation:	126 – 514 m a.s.l.
Study focus:	Monitoring of thermal, hydraulic and chemical regime of shallow aquifers in order to evaluate possible conflicts of use between drinking water supply and SGE use

12. Cork pilot area (Ireland)

Population:	125 622 (2016)
Area:	40.7km^2
Mean annual temperature:	9.7°C
Elevation:	0 - 115 m a.s.l.
Study focus:	Creation of SGE resource and conflict maps as a basis for future planning and management of SGE use

13. Brussels pilot area (Belgium)

Population:	1 205 309
Area:	161.38 km^2
Mean annual temperature:	11.8°C
Elevation:	10 - 130 m a.s.l.
Study focus:	Characterizing the shallow subsurface below Brussels with regard to SGE use by different exploration methods

14. Warsaw pilot area (Poland)

Population:	1 764 615 (2018)
Area:	517 km^2
Mean annual temperature:	8.3°C
Elevation:	78-121 m a.s.l.
Study focus:	Preparation of a GIS database, gathering of borehole data, geophysical investigations and the acquisition of new thermal properties data in the field and lab.

2 OUTCOMES IN THE PILOT AREAS

2.1 City of Ljubljana (Slovenia)

Mitja Janža, Simona Adrinek, Dejan Šram
Geological Survey of Slovenia

2.1.1 Focus of activities inside GeoERA-MUSE

The pilot area of Ljubljana is one of the most urbanized areas in Slovenia. The share of geothermal energy use for heating and cooling in the pilot area is currently very low. In the area of interest conflicts between shallow geothermal energy (SGE) systems and other uses of the subsurface (e.g., drinking water supply) can be expected in the future. The aim of the activities in the pilot area is to analyse geothermal potential, hazards and interference between SGE systems and other subsurface uses and to integrate these aspects into strategies and actions for integrated groundwater management and sustainable use of subsurface resources. The planned activities included continuous measurements of groundwater level, temperature and electrical conductivity, established in 12 observation wells in the urban area of Ljubljana. The obtained data were implemented in the 3D geological model of the pilot area, which was used together with the field measurements to update the GIS layers of measured groundwater depth/level and groundwater temperature.

2.1.2 Outcomes of field measurements

In 2017, continuous measurements in the observation wells in the Ljubljana municipality area were established within the GeoPLASMA-CE project. In 2019, 12 of these observation wells were included into the MUSE monitoring system (Figure 2). Single-level (7 locations) and multi-level (5 locations) measurements were performed with GSR 120 NTG loggers, measuring groundwater temperature, water level and electrical conductivity of groundwater at one-hour intervals. The spatial distribution of measurement locations was designed to capture the influence of factors which impact groundwater temperature in the study area (e.g., recharge from the Sava River and the impact of the urban area). Manual groundwater level and temperature measurements were taken in the selected wells during the project (Figure 2).

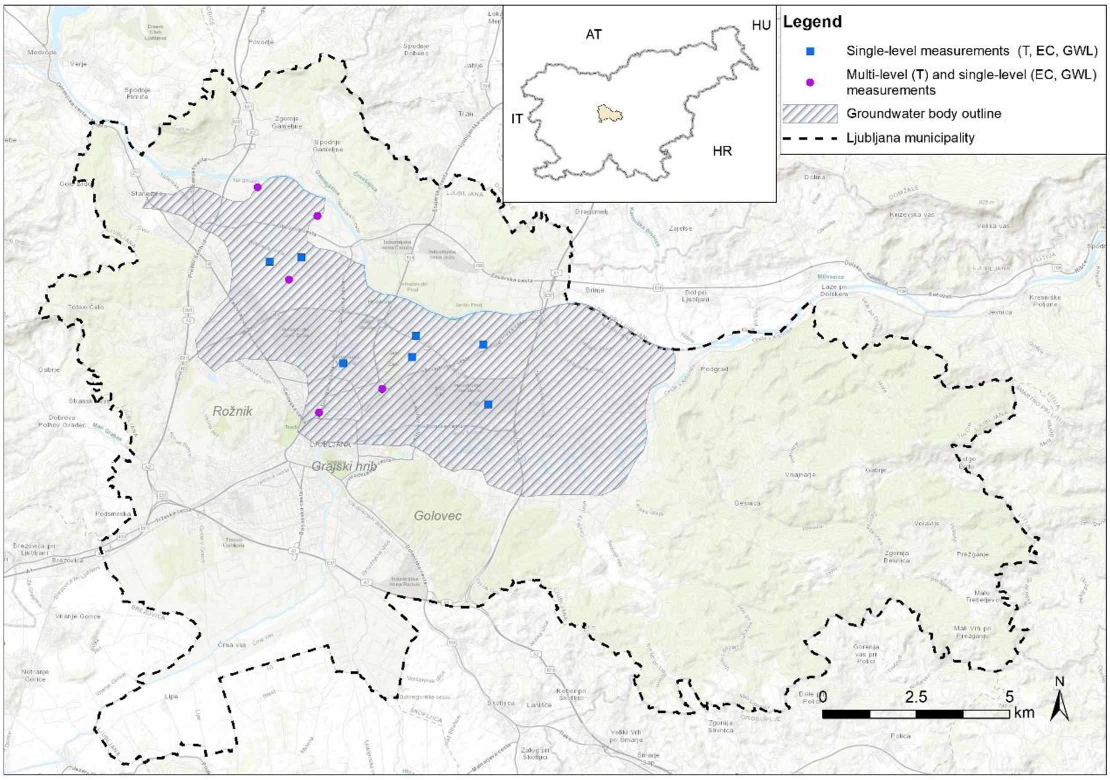

Figure 2. Ljubljana urban area groundwater monitoring network. Figure demonstrates groundwater monitoring points, where groundwater temperature, water level and electrical conductivity were monitored during the period 2019 – 2021.

2.1.3 Outcomes of GIS datasets delivered to EGDI

The parameters used in the study were chosen to determine geothermal conditions in the subsurface of the study area and factors that determine these conditions for shallow geothermal utilisation.

List of GIS datasets provided to EGDI:

1. **Land surface temperature (degC)** is a raster dataset which represents the average annual surface temperature distribution in the Ljubljana pilot area. It is derived from the MODIS Land Surface Temperature Dataset, at 250 m pixel resolution.
2. **Thermal conductivity (W/mK)** is a raster dataset which represents the average thermal conductivity at the pilot area from 0 – 100 m depth.
3. **Subsurface infrastructure** is a vector dataset which represent the underground subsurface infrastructure (electricity, sewage, water etc).
4. **Average subsurface temperature (degC)** is a raster dataset which represent the estimated annual average subsurface temperature for a 0 – 100 m depth interval.
5. **Natural reserves** is a vector dataset which represents the areas of natural reserves at the pilot area.

6. **Groundwater protection areas** is a vector dataset that represents drinking water protected areas (safeguard zones) to sustain safe drinking water supplies.
7. **Groundwater body** is a vector dataset that outlines the Quaternary aquifer.

2.1.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

MUSE project has contributed to disseminate knowledge on SGE and to promote the use of SGE resources. It has also provided an opportunity to participate in some SGE projects in the pilot area.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

The activities within the MUSE project enabled us to continue cooperation with local stakeholders and update of existing databases created in GeoPLASMA-CE project. The measurements carried out provided new data on subsurface conditions, in particular on aquifer and groundwater properties, which will help in planning of new geothermal systems in the Ljubljana pilot area.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

The datasets updated in MUSE project are prepared in a form that can be implemented in local energy plan and the spatial plan of the City of Ljubljana. Local authorities have expressed interest to include information on SGE potential into their planning strategies.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

The datasets and information produced have been used in two SGE projects in the area of Municipality of Ljubljana: for the planning of the heating and cooling of the planned Science Centre and for the construction of an open-loop system for the heating of the primary school (part of the refurbishment).

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

In Slovenia, permitting procedures are regulated by national authorities and it is not expected that the datasets produced will be used for that purpose.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

All the datasets produced for the Ljubljana pilot area will be available at EGDI webpage and its WMS services. Data are going to be available for all users directly from GeoZS on request.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management in your pilot area? If yes, please provide a brief explanation

No.

Table 2.1.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Ljubljana.

Permitting and licensing procedures	**2**
Local environmental, energy and climate mitigation strategies	**5**
Spatial planning including energy plans	**5**
Investment decisions by public or private entities	**4**
Local (web based) information systems	**4**
Other aspects – *please specify*	**-**

2.1.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

The workflows applied in the project area enabled elaboration of output data sets in a standardised way. Scientifically sound workflows and access to datasets through EGDI will assure good applicability of project results.

2. Performance of field measurements in comparison to the initial plans

In Ljubljana pilot area the initial plans were achieved regarding the field measurements. A monitoring network of 12 observation wells obtained the data, with a few periods of measurement failure due to equipment damage. The lengths of observation time series are different for each observation well due to optimisation of the observation network.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

The field work and data analysis enabled us more accurate and reliable spatial interpretation of geothermal parameters in the pilot area.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

There were no major deviations in field work and the preparation of output data sets. All selected and delivered output datasets were prepared based on the measured data.

2.1.6 Outlook

It would be very useful to use MUSE datasets to upgrade 3D groundwater flow and heat transport models and use it for simulation of the impact of new SGE installations.

2.2 City of Linköping (Sweden)

Mikael Erlström

Geological Survey of Sweden

The pilot study focuses on providing geological guidance to the design and placing of a large-scale High Temperature Energy Storage (HTES) in Linköping in the eastern part of south Sweden (Figure 3). Linköping municipality has c. 160 000 inhabitants of which c. 106 000 live in the city of Linköping, which is the fifth largest city in Sweden.

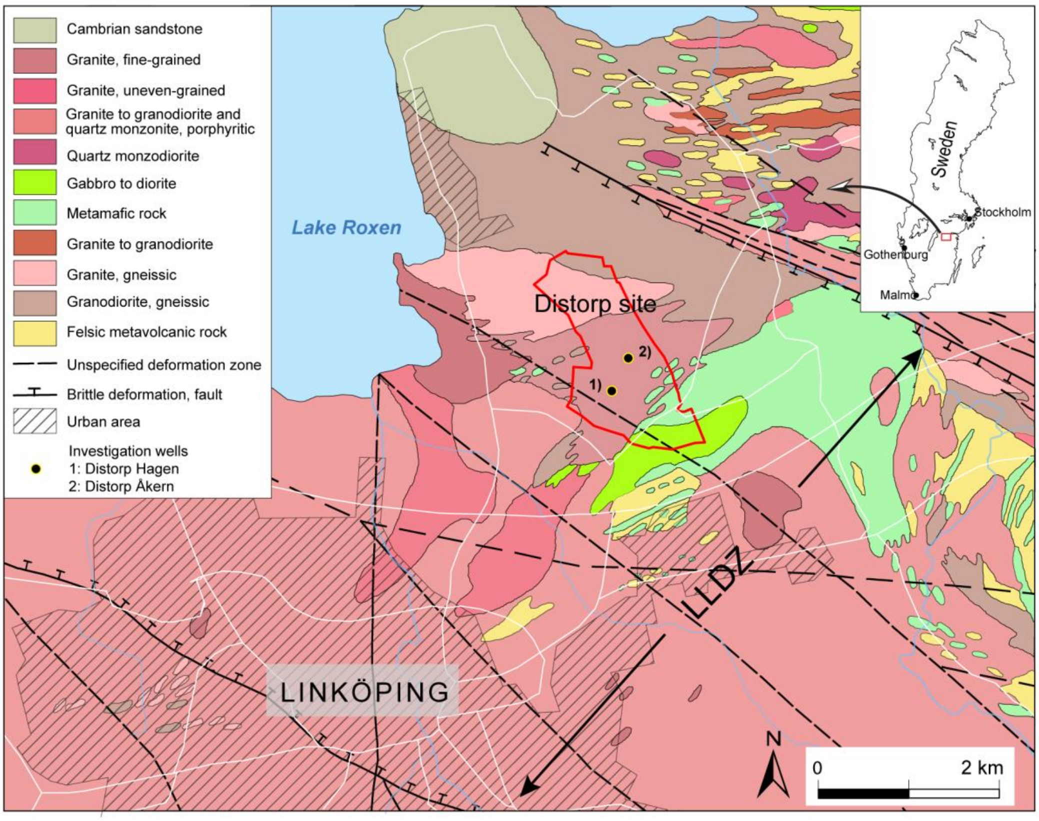

Figure 3. Geological map with the location of the Distorp site, i.e Linköping pilot study area (modified after Hesselbrandt et al., in prep.).

The average yearly temperature in Linköping is 6.1°C, where the monthly average temperatures range between -2.7°C in the winter and 16.8°C in the summer. The number of yearly heating degree days (HDD) is 4682 (period 2011–2016). The relatively high HDD value results in a great need for heating. Today the heating demand in the city is mainly provided by a district heating system powered by a waste incineration plant, with a heat capacity of 510 GWh corresponding to the heating of about 25 000 houses. In the

Linköping municipality there is also c 4000 private, primarily closed looped SGEs in the crystalline basement.

The local energy company (Tekniska verken in Linköping AB) explores, as a step towards sustainable use of excess heat from the incineration plant to build a HTES in the crystalline bedrock. The aim is to facilitate a switch c. 70 GMh heat between summer and winter. This would increase the flexibility between energy supply and demand as well as a possibility to phase out an older fossil fuelled plant. The initial design includes up to 1300 wells to 300 m depth in the crystalline basement.

To get a high level of confidence on the geological conditions for a large-scale HTES plant is a challenging task and requires a toolbox with various methods. General assumptions are often enough for smaller and low temperature BTES. However, large-scale high temperature systems connected to district heating production requires that the geological conditions are better known.

The pre-studies regarding the HTES at Linköping began already in 2017, before the start of the MUSE-project. The Geological Survey of Sweden was already contacted for support on the procurement of the investigation boreholes. This first phase included drilling of two 300 m deep percussion drilled boreholes and descriptions of rock cuttings, measuring groundwater levels and temperatures, performing hydraulic capacity tests, thermal response tests (TRT) and distributed thermal response tests (DTRT) (Acuña, Stokuca, Mazzotti, & Munter, 2018).

Subsequently it was possible to use this data and complement it with new field data performed within the GeoERA-MUSE project. This allowed us to evaluate and test the applicability of various geophysical methods for assessing the geological site prerequisites. Ground geophysical surveys with magnetometer and Very Low Frequency (VLF) Method combined with borehole investigations, geophysical wireline logging, thermal conductivity measurements and drone mapping of fractures were performed.

2.2.1 Focus of activities inside GeoERA-MUSE

The overall aims were:

- to evaluate the applicability of different field methods, not typically applied in pre-investigations,
- to exemplify how multi-disciplinary pre-investigations can support the placing and design of a HTES system,
- to provide guidance on how and what type of geological information can be relevant to collect for a large-scale geothermal system in a crystalline bedrock setting.

The planned and performed field-investigations resulted, besides an updating of the data-base on thermal properties of various rock types, in a magnetic grid and grid of the evaluated thermal conductivity for the bedrock surface. The depth to the bedrock surface, i.e. overburden thickness already exists at the Geological Survey of Sweden but it is also included in the GIS deliverable.

2.2.2 Outcomes of field measurements

Figure 4 presents the various steps of the multi-disciplinary investigations and methodologies used as well as the obtained properties involved in the evaluation of the Linköping site, these being potentially crucial as input to the HTES modelling.

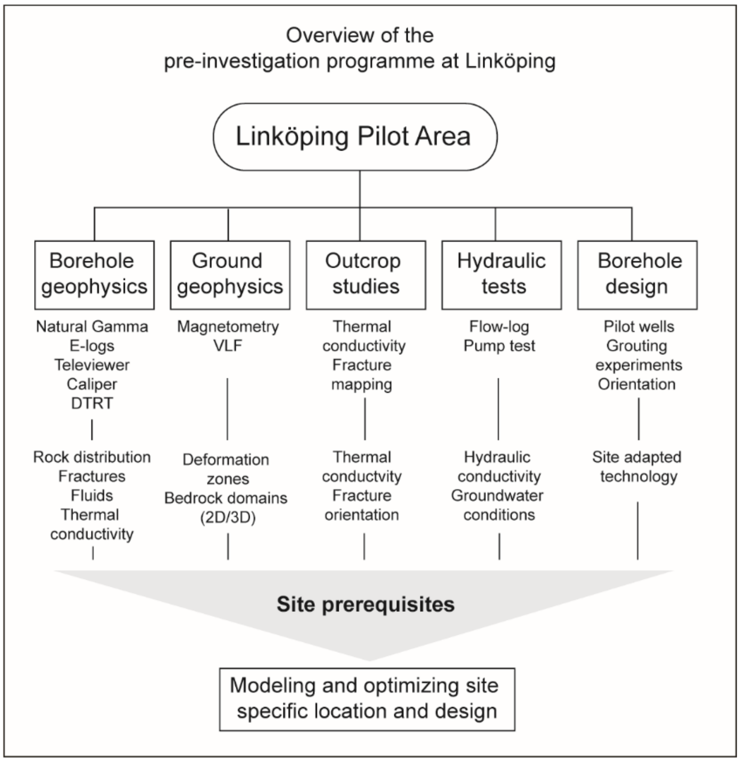

Figure 4. Flow-chart schematically describing the various methods performed in the Linköping pilot area (modified after Hesselbrandt et al., in prep.).

The GeoERA-MUSE field work and evaluations were jointly performed with work by a group of consultants from Bengt Dahlgren AB and the Royal Institute of Technology in Stockholm (Hesselbrandt, Acuña, & Funehag, 2020; Acuña, et al, 2021). The field work began in late 2018 with a geological and geophysical survey, starting with a detailed description and geophysical wire-line logging of the two 300 m deep boreholes (Figure 5). In 2019 and 2020 the geological descriptions of outcrops, sampling for petrophysical and TCS lab measurements as well as measurements of the natural gamma radiation and magnetic susceptibility was performed. Additionally, magnetic field and VLF measurements were collected (Figure 6). Some outcrops were imaged using a drone for fracture interpretation.

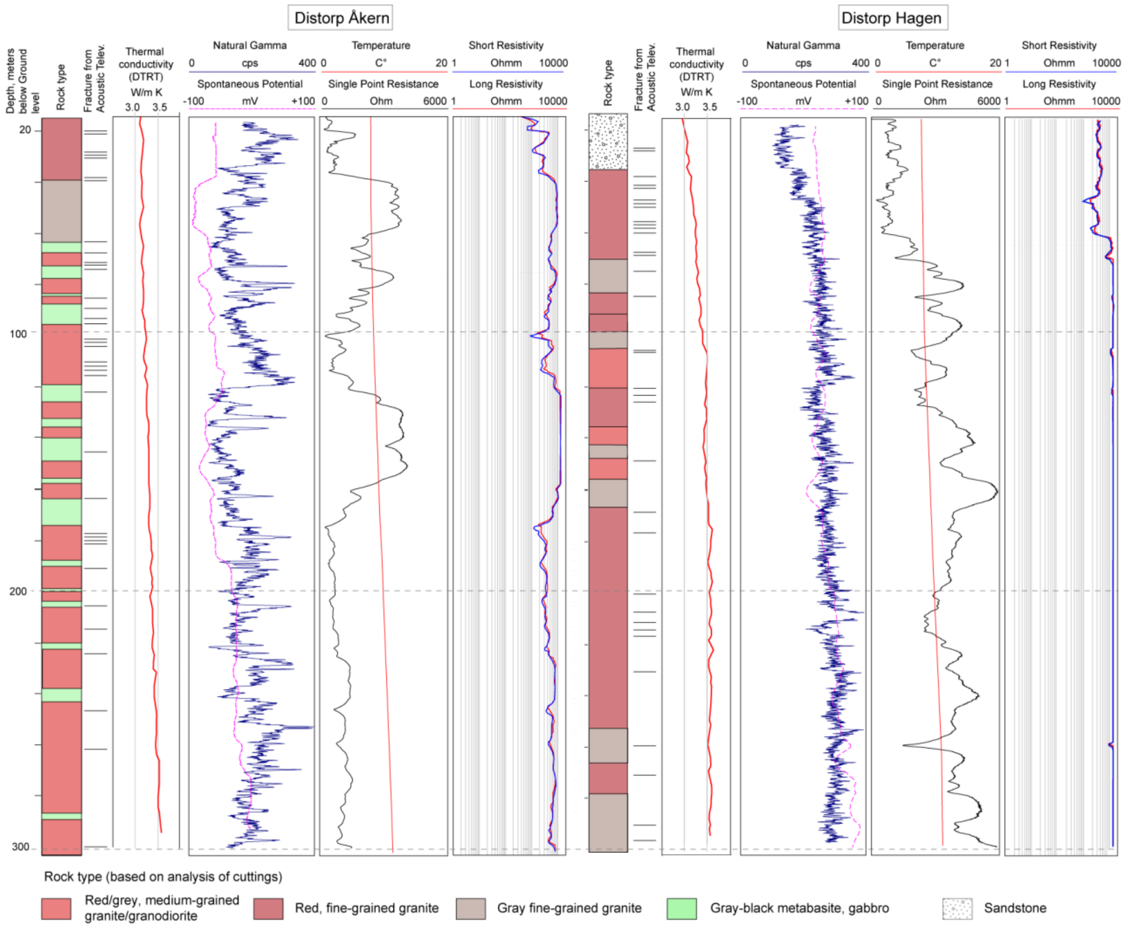

Figure 5. Composite borehole logs with lithology and wire-line logging and DTRT data the Linköping pilot area.

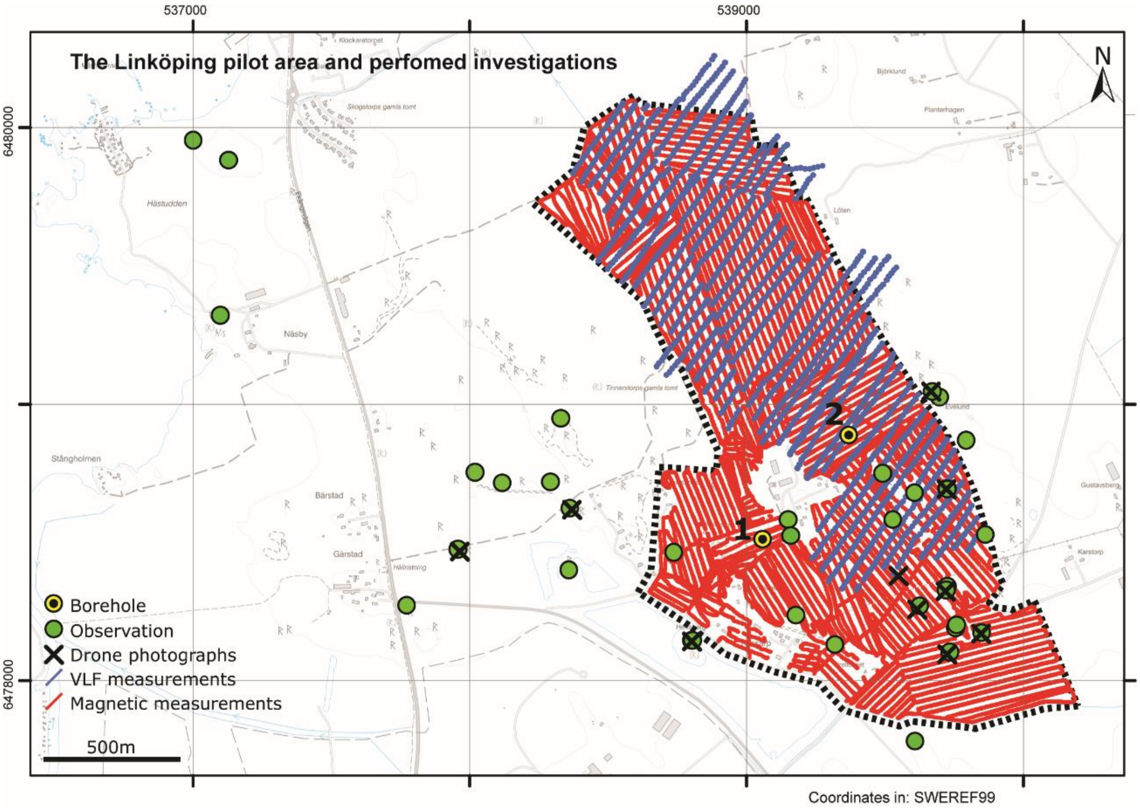

Figure 6. Illustration showing the performed Linköping pilot area field investigations.

The dominating rock types in the immediate subsurface rock mass consist of various granitoid rock types with minor volumes of mafic rocks (Figure 3). Regional thermal data based on modal mineralogical analysis of rock samples give thermal conductivities for the granites of between 3.2 and 3.4 W/mK, while the mafic rocks have values between 2.5 and 2.7 W/mK. TCS-analyses on sampled rocks from the site confirm the values in the modal-based regional database. The 23 TCS-analyses give a mean thermal conductivity of 3.08 W/mK for the granites and 2.42 W/mK for the mafic rocks.

The detailed study of the two investigation wells reveal that the subsurface bedrock mass is not as uniform as expected from the regional bedrock map (Figure 5). The DRTR measurements in the Distorp Åker well gave thermal conductivities between 3.09 and 3.58 W/mK while Distorp Hagen well had values ranging between 2.85 and 3.64 W/mK. TRT measurements show that the effective thermal conductivity at Distorp Hagen is slightly lower than Distorp Åkern, 3.05 and 3.28 W/mK, respectively. There is also a good correlation between the natural gamma ray log and the thermal response tests, especially the DTRT data.

Strong magnetic anomalies within the study area are interpreted as areas with mafic rocks, hence, lower thermal conductivity. The magnetic field data also revealed two zones with a northwest-southeast orientation that are likely hydraulically important. A linear region with relatively low resistivity values and a northwest-southeast orientation is seen in the resistivity map.

By combining bedrock studies, TCS-data and the magnetic survey a prognosis map of the thermal conductivity of the bedrock in the study area was constructed (Figure 7). Here the mean average thermal conductivities of 3.08 and 2.42 W/mK are assigned to granitic and mafic rocks, respectively.

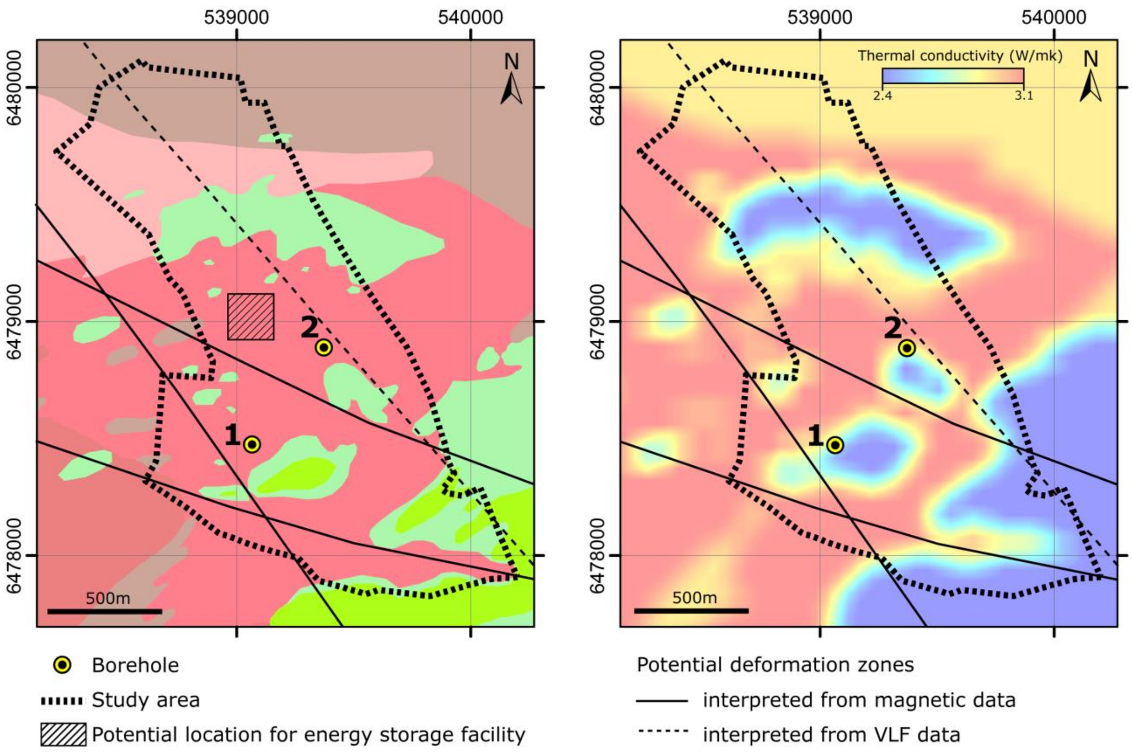

Figure 7. Revised bedrock map of the Linköping pilot area based on the magnetic field work with proposed best location of the HTES well cluster (left). A prognosis map of the bedrock thermal conductivity is shown in the right map.

Furthermore, the orientation and frequency of fracturing was studied using drone imaging of outcrops. This showed a predominant fracture set in the study area with an azimuth of about 105°, coinciding with the regional trend. Secondary fracture sets appear to exist with azimuths of 15° and 165° secondary. This gives important statistical data to the hydraulic model of the site.

2.2.3 Outcomes of GIS datasets delivered to EGDI

The field work has resulted in deliverables to the EGDI concerning:

1. **Wells used for geothermal, drinking or industrial use** in the Linköping community
2. **Water protection areas**,
3. **Grids showing depth to the bedrock surface** (i.e. overburden thickness),
4. **Mean thermal conductivity for the bedrock** down to 100 m and a magnetic grid for the site area.

These data sets were chosen as they are the most important basic input data for the HTES design.

2.2.4 Impact of the achieved results on local management and energy strategies

The investment cost associated to multi-well HTES is substantial. An arbitrary assessment of design and placing based on limited data can yield high risks regarding performance, longevity, and impact on the surrounding environment. The outcome of the work performed here shows that extended investigations can provide valuable support for lesser risk of placing a large-scale system badly with respect to given parameters for a successful performance. In this case it has been possibly to provide important guidance on how a more substantial investigation could pay-off, especially in systems with considerable CAPEX.

In Sweden SGEs are commonly applied for heating of individual houses. For these generally there are no special regulations from local management or any specific energy strategies for SGEs or HTES-BTES. Main concern is if these are to be located within water protection areas. However, the increasing number of multi-well HTES-BTES systems increases the need of assessing the thermal impact on the surrounding environment. This have also yielded an increasing awareness from the local management and energy planners on how to handle these issues. For this the results from the study at Linköping has provided valuable guidance on what type of investigations could be performed and how these can give important empirical data, which qualitatively increases the reliability on the models and design of these systems. In general, there is a need to provide guiding documents on how the local authorities should handle these types of large-scale systems regarding regulatory issues and permits.

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Not explicitly since the pilot deals with the placing of a large-scale high temperature energy storage scheme that will be connected to the district heating system and thus not a normal SGE system where other aspects are considered.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Not more than the Geological Survey of Sweden already provide regarding base information on SGEs.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

The data retrieved from the field work had led to a revision of the local geological maps and in that respect, it will provide a better basis for future SGEs.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

No.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

No.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

It will be available in the Geological Survey's public GIS data base.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management in your pilot area? If yes, please provide a brief explanation

No.

Table 2.2.4-1.Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Linköping.

Permitting and licensing procedures	**1**
Local environmental, energy and climate mitigation strategies	**1**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**1**
Other aspects – *please specify*	**-**

2.2.5 Lessons learned in the pilot area

The use of conceptual and simulation models is central in assessing system thermal performance and environmental impact. In this context, data collected from extensive field observations are crucial for selecting appropriate model parameters as well as for model validation purposes. Our field work illustrates that detailed ground-geophysical surveys combined with detailed studies and analyses of boreholes and outcrops improves and modifies much of what may previously be known about the geology in an area with only regional data. Thus, data that could be crucial for selecting the best location of a large BTES well-cluster like the one in Linköping. However, it must be noted that the experiences from Linköping is realted to a crystalline bedrock setting.

The magnetic survey proved to be most useful in distinguishing mafic bodies with associated relatively lower thermal conductivity and areas with more favourable (higher) thermal conductivity dominated by granitoid rock types. A translation of the results to thermal conductivity also made it possible to get an assessment map of the thermal conductivity for the upper part of the bedrock.

Furthermore, the study showed that the use of ground geophysical measurement with magnetometer and VLF are useful methods to collect areal coverage information on the local scale.

The VLF-survey also gave supplementary information on the occurrence of deformations zones, interpreted to be significant water-conductive structures, that are judged to be a risk factor for the location of the HT-BTES well-cluster. The use of drone-imaging of outcrops and statistical analysis of the fracturing also added value regarding fracture orientation and groundwater pathways.

All these ground geophysical methods have in this geological setting provided crucial geological information, which otherwise would have been unrevealed and a risk in an arbitrary placing of the HTES well-cluster. The use of drone-based magnetometry and VLF may in the future likely make these types of surveys even more cost-efficient and thus increase their applicability in similar geological settings. These methods are all recommended to be included in a toolbox of possible methods that could be applied for pre-investigations for large-scale HTES, given the different prerequisites that prevail for a specific geological setting. The possibility to create 3D-grids of the data furthermore allows an in-depth visualization and applicability of the geophysical data in the modelling work.

The use of percussion-drilled investigation wells is not the best way to retrieve data on the rock mass properties. Although data from TRT and DTRT measurement and geophysical wire-line logging provide valuable information, there is a problem to correlate the precise rock type to the geophysical and thermal properties. Retrieval of rock cores with measurements of the susceptibility and analyses of the thermal conductivity coupled to rock type would greatly enhance the geophysical model.

The responses from natural gamma ray logs clearly correlate with the thermal responses from the results of the 2-m interval DTRT measurements. Furthermore, if spectral gamma ray measurements are used this would enable calculations of heat productivity and more clearly distinguish potassium-poor mafic rock types, such as gabbro, from potassium-rich granitoids.

The scope of methods used depends on the setting and size of the planed site. However, the use of ground geophysical methods (VLF, magnetometer) in combination with test wells, with at least one core drilling are recommended for pre-investigations of a larger scale HTES/BTES.

1. Applicability of workflows and the elaboration of output data sets

See above.

2. Performance of field measurements in comparison to the initial plans

As planned.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

The ability to render a thermal prognosis map using combinations of TCs measurements and magnetic data was a nice surprise/highlight of the work.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

Not more than that some field work had to be re-scheduled due to the Covid-19 situation.

2.2.6 Outlook

The HTES plant in Linköping is still not decided but the field-studies have provided a proposed location where the geological conditions are most suitable. The further work at Linköping involves evaluation of a borehole-design where grouted tight boreholes could be used, i.e. heat-exchange without collectors. Furthermore, a manuscript on the multidisciplinary field work at Linköping is under peer-review to be published in *Energies* journal (Hesselbrandt, Erlström, Sopher, & Acuña, n.d.). Future work will also test the possibility to perform drone-based geophysical surveys in the Linköping area to test if this will speed up the way to collect high-resolution areal coverage data. There are also plans to further evaluate the possibility to present 3D-geophysical data in the area.

2.3 City of Zaragoza (Spain)

Eduardo Garrido, Alejandro García, Miguel Mejías, Carlos Baquedano, Cristina Pérez

Instituto Geológico y Minero de España (IGME, CSIC)

2.3.1 Focus of activities inside GeoERA-MUSE

The objective of the activity carried out has been the maintenance and control of the geothermal control network piezometers of Zaragoza and the updating of data from the GWHE operating in the urban area of the city. Through the control network, it is intended to continue with the data collection of the main aquifer parameters (piezometric level and groundwater temperature) that are considered sensitive variables to the impact generated by thermal discharges of GWHPs. The control also ensures the availability of long-term time series data, which allows monitoring of the thermal evolution of the aquifer on a longer time scale. By the addition of the data into the existing numerical model of underground flow and heat transport (GEOTERZ) it is possible to improve the calibration and the final results of the model. Under these conditions, several predictions have been made on the long-term impact of potentially conflict-generating thermal discharges due to interference in the use of groundwater with other GWHPs. To prepare the GIS layers, prior information from the IGME has been made available, which has been adapted to the project standards.

2.3.2 Outcomes of field measurements

From July 2018 to June 2021, data from a geothermal control network of 45 points was obtained. 37 piezometers have been set up with data loggers to make continuous piezometric level and temperature observations, recording data every 120 minutes (2hrs). In addition, there is a similar device used for barometric compensation. Due to battery life problems, the number of working devices has been limited to 31 devices towards the end, which decreases the number of records expected from each datalogger. This fact has required maintenance and battery replacement operations in 17 dataloggers. 6 field campaigns have been carried out (December 2018, January-February 2019, November-December 2019, August and December 2020 and April 2021) from which 148 specific groundwater level and temperature data have been obtained from 33 piezometers. At the same time, basic information and technical characteristics of the existing GWHP schemes in the area has been compiled.

2.3.3 Outcomes of GIS datasets delivered to EGDI

The GIS datasets delivered to EGDI include:

1. **Net Aquifer Thickness** - which reconstructs the geometry of the urban aquifer; a total of 626 lithological descriptions of boreholes have been considered. These lithological descriptions were taken from Water Points Inventory (IPA) database of the local water administrator (Ebro Hydrographic Confederation). From the 557

boreholes, 174 reach Miocene materials confirming the aquifer bedrock. In the interpretation of the geological model, six electrical resistivity profiles were considered as auxiliary support.

2. **Groundwater body suitable for open-loop systems** and correspond to the alluvial aquifer of Zaragoza defined by the local water Authority.
3. ***Area suited for groundwater disposal to surface water or municipal drains***. This layer contains the extent of areas suited for groundwater disposal to surface water and areas suited for groundwater disposal to municipal drains.
4. **Other groundwater use**, which includes the boreholes for groundwater abstraction (groundwater wells) and for quantitative and qualitative of groundwater monitoring (piezometers) in the city of Zaragoza.
5. **Hydraulic conductivity.** The layer contains the spatial distribution of hydraulic conductivity of the alluvial aquifer of Zaragoza.
6. **Hydraulic transmissivity** showing the spatial distribution of hydraulic transmissivity of the alluvial aquifer of Zaragoza.
7. **Existing shallow geothermal energy systems**. Only systems using open loop geothermal heat exchangers in the city of Zaragoza were mapped (closed loop systems were not mapped). The data is not exhaustive and other facilities may exist.
8. **Specific yield**.

All these GIS layers were selected because those where available in different formats to be transposed to a GIS platform. In addition, those parameters describe adequately the pilot area of Zaragoza since the main type of geothermal energy systems operating in the shallow alluvial aquifers are open loop or GWHPs.

2.3.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Yes, but relatively, because Zaragoza is a city with a well-known aquifer that already has a high degree of implementation of the SGE in large and medium-sized public or private buildings. Awareness should be emphasized at a lower level, promoting its use for small buildings, private companies and individuals.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Yes. A new collaboration agreement is being processed with the Local Water Authority (CHE – *Confederación Hidrográfica del Ebro*) that will allow continuation of the work in the pilot city, to improve the provision of hydrogeological information, technical characteristics of the GWHE, and to support the numerical modelling of underground flow and heat transport processes. This tool is already used to predict impacts, helping the CHE during the authorization and permitting procedure for thermal discharges into the aquifer.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Yes. They can set new criteria when allowing or updating thermal discharge authorizations. However, the data from the control network and the simulations of the numerical models are already used to adopt criteria to limit the values of flow and temperature of the GWHE thermal discharges. The datasets can be useful for urban planning managers to adopt new global strategies for the city and sometimes to order the facilities or implement district heating and cooling systems.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

Yes. The data can be used by technical consulting companies to assess the impact of thermal discharges or be used in studies of different hydrogeological problems.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Yes. The data are useful for the CHE, but requests the support of the IGME for its interpretation and for the assessment of the suitability of geothermal exploitations of groundwater. The CHE is the agency with the legal capacity to authorize (or not) new groundwater exploitation and the emission of thermal discharges.

6. Will the datasets produced for your pilot areas be available in a local (web based) information system or data repository? If yes, please provide a brief explanation

Yes. The specific measurements can be consulted and downloaded from the IGME groundwater database, available through the web: https://info.igme.es/BDAguas/. The characteristics of the piezometers of the geothermal control network and some wells used by the GWHEs are also accessible.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

The data can be queried on the web. The database is in the process of adaptation and updating. When the new database is finalized, the records obtained in the dataloggers and the hydrogeological information from the wells of all the GWHEs will be incorporated. On the other hand, the IGME website allows the visualization and query of spatial data sets through WMS. This allows you to view additional information for the layers (legends, metadata, etc.) and other elements that can be incorporated (detail files, photos, etc.).

Table 2.3.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Zaragoza.

Permitting and licensing procedures	**5**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**2**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**4**
Other aspects – *please specify*	**-**

2.3.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

An important part of the information comes from previous work, which, since it is in digital format, has not required excessive dedication. The incorporation of new data and its transformation into others of interest to the project has been carried out with agility, since already established protocols and routines have generally been followed.

2. Performance of field measurements in comparison to the initial plans

Unforeseen problems have arisen related to piezometers destruction and problems with physical access to some plants. Also due to breakdowns or battery drain in the measuring devices.

3. Greatest surprises or highlights linked to field work and the preparation of output datasets

A positive response has been observed in the thermal evolution of some piezometers, possibly as a result of the management measures adopted for thermal discharges and the improvement of GWHE management.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

The Covid-19 pandemic health situation has forced a rethinking and reduction of the number of field campaigns. It has also limited the flow of information and cooperation between entities that should facilitate access to some control points.

2.3.6 Outlook

A new collaboration agreement is being processed with the Local Water Authority (CHE) that will allow continuation of the monitoring work in the pilot city, to expand the hydrogeological information, the GWHE technical characteristics and, most of all, to improve and support the numerical model of underground flow and heat transport. This is a tool that has proven to be useful for predicting impacts and advising the CHE during the authorization procedure for thermal discharges to the aquifer. It is also expected to contact the local government to report on the actions carried out and promote joint activities to disseminate and promote the use of these technologies, to take advantage of the geothermal resources of the aquifer.

2.4 City of Zagreb (Croatia)

Staša Borović, Kosta Urumović, Marco Pola, Mirja Pavić
Croatian Geological Survey

2.4.1 Focus of activities inside GeoERA-MUSE

Zagreb is the capital of Croatia, and by far the largest urban agglomeration in the country (≈800,000 inhabitants). The city area can be divided into the alluvial plain of the Sava River (ZG-AL, blue polygon in

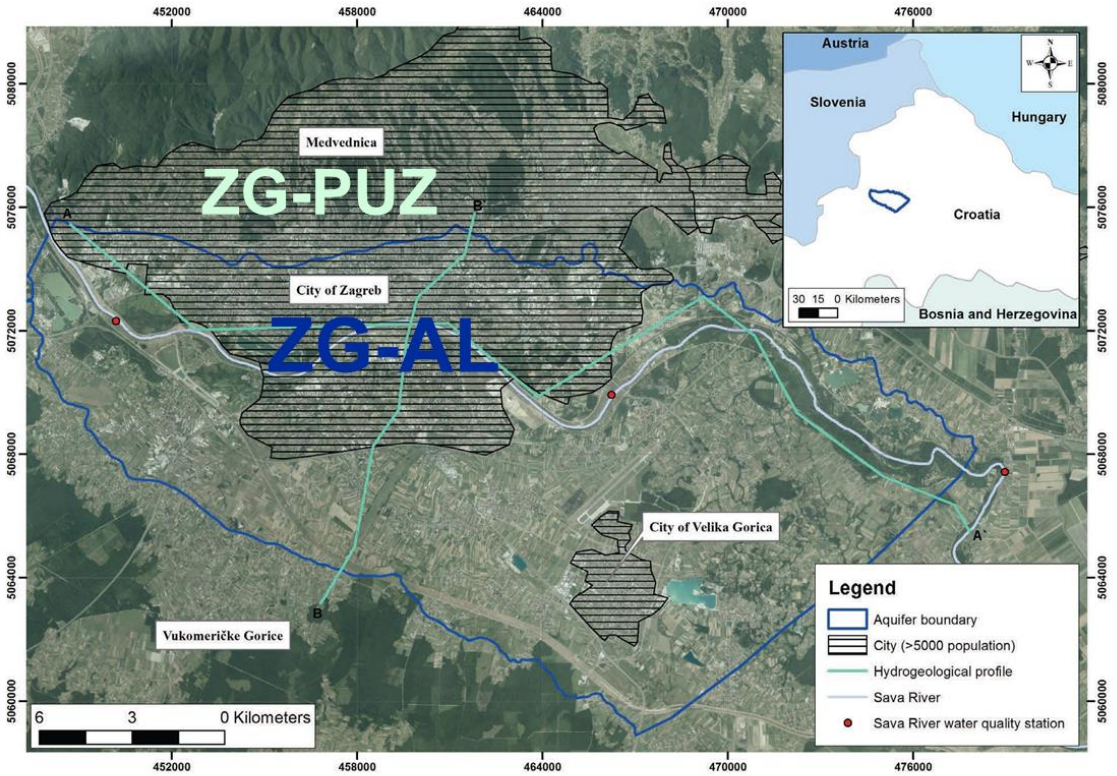

Figure 8) and Podsljeme urbanized zone (ZG-PUZ) at the foothills of Medvednica Mt. (Figure 8).

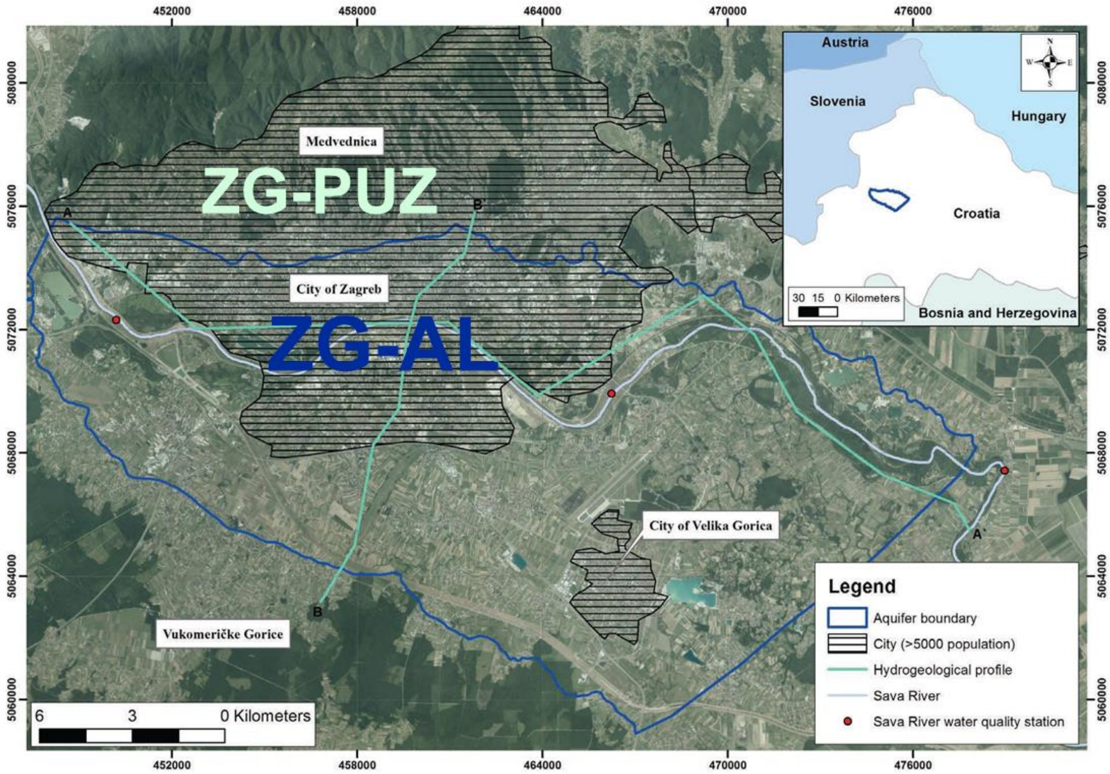

Figure 8. City of Zagreb and its two distinctive areas: Podsljeme urbanised zone (ZG-PUZ) and Zagreb Alluvium (ZG-AL) (modified from Kovač et al., 2017).

The aquifer system (ZG-AL) comprises two Quaternary aquifers. Hydrogeologically, the Quaternary deposits are divided into three basic units: thin overburden of clay and silt; a shallow Holocene aquifer of medium-grained gravel mixed with sands; and deeper aquifers from the Middle and Upper Pleistocene, with frequent lateral and vertical alterations of gravel, sand and clay.

Zagreb, as other larger urban areas, has significant heating and cooling loads, and it is clear that many investors and developers opt for the installation of different types of heat pumps, instead of gas-fired heating and typical air-source heat pump cooling systems. Unfortunately, the number of installed heat pump systems is not known, and there is no solution in sight for chronic lack of data (the regulations on construction are becoming more lenient, rather than stricter, as described in more detail in MUSE report D3.1).

Possibilities for closed loop heat pump utilisation have been investigated by previous researches, so in the scope of MUSE we selected to investigate the question of whether open loop systems cause thermal pollution in the Zagreb aquifer (also used for water supply) and, if they do, what is the magnitude of that disturbance. Therefore, two test sites were chosen: one is a residential building, while the other is a large IKEA store and accompanying facilities. Obviously, we were considering a smaller and a larger system to test if there are differences in their impact. Due to the significant extent and thickness of the aquifer, our hypothesis was that we will not observe significant temperature deviations because the aquifer is characterised by very high hydraulic conductivities (up to $3x10^3 – 4x10^3$ m/day) so thermal disturbance should be dissipated rapidly.

2.4.2 Outcomes of field measurements

Automatic data loggers were installed at both sites - in an observation well in a smaller system and a production well in a larger system, measuring groundwater levels and temperatures. A barro-logger for measuring the atmospheric pressure was also installed for compensation of the groundwater level data.

In Figure 9, groundwater levels and temperatures are shown for the small residential groundwater heat pump installation (Veslačka), while Figure 10 shows the situation at a larger GWHP system (IKEA).

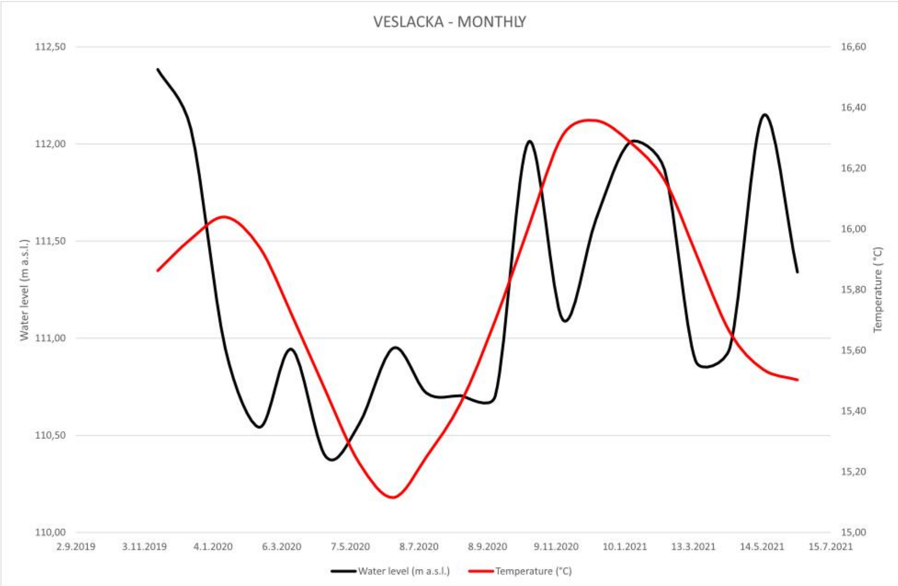

Figure 9. Groundwater levels (blue) and temperatures (red) in the small groundwater heat pump system (Veslačka) between 2019 and 2021.

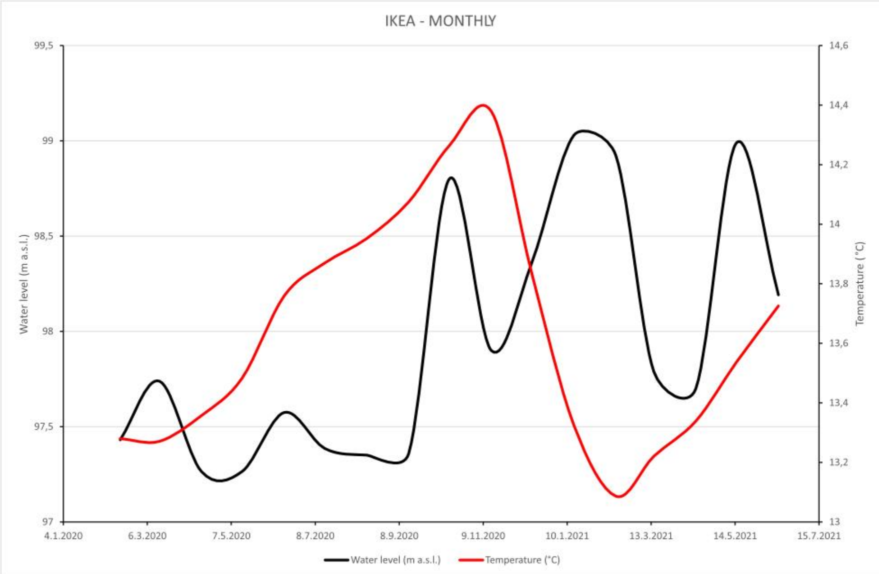

Figure 10. Groundwater levels (blue) and temperatures (red) in the large groundwater heat pump system (IKEA store).

As can be observed from Figure 9 and Figure 10 the groundwater levels and temperatures show a normal annual seasonal variation. The amplitudes are small and in accordance with the seasonal data for Zagreb alluvial aquifer. The temperature amplitude was only 2.2 °C in Veslačka, and 1.83 °C in IKEA, while the recorded amplitude in the nearby observation well of the Croatian water management authority closer to Sava River is 5.5 °C.

2.4.3 Outcomes of GIS datasets delivered to EGDI

As a result of above described pilot area activities, the following data to the EGDI were delivered:

1. **Groundwater protection zones;**
2. **Natural reserves;**
3. **Landfills and contaminated areas;**
4. **Land surface temperature (degC)** - is a raster dataset which represents the average annual air temperature distribution of the Zagreb urban area;
5. **Measured groundwater level (m);**
6. **Measured groundwater temperature (degC).**

2.4.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

The created datasets certainly helped to raise awareness in the installation-scale. That is, of course, because of our collaboration with the users (system operators) and the discussions we had considering the procured data. Clearly, any operator is interested in the long-term forecast of their heat pump operation, so the fact that we observed negligible temperature variations (in comparison to the usual groundwater levels and temperatures) certainly reassured them and, hopefully, encouraged them for future projects in near and similar environments. Also, they are now aware that there are researchers who are interested in this topic whom undertake data collection and analysis, and we are hopeful that in the future they will come forward and request our advice.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

At the moment we do not have such a plan, but since we are in constant positive contact, we believe that in case of dilemmas and/or problems they would reach out to us as a partner and consulting institution for initial data, guidance, recommendations or further research.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

We have no reason to believe that our data sets collected in the scope of MUSE project would be used as a foundation for any energy or environmental planning.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

We have no reason to believe that our data sets collected in the scope of MUSE project would be used as a foundation for any investment or other decision by local stakeholders.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

No.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

There is no data repository or web based local information system dealing with the topic of heat pumps in general, or ground(water) heat pumps specifically. However, on 30/09/2020 S. Borović held a lecture on the topic of MUSE at the seminar of the Croatian heat pump association where the problems of uncontrolled development of such systems in urban environment were discussed. The Croatian heat pump association is actively communicating with the national and municipal (City of Zagreb) authorities in order to establish state-of-the-art data base of the heat pump systems. The national Environmental Protection and Energy Efficiency Fund has recently announced a call for the development of such a data base, and the Croatian heat pump association is preparing a proposal for its implementation in collaboration with institutions dealing with mechanical engineering, energetics and geological engineering.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

(Unanswered)

Table 2.4.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Zagreb.

Permitting and licensing procedures	**1**
Local environmental, energy and climate mitigation strategies	**1**
Spatial planning including energy plans	**1**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**1**
Other aspects – *please specify*	**-**

2.4.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Through the preparation of datasets for upload to the EGDI a few colleagues at HGI-CGS received new insights on data analysis, elaboration and presentation, which will be useful in the future work. We would like to emphasise the utility of the workshops (both physical and virtual) for the exchange of experiences with different workflows with colleagues from partner GSO institutions, and we believe this will be very useful in our future work.

2. Performance of field measurements in comparison to the initial plans

The deviation from the initial plan was the fact that we started monitoring later than expected because it was initially hard to arrange access with the site users. However, in the end we got a satisfactory dataset as planned.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

Since we have engaged in a small-scale pilot activity, the results were expected (as described in the initial part of this report). However, we tested a hypothesis and confirmed it so we shall be more confident in our future assessments.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

There were no major deviations in field work and the preparation of output data sets.

2.4.6 Outlook

At this moment the HGI-CGS is not involved in any projects tackling a topic similar to MUSE. As described earlier, however, S. Borović as a member of the Governing board of the Croatian heat pump association is involved with the experts from other areas of technical sciences in the proposal for the development of the database of heat pump installations on a national level. Also, HGI-CGS as a part of the EuroGeoSurveys group, will try to procure funding through the EU Coordination and support action for activities aimed at (among other) GeoEnergy topics where shallow geothermal is certainly an aspect, so the research and collaboration will continue.

2.5 City of Aarhus (Denmark)

Claus Ditlefsen, Mette H. Mortensen, Anders J. Kallesøe, Thomas Vangkilde-Pedersen

Geological Survey of Denmark and Greenland

2.5.1 Focus of activities inside GeoERA-MUSE

Aarhus Municipality consists of a large fast-growing urban area surrounded by open land with suburbs and smaller villages. Heat is primarily supplied by the district heating company 'AffaldVarme Aarhus'. As part of the municipality's overall climate plan, they are committed to reducing CO_2 emissions, e.g., by examining the possibilities utilizing SGE and of storing surplus heat in the subsurface. Thus, the aim of the pilot case study is to investigate the possibilities of integrating SGE and energy storage in a mature central district heating system.

The investigations have been carried out as a desktop study using a wide range of existing geological and geophysical data and a 3D geological model to map potential geothermal resources. Based on the catalogue of relevant SGE technologies prepared in WP2, potential sites for geological energy storage using ATES and BTES technologies respectively have been mapped and potential conflicts of use have been addressed.

It is expected that the results will feed into a coming update of the heating plans for Aarhus. In general the GIS layers delivered to EGDI aims to visualize:

1) Aquifers with limited abstraction of drinking water and medium- to high-pumping yields.

2) Deposits with limited groundwater flow suited to BTES installations.

The results form Aarhus also feeds into the Danish part of the EU GEOTHERMICA project
HEATSTORE that aims to explore the potential for UTES in Denmark, (Kallesøe & Vangkilde-Pedersen. 2019).

2.5.2 Outcomes of field measurements

Field measurements were not among the planned activities in Aarhus.

2.5.3 Outcomes of GIS datasets delivered to EGDI

A mapping of potential sites for ATES facilities has been carried out using comprehensive sets of existing geological and geophysical data as well as an existing 3D geological model developed within the national groundwater mapping program.

The approach has been to seek out extensive aquifers (i.e. > 25 acres and thicker than 15 m) with a tentative distance of more than 500 m to existing drinking water wells, (Figure 11). Furthermore, it has been assessed that within the designated drinking water protection areas (OSD) only balanced low temperature ATES can safely be operated without potential risk of negative thermal effects on drinking water resources. In each potential area this needs to be evaluated further by hydrothermal modelling of local temperature and groundwater flow.

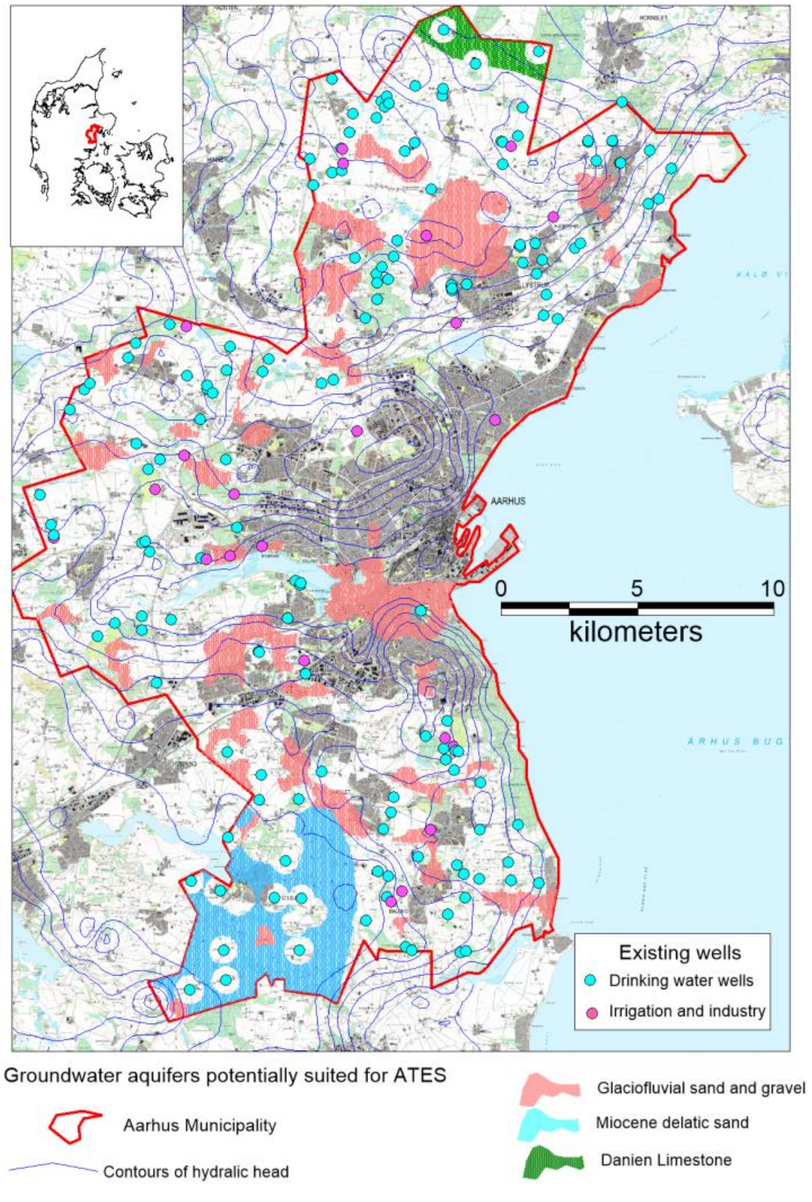

Figure 11.Aquifers potentially suited for ATES. Aquifer thickness more than 15 m. Distance to existing water abstraction wells more than 500 m.

Outside OSD one urban locality has been found that could potentially host ATES at higher temperatures. However, this also needs to be further evaluated by modelling local temperature and groundwater flow applying a realistic range of storage temperatures in the model.

Likewise, a mapping of sites potentially suited for BTES has been conducted using sets of existing geological and geophysical data. For this purpose, areas with limited groundwater flow have been mapped, as shown in Figure 12. The impermeable Paleogene clays below Aarhus have been recognized as potential formations. To minimize drilling depth and facilitate installation of the closed loop boreholes, areas where the clay is found less than 25 m below the surface has been mapped.

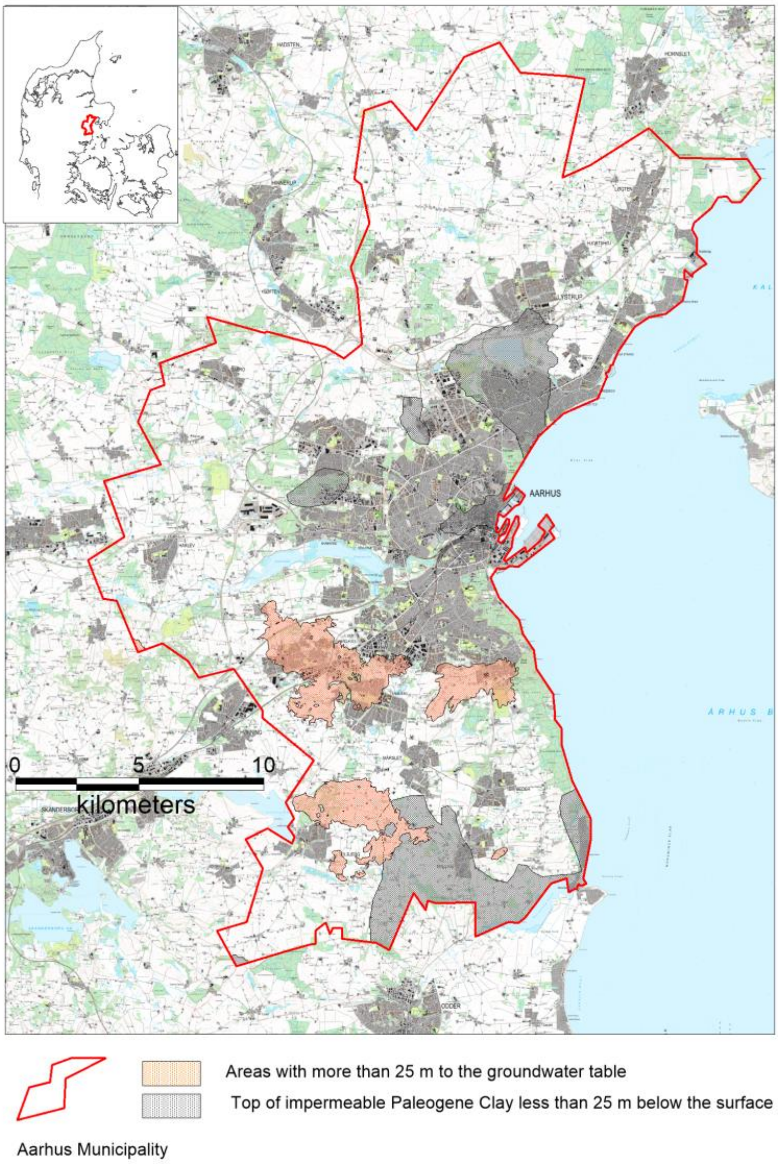

Figure 12. Selected areas with limited groundwater flow potentially suited for BTES

In the higher parts of the landscape south of Aarhus City, soundings of the water table indicate the presence of an unsaturated zone that in places are more than 20 m thick. These areas are regarded as potentially suitable for BTES. However, since most of the potential sites are located within water protection areas, further investigations are needed.

To visualize the main results the following datasets were delivered to EGDI:

1. **Groundwater protection areas**- with the application for highlighting potential conflicts of use.
2. **Boreholes for other groundwater use** (consumption and industry) - potential conflicts of use.
3. **Shallow geothermal energy systems** / boreholes - present SGE application in the area.
4. **Net aquifer thickness** - areas suited for Open loop systems.
5. **Observed specific yield** - estimation of permeability in aquifers suited for open loop systems.
6. **Traffic light map – Open loop systems** - overview of areas potentially suited for open loop systems.
7. **Traffic light map – Closed loop systems** - overview of areas potentially suited for open loop systems.

2.5.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Throughout the project, there has been an ongoing dialogue with the district heating company and their technical advisers. Some initial datasets (preliminary BTES Traffic light map a. o.) have already been used by consultants hired by the municipality and presented in an overall catalogue of technological possibilities. Most recently, the municipality has received, read and acknowledged a comprehensive report describing the results from MUSE, Aarhus in Danish (Ditlefsen 2021).

Thus, the awareness of SGE solutions at the central heating company / the municipality has been raised.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

As mentioned above some of the data has already been used. GEUS will continue the dialog with the stakeholder and when relevant we will be able to supply them with new updated datasets, etc.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Some initial datasets (preliminary BTES Traffic light map a. o.) have already been incorporated in the municipalities overall catalogue of technological possibilities. This catalogue will feed into coming local energy plans.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

At the moment the central heating company in Aarhus is in the process of evaluating different renewable energy solutions and therefore they are not ready to make any investments in SGE solutions. When this analysis has been carried out, it is expected that SGE solutions to a certain extent will be integrated in the central heating system in Aarhus.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

It is also expected that the datasets produced in MUSE will be used by local and national authorities for environmental impact assessments as part of coming permitting procedures.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

The datasets produced in MUSE will also be available online in a national screening application for energy storage and SGE use, see link.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

Subsurface temperature data is sparse and supplementary thermal modelling is needed for environment impact assessments

Table 2.5.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Aarhus.

Permitting and licensing procedures	**2**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**2**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**4**
Other aspects	**-**

2.5.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

The applicability of the produced workflows clearly depends on the character, amount and distribution of input data. This is particularly true when output parameters are to be visualized as extensive raster grids. Therefore, workflows produced in one area in MUSE often have to be modified to fit in another area where available input data differs. Lack or uneven distribution of data may also entail that a particular parameter has to be displayed as point data instead of as extensive grids.

Though workflows produced for one city in may not be fully applicable in another, they may clearly serve as inspiration for future work especially when new field measurements are being planned.

2. Performance of field measurements in comparison to the initial plans

No fieldwork was planned in the present area.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

It has been found that the national hydrogeological 3D model of groundwater resources (FOHM) was very suitable for initial mapping of shallow geothermal resources in Aarhus.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

Our main stakeholder from the start took great interest in the output from MUSE. However, their timing showed to deviated from the schedules in MUSE. Thus, one year into the project they asked for what they could get of initial resource maps for a catalogue of technological possibilities in Aarhus. Though their focus afterwards shifted somewhat towards deep geothermal resources the dialogue was maintained and most recently they received, and acknowledged a comprehensive report describing the results from MUSE, Aarhus written in Danish (Ditlefsen 2021).

2.5.6 Outlook

At the moment the central heating company in Aarhus is in the process of evaluating different renewable energy solutions and therefore they are not ready do any testing and implementation. When this analysis has been carried out, it is expected that SGE solutions to a certain extent will be integrated in the central heating system in Aarhus. GEUS will continue the dialog with the stakeholder and when relevant we will be able to supply them with new updated datasets.

2.6 City of Girona (Catalonia, NE Spain)

Ignasi Herms, Georgina Arnó, Vaiva Cypaite, Víctor Camps, Montse Colomer, Ariadna Conesa

Institut Cartogràfic i Geològic de Catalunya

2.6.1 Focus of activities inside GeoERA-MUSE

Field measurements in the Girona urban area focused on obtaining information about the thermal groundwater and subsoil status and gaining a better understanding about the subsurface geological setting. Data was obtained by continuous groundwater level and temperature measurements, TRT tests and drilling new boreholes in the study area. Geological information obtained from new drillholes was implemented into a 3D Geological model of Girona urban area which together with field measurements were used to produce the following GIS layers: surface temperature, average interval subsurface temperature, annual thermal load (closed loop system), measured groundwater depth/level, measured groundwater temperature, specific annual thermal load of closed and open loop systems, specific thermal capacity (open loop systems) and a decision support map for shallow geothermal energy use.

2.6.2 Outcomes of field measurements

Between February 2019 and January 2020, 11 new wells were drilled by the ICGC in the study area: SXG-01, SXG-02, SXG-03, SXG-04, SXG-05, SXG-06, SXG-07, SXG-08, SXG 09, SXG-10 and SXG-11 (Figure 13). In the following wells TRT tests was also done: SXG-01, SXG-03, SXG-06, SXG-07 and SXG-10. Furthermore, in 2019 a shallow geothermal monitoring network was installed which consists of primary and secondary monitoring points. Primary network equipped with telemetry provided data on subsoil temperature and groundwater level fluctuations. These data were obtained by the installation of temperature sensor strings as well as a punctual sensor to measure groundwater level and temperature in the newly drilled boreholes. Whereas secondary monitoring network was installed in already available wells and piezometers and data was recorded by only single point sensors. During the course of the project, monthly manual temperature profiling was also undertaken in selected wells (Figure 13).

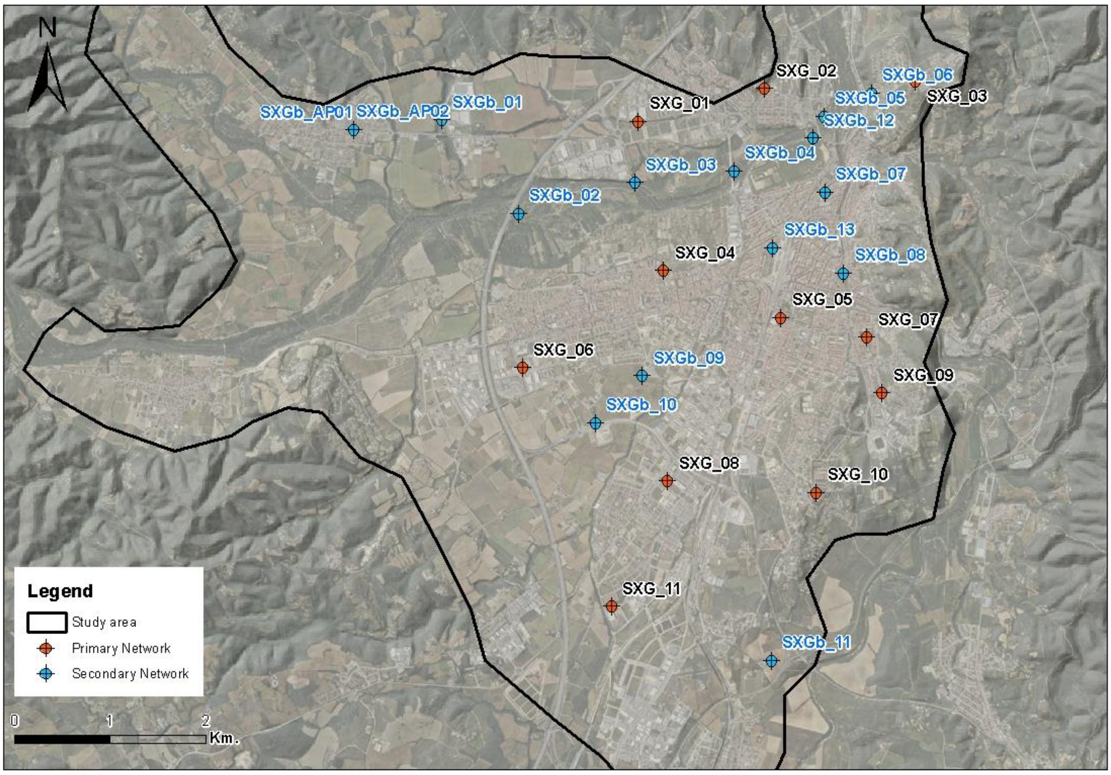

Figure 13. Shallow geothermal monitoring network in Girona urban area demonstrate where groundwater temperature and levels were monitored between 2019 and 2020.

2.6.3 Outcomes of GIS datasets delivered to EGDI

In the Girona urban area the main purpose of the MUSE project was to determine shallow geothermal potential, and therefore the performed field measurement and GIS datasets were designed and selected to fulfil this purpose. For instance, newly drilled boreholes and 3D geological model was used to define aquifer thickness and hydraulic transmissivity. Measurements of groundwater level and temperature were used to define average interval subsurface temperature, groundwater depth/level and groundwater temperature. All previously mentioned layers combined with data obtained from TRT test was used to determine annual thermal load of closed and open loop systems, specific annual thermal load - open loop systems, specific thermal capacity - open loop systems and prepare a decision support map for the use of shallow geothermal use.

List of GIS datasets delivered to EGDI:

1. **Land surface temperature (degC)** is a raster dataset which represents the average annual air temperature distribution of the Girona urban area. This layer was developed using a spatial interpolation scheme based on Multiple Linear Regression from available data of 187 weather stations.
2. **Net aquifer thickness (m)** is a set of 3 raster datasets which represent total thickness (unsaturated and saturated zone) of Eocene, Neogene and Quaternary

aquifers. These layers come from the 3D geological model developed by the ICGC in the framework of the MUSE project.

3. **Hydraulic transmissivity (m^2/d)** is a raster dataset which was calculated by multiplying the weighted hydraulic conductivity of each aquifer by its saturated thickness. Hydraulic transmissivity (m^2/d) was calculated for Eocene, Neogene and Quaternary aquifers.
4. **Average interval subsurface temperature (degC)** is a raster dataset which represents the estimated average subsurface temperature for a given depth interval (0 - 100 m) obtained by interpolation of the undisturbed subsurface temperature measurements made at 50 meters depth in the period 2018–2021 at 17 control points distributed within the pilot area.
5. **Annual thermal load - closed loop system (MWh/a)** is a raster dataset which represents annual thermal work for heating and it was calculated using G.POT method (Casasso et al, 2017). Calculation of annual thermal load of closed loop systems takes into account the thermal conductivity and thermal capacity of the ground, undisturbed ground temperature, borehole parameters and settings of the plant.
6. **Measured groundwater depth/level (m)** is a point vector shapefile which contains the average groundwater depth measurements representative of the period 2018-2020, complemented with measurements made between 2007 and 2012 in a total of 88 water points distributed within the pilot area.
7. **Measured groundwater temperature (degC)** is a point vector shapefile which contains the average groundwater temperature at a depth of 50 meters measured at 17 control points distributed within the pilot area.
8. **Thermal capacity - open loop systems (kW)** raster dataset which represents the sum of thermal capacities (for OLS - open loop systems) of the three aquifers existing in the Girona urban pilot area: the detrital Quaternary unconfined aquifer, the Neogene confined aquifer (consisting on detrital sediments associated with alluvial fan deposits) and the Eocene confined aquifer (consisting of nummulitic limestones). Thermal capacity for OLS for each aquifer was calculated by multiplying maximum groundwater flux pumped out by a totally-penetrating well (with a maximum limit set to 100 l/s), groundwater heat capacity and temperature differential as a result of heat exchange (fixed to 5°C). Groundwater flux was calculated for each aquifer separately considering aquifer type (unconfined or confined), hydraulic transmissivity, the drawdown (maximum fixed at 25% of saturated aquifer thickness), radius of influence (250m for unconfined aquifer and 2500m for confined aquifer) and a well radius of 0.25m.

2.6.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Shallow geothermal energy systems are under development not only in Girona urban area, but also in the entire territory of Catalonia, although at high rate up to 20% per year. The MUSE project has contributed to spreading knowledge about SGE and promoted the utilisation of shallow geothermal resources, both for closed and open loop systems.

Furthermore, it has given the opportunity to get in contact with local administrations and stakeholders and make them aware of the advantages and versatility of SGE technology.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Different concrete actions have been planned in terms of cooperation with local actors. On the one hand, the data sets produced in MUSE will also be published on the ICGC website in Catalan in order to also make it easier for local stakeholders to have this information for their management. On the other hand, the ICGC is developing a new MATLAB-based APP focused on the municipality to pre-evaluate the implementation of new close loop shallow geothermal facilities that will directly consume some of the GIS data generated in MUSE. The ICGC aims to work closely together to ensure a practical and useful end for all results achieved in the MUSE project.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Under the 20/20/20 strategy Spanish municipalities committed to define and execute Sustainable Energy and Climate Action Plans (SECAP). The produced datasets will directly impact the content of SECAPs by introducing SGE as a real renewable energy alternative for decarbonisation not considered until now. In 2021, drafting of the new SECAPs for all municipalities in the Girona province has begun, some of them included in the studied area where the Girona city in MUSE is situated. On this occasion, ICGC has advised the regional government to define proposals for the inclusion of shallow geothermal energy in the guide to be used by consultants, based on the acquired knowledge, in order to draft these new PACEs. In addition, the provincial government will provide advice to the municipalities to integrate and define these actions. We hope that these new PACEs will be drafted and approved throughout 2021-2022, and that new shallow geothermal projects will be promoted in the coming years.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

No other investment is defined in Girona pilot, but datasets will be the seeds for upcoming SGE projects in the area including future installations in local stakeholder quarters. Also, ICGC is developing a new MATLAB-based APP focused on the municipality to pre-evaluate, the implementation of new close loop shallow geothermal facilities that will directly consume some of the GIS data generated in MUSE and other kind of data for their economical suitability.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

In Catalonia permitting procedures are developed and regulated by the Catalan and Spanish governments. So, the impact of the MUSE datasets in that area is expected to take place in the longer-term.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

All the datasets produced in the Girona pilot will be available from the ICGC website through an online viewer, WMS service and by downloading data files. Furthermore, ICGC is working on a MATLAB-based APP for the design of small size heating and cooling systems (up to 70 kW) based on geothermal heat pumps and vertical close-loop ground heat exchangers. This tool will be self-executable and it will be accessible for free throughout the ICGC website.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

No, there aren't.

Table 2.6.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Girona.

Permitting and licensing procedures	**2**
Local environmental, energy and climate mitigation strategies	**5**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**5**
Other aspects – *please specify*	**-**

2.6.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Sometimes output data sets could be developed by applying different workflows. There is no workflow better than another. It depends on the initial available data and the objective of the output data set. Ideally, uncertainty always should accompany the obtained results so users will always be aware of it.

2. Performance of field measurements in comparison to the initial plans

In the Girona pilot area the initial plans were achieved regarding the field measurements. A primary network of 11 geothermal monitoring points of around 100 m length each, drilled specifically for that purpose, were implemented. A remote monitoring system allows ICGC to get data in real-time about temperature at different depths and groundwater level. A secondary network of 13 already existing monitoring water points was used to obtain periodic temperature profiles and groundwater table depth observations every 2 months.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

In the case of the Girona pilot area, the field work carried out had a direct impact on the data extracted from the 11 geothermal drillholes as these inform several aspects of shallow SGE assessment. That is, a 3D geological model has been developed as a first step to perform a 3D geothermal and hydrogeological model in the upcoming months (outside the framework of MUSE project). Having defined 3D lithological units and their spatial distribution made it much easier to calculate and prepare the output data related to hydrogeological and ground thermal properties distribution.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

There were no major deviations in field work and the preparation of output data sets. All selected and delivered output datasets were prepared based on the available data, either collected during field work or owned by ICGC.

2.6.6 Outlook

It is planned to develop a 3D flow and heat transport model in order to simulate groundwater flow and characterise thermal parameters and assess future ground exploitation.

2.7 City of Prague (Czech Republic)

Jan Holeček, Jaroslav Řihošek

Czech Geological Survey

2.7.1 Focus of activities inside GeoERA-MUSE

The geothermal sector in the Czech Republic is still in the development phase, and this is also true for the MUSE pilot area in Prague – the capital of Czech Republic. As the number of heat pumps will rise in densely populated areas over the time; the risk of negative interferences of adjacent geothermal installations also increases. Some of these interferences can lead to malfunction of the installations and consequently legal disputes between owners can arise.

Our motivation is to develop a toolset which can inform stakeholders and authorities not only about geothermal potential but also about the possible risks before the construction of a new heat pump. No register of existing and operated heat pump installations exist in the Czech Republic. This may be a problem, because spatial data concerning the use of geothermal energy does not exist. Neither investors nor local authorities have any information about closely located geothermal installations and they are not able to manage a strategy for use of GT energy. Moreover, the general awareness about possibilities of geothermal energy is rather low in comparison to other kinds of renewable sources (photovoltaic, wind energy, biomass fuels etc.). The general public is not very informed about the possibility of heat pumps usage for air conditioning purposes.

Our activities in MUSE were focused on obtaining information about the existing geothermal heat pump installations in the area of city of Prague. The other part of activities comprise the collection of different thematic GIS layers to facilitate the analysis of geothermal potential and lower risks for newly installed heat pumps.

2.7.2 Outcomes of field measurements

No new field measurements were planned and performed in Prague pilot area. The activities were focused on collection of existing data from different sources.

2.7.3 Outcomes of GIS datasets delivered to EGDI

The following datasets from MUSE template catalogue were prepared for Prague pilot area:

1. **Shallow geothermal energy systems -** a point layer showing examples of good practice of installed heat pumps in Prague.
2. **Groundwater protection** is a polygon layer showing areas of groundwater protection zones according to Czech Water Act.
3. **Other groundwater use -** dataset contains the locations of observation wells for quantitative and qualitative monitoring of groundwater, wells used for water

supply (e.g., communal use, industry, etc.), and the other active wells reported up to 30/09/2019.

4. **Flood hazard** is polygon layer showing flooding area of Vltava River and other adjacent streams.
5. **Natural reserves** polygon layer showing areas of nature protection and conservation.
6. **Mining areas** is the polygon layer showing areas with mining history in the past (e.g. coal or iron ore mining, rock quarries.)
7. **Landslides** is the polygon layer showing areas with the risk of landslide or areas with historical occurrence of landslides.
8. **Land surface temperature** is the raster layer showing the average temperature at surface in °C degrees.
9. **Potentially karsified zones** is the polygon layer showing areas with possible occurrences of underground cavities due to karstification.
10. **Faults** is the line layer showing tectonic faults and zones.

The layers were chosen with respect to risks during building and operation of new geothermal heat pumps in urban areas. Some layers are also designated to planning process (e.g. surface temperature). We were not able to collect all necessary data for some other important parameters (e.g. groundwater geochemistry, depth of water table) and these topics must be solved individually during planning of new heat pump/ geothermal schemes.

2.7.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Not yet. The local energy concept takes geothermal energy of only marginal importance. Local authorities prefer other kinds of renewable energy sources over the geothermal energy. The catalogue of existing geothermal installations can serve as an example of good practise. Beside small ”house” installations also medium and large realised projects can be found in Prague. The largest one includes a closed loop geothermal borehole array consisting of 150 boreholes of up to 150 m in length. We hope that the outcomes of MUSE will encourage investors and will raise awareness about the advantages of SGE.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

The outcomes of MUSE will be communicated with the city hall of Prague, energy and natural environment departments. We hope the results will help to promote SGE in the pilot area.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Probably not. The energy and environmental plan of the capital Prague is updated once every couple of years. Although renewable energy sources are gaining prominence, geothermal energy is still seen as a less important source of energy. It is rather less likely that the presented results would be included in the energy concept of the city of Prague.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

Yes. The produced datasets will be freely available to the general public for free use. We believe that the information provided will be useful for many investors from both the private and commercial spheres.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

No. Due to the fact that there is no uniform procedure for permitting geothermal installations in the Czech Republic, it is unlikely that the outputs of the MUSE project will be used in the permitting procedure.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

Yes. The prepared data layers will be available in the EGDI system. Data will be available also in the internal shared data storage of Czech Geological Survey.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management in your pilot area? If yes, please provide a brief explanation

In the urban environment of the city, there are a number of obstacles in the construction of a geothermal installation. Within the MUSE project, we managed to collect only a part of the phenomena. There are other factors and data (e.g. presence of energy networks etc.) that we have not been able to collect because they are privately owned by companies. These data have to be also evaluated before the construction of the geothermal installation.

Table 2.7.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Prague.

Permitting and licensing procedures	**1**
Local environmental, energy and climate mitigation strategies	**2**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**2**
Other aspects – *please specify*	**-**

2.7.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Within MUSE project, workflows and procedures were created and these can be transferred to other areas during mapping of conflicts of use of geothermal energy. These standardized procedures are one of the biggest outcomes of the MUSE project in the Prague pilot area.

2. Performance of field measurements in comparison to the initial plans

No field measurements were planned nor performed in the pilot area of Prague.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

We were surprised by some difficulties to collect some kind of data. Time cost for preparation of some data sets was much bigger than it was originally expected. This is the experience that has to be taken into account during the preparation of future projects.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

No field measurements were planned nor performed in the pilot area of Prague.

2.7.6 Outlook

With a one-year shift, the Czech Geological Survey is developing a national project for the analysis of the geothermal potential of the Czech Republic. Part of the results of the MUSE project will also be used in devising the above-mentioned project; mainly the research methodology and workflows that will be used.

2.8 City of Vienna (Austria)

Geologische Bundesanstalt

Gregor Goetzl, Cornelia Steiner

Geological Survey of Austria

2.8.1 Focus of activities inside GeoERA-MUSE

The main shallow groundwater body suitable for groundwater heat exchangers in Vienna is the groundwater body Marchfeld, which comprises the districts 21 and 22 on the western side of the river Danube. These highly porous gravels deposited by the Danube extend to the eastern side of the river and mainly cover the districts 2, 3, 20 and 11. The part on the western side has already been investigated intensively within the GeoPLASMA-CE project. Therefore, the focus of MUSE was on the groundwater body on the right (eastern) side of the Danube. In this highly urbanized area we investigated the resources of shallow geothermal energy, mainly for groundwater heat exchangers, but also for closed loop borehole heat exchangers.

We preselected the following GIS-layers to be elaborated in MUSE:

Parameter name	Unit	Category	displayed in EGDI
Average interval subsurface temperature	degC	closed-loop	Yes
Average interval bulk thermal conductivity	W/m/K	closed-loop	Yes
Maximum groundwater temperature	degC	open-loop	Yes
Minimum groundwater temperature	degC	open-loop	Yes
Hydraulic productivity	l/s	open-loop	Yes
Natural reserves and protection areas	None	conflict map	Yes
Surface temperature	degC	closed-loop	Yes
Groundwater zones suitable for the use of open loop systems	None	open-loop	Yes
Specific annual thermal load - open loop systems	kWh/m²/a	open-loop	Yes
Specific thermal capacity - open loop systems	kW	open-loop	Yes
Traffic light map closed loop system	None	general information	Yes
Traffic light map open loop system	None	general information	Yes
Water protection zones	None	conflict map	Yes

The field measurements intended to increase the knowledge of the groundwater body. Information about the geometry of the groundwater body is already available from the municipality Vienna water (MA 45) and Vienna water management office (WGM). Time series of groundwater temperature measurements are available for a few boreholes as well. However, there are many different anthropogenic heat sources expected in this urban environment. They impact the temperature very locally, and a denser monitoring network would be necessary to identify and more accurately delimit urban heat islands.

In order to increase the knowledge of possible urban heat islands in the pilot area, we conducted groundwater temperature measurements in 8 boreholes. The selected boreholes are located in the downstream vicinity of several large known groundwater heat exchangers. The goal was to demonstrate the impact of these existing systems on the aquifer groundwater temperature. Figure 14 shows the location of the boreholes inside the pilot area of Vienna.

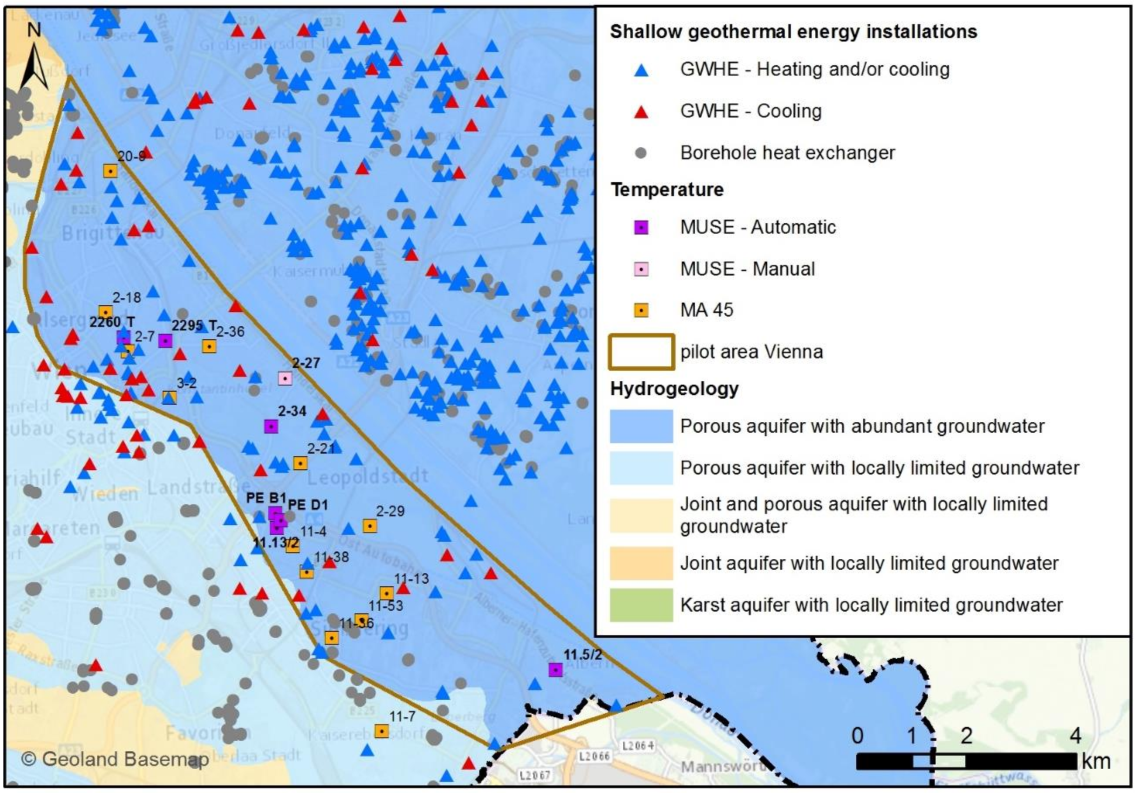

Figure 14. Overview of pilot area Vienna including existing shallow geothermal energy installations (GWHE – groundwater heat exchanger) and boreholes with groundwater temperature measurements conducted by Geological Survey of Austria and Municipal department for Vienna Waters (Ma 45).

Seven of the investigated boreholes were equipped with in-house developed loggers, which measure the groundwater temperature at multiple depths. Additionally, data loggers were installed to measure the water level in those boreholes. The measuring interval was set to once a day (24hrs). In the 8th borehole we measured the temperature manually with a well-dipper during our monthly tours to check the data loggers at the other locations.

2.8.2 Outcomes of field measurements

Based on a first inspection of possible boreholes, which took place in March 2019, 7 boreholes were selected to be equipped with data loggers. The temperature loggers were built at the Geological Survey of Austria specifically to meet the length of and depth to the groundwater level at each borehole. Groundwater temperature and water level loggers were installed on 30 August 2019. From that time onwards, the data loggers were checked once a month to see if they were working properly and to change the battery if necessary.

The boreholes were assigned to three small case-study areas called Erdberg, Prater and Praterstern. At Erdberg (Figure 15) we focused on one large building "OEAMTC", which uses a GWHE (12.4 l/s) for heating and cooling as well as BHEs. Here we observe a large impact on the groundwater temperature within 200 m of the geothermal schemes.

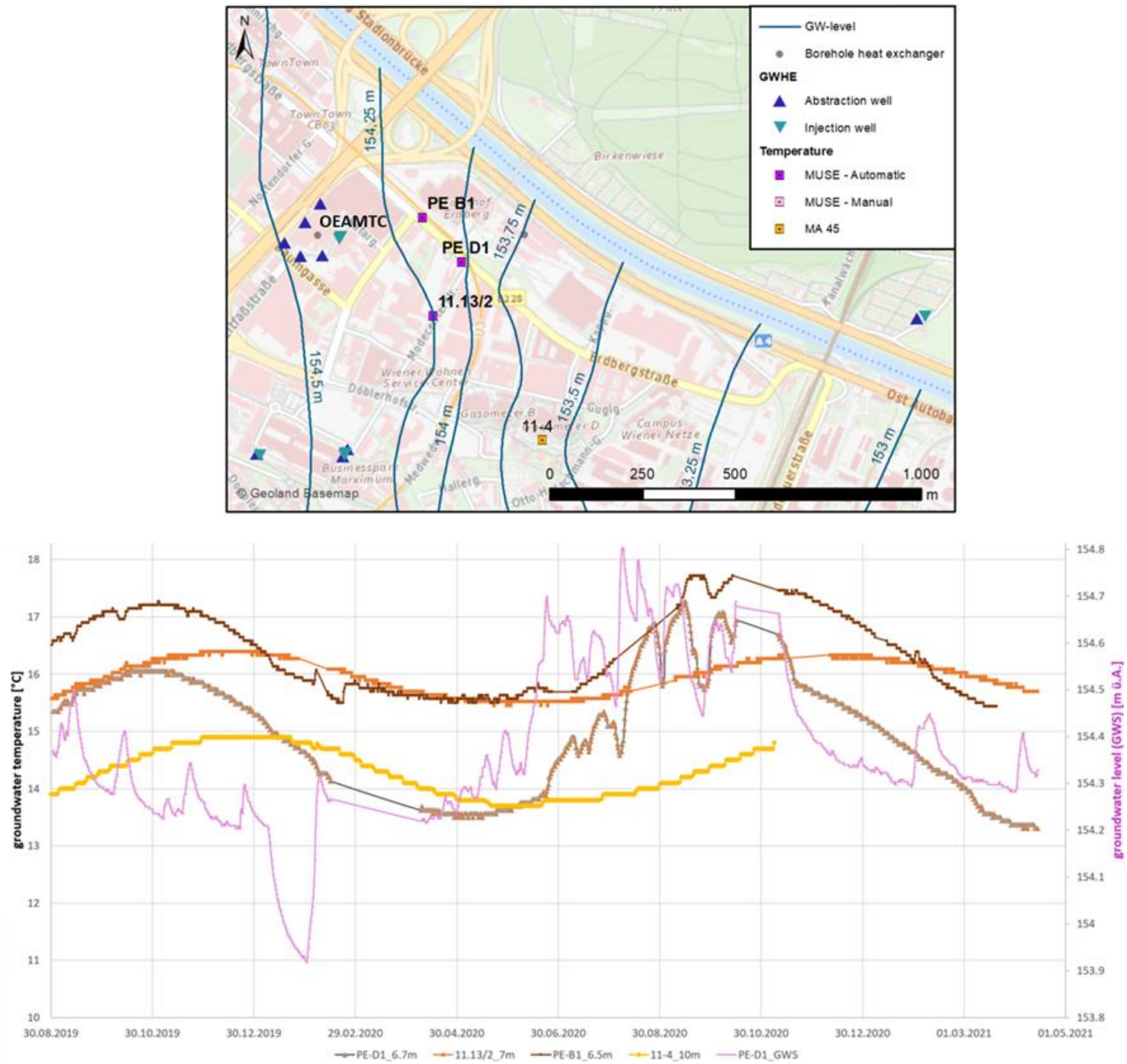

Figure 15. Overview of case-study area Erdberg (above) and results of field measurements (below).

At Prater (Figure 16), which is a green area with a lower density of buildings but hosts two large GWHE installations (using 150 l/s and 10 l/s for heating and cooling). The thermal influence in this area is not as high as expected.

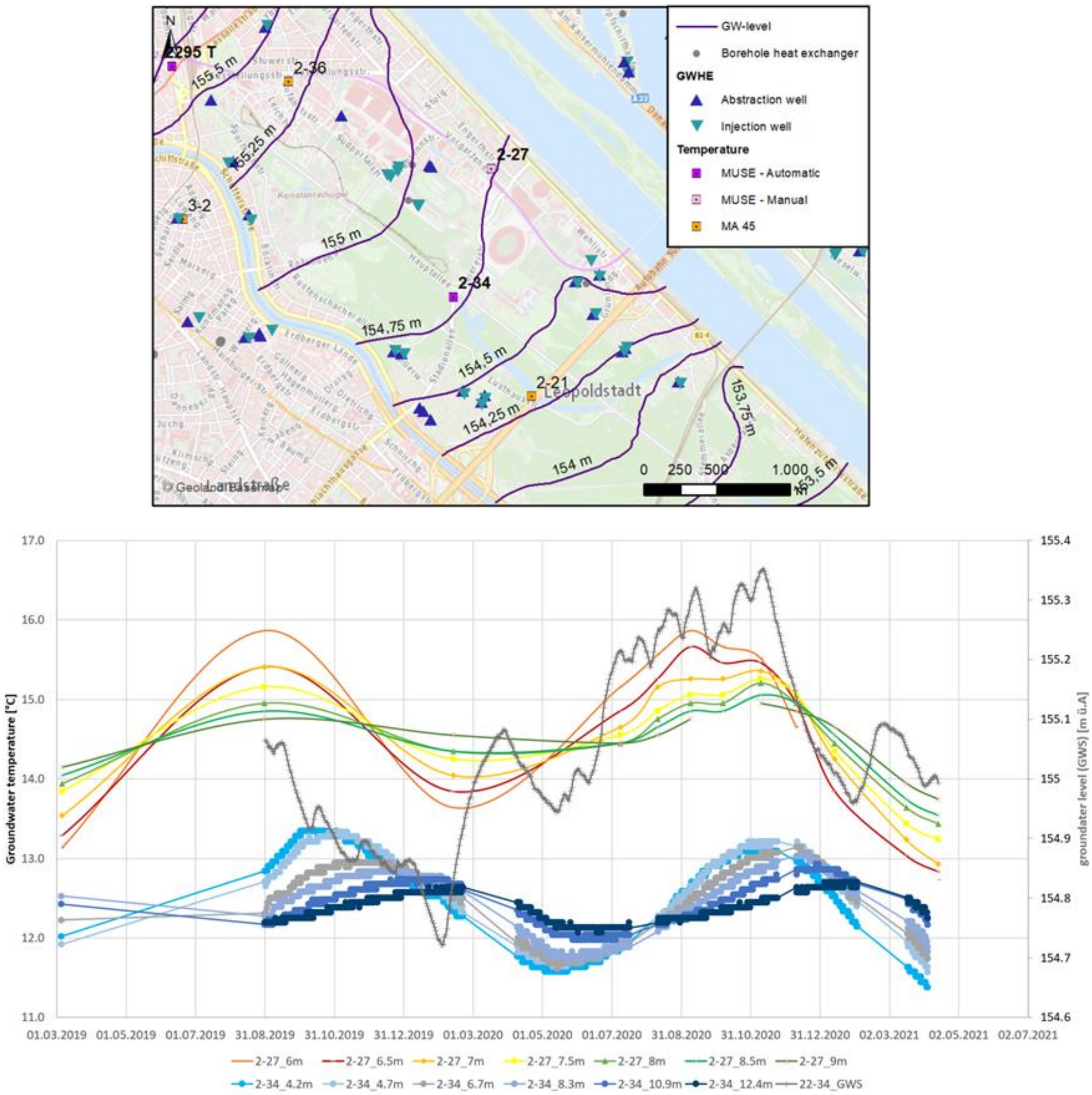

Figure 16. Overview map of case-study area Prater (above) and results of field measurements (below).

Praterstern (Figure 17) is a densely built-up area. Here we saw besides an impact of a larger GWHE (10.5 l/s), a temperature increase due to the metro line, which runs close to the boreholes. One borehole is located in a park and hence shows the lowest temperatures in this area, its average temperature coincides with the average groundwater temperature of Vienna, 13 °C.

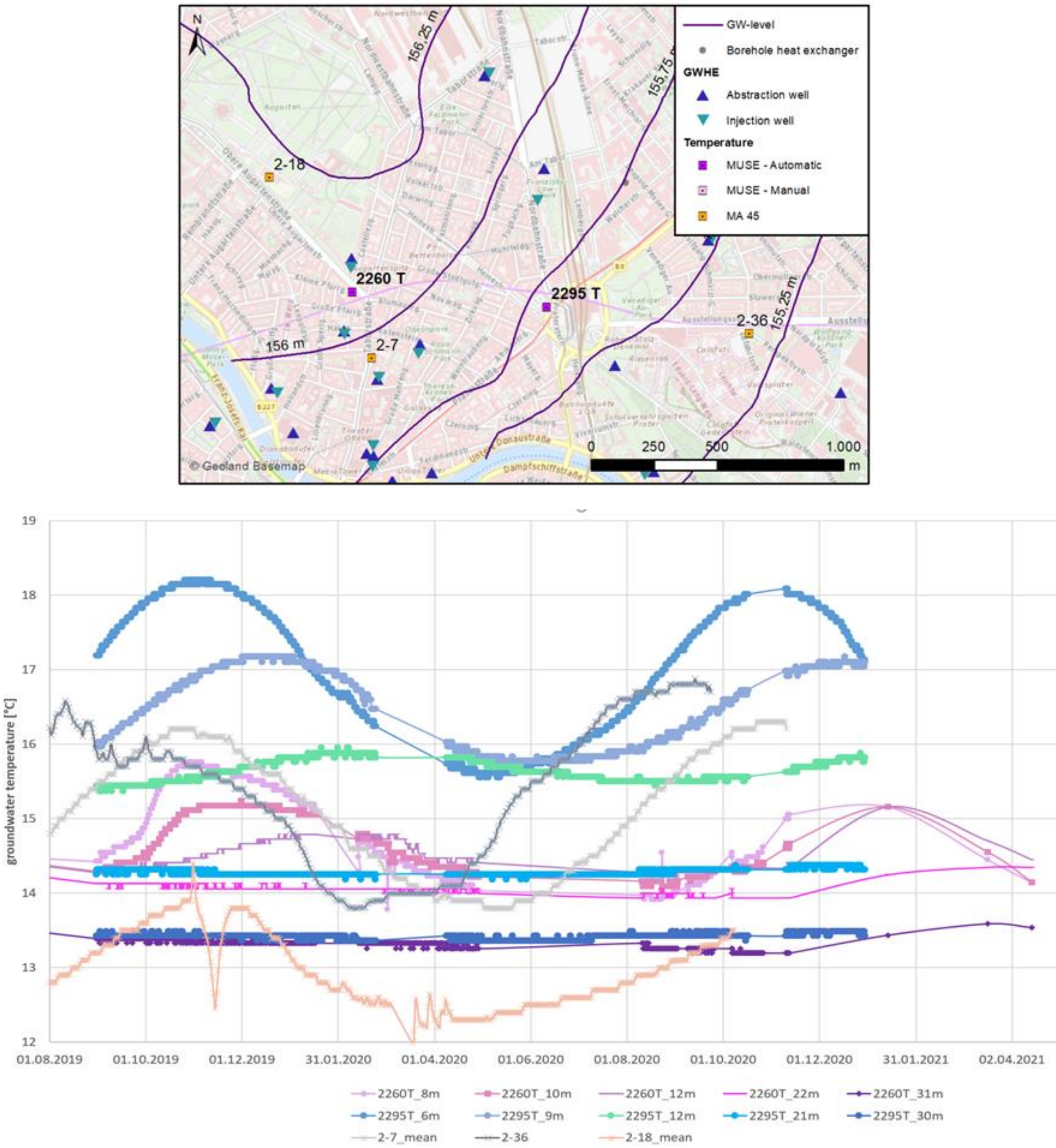

Figure 17. Overview map of case-study area Praterstern (above) and results of field measurements (below).

Our field measurements demonstrate the local influence on the groundwater temperature by GWHEs and the metro, which could be directly related to the boreholes. The time series show an increasing amplitude in close vicinity to large GWHE installations. In larger distances the natural periodicity resembles a sine wave, but the influence is still indicated with a higher mean temperature.

2.8.3 Outcomes of GIS datasets delivered to EGDI

The following data sets have been elaborated for the pilot area Vienna:

Parameter name	Unit	Category	displayed in EGDI
Average interval subsurface temperature	degC	closed-loop	yes
Average interval bulk thermal conductivity	W/m/K	closed-loop	yes
Maximum groundwater temperature	degC	open-loop	yes
Minimum groundwater temperature	degC	open-loop	yes
Heat transfer rate	W/m	closed-loop	yes
Hydraulic productivity	l/s	open-loop	Yes
Natural reserves and protection areas	None	conflict map	Yes
Surface temperature	degC	closed-loop	yes
Groundwater zones suitable for the use of open loop systems	None	open-loop	yes
Specific annual thermal load - closed loop systems	$kWh/m^2/a$	closed-loop	yes
Specific annual thermal load - open loop systems	$kWh/m^2/a$	open-loop	yes
Specific thermal capacity - open loop systems	kW	open-loop	yes
Traffic light map closed loop system	None	general information	yes
Traffic light map open loop system	None	general information	yes
Water protection zones	None	conflict map	yes

The parameters have been selected based on the availability of input data and relevance for the pilot area with special regard to the complementary national project GEL-SEP. We intended to provide the relevant hydrogeological and geological parameters for planners of shallow geothermal energy installations as well as for local authorities. To meet the needs of energy planners, who are also part of our stakeholders, we additionally selected capacity and energy related parameters.

2.8.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Publication of the data sets, which provide all geological, hydrogeological as well as energy related information necessary for planning of shallow geothermal energy applications, on the local web information system of Vienna will certainly raise awareness further. We elaborated our results in cooperation with GEL-SEP “Green Energy Lab – Spatial Energy Planning”, a nationally-funded project which developed methods for calculation of shallow geothermal energy resources in Vienna, parts of Salzburg and parts of Styria. Inside the *energyATLAS*, our results will be accompanied by other renewable energy resources like solar energy. We presume that the lesser known technology of shallow geothermal energy will benefit from this joint appearance. Another benefit to raise awareness is the implementation of the *energyATLAS* into the widely known and trusted *viennaGIS*, the web GIS of the city.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Yes, we are in close cooperation with one of our key stakeholders in MUSE, who is also our client on the GEL-SEP project, the municipal department for energy planning in Vienna (MA 20). They are most interested in our results to be made publically available for further use. The results will be made available to everyone free of charge in the *energyATLAS*, which is described below.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

The GEL-SEP project is currently developing an *energyATLAS* that will show resources and existing infrastructure of different renewable energy sources. It is planned to include our MUSE results as well. This tool provides all the basic information to include shallow geothermal heat potential into spatial energy planning. The information will be provided as maps and reports. Aside being published online as maps, our results will also feed into automatically generated reports about status analyses of energy for city districts. This planning instrument provides a summary of all renewable energy sources in the city districts.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

The data sets provide a great first estimation of available resources and therefore can help in the decision making process and selection of the low carbon source for heating and cooling of new or refurbished buildings. We already know from planners that they will use our data sets exactly for this purpose. Planners already use the maps (thermal conductivity and suitability for open-loop systems), which are provided at the viennaGIS, frequently. Hence we are certain that our results from MUSE will be widely accepted and used as well.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

At the moment the local authorities do not plan to use the produced data sets in the permitting procedures.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

Yes, all data sets will be included in the viennaGIS, as part of the above mentioned energyATLAS. This web interface will be published in fall 2021.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management in your pilot area? If yes, please provide a brief explanation

The assessment of resources can only be as good as the quality of the input data. In the city of Vienna the density of geological and hydrogeological data in general is rather good. The western part of the city comprises shallow groundwater bodies connected to small streams coming out of the “Wienerwald”, a hilly area. However, the properties of these groundwater bodies, including the top and bottom depth/elevations, as well as the hydraulic conductivity, have not been described well enough to be included in resource calculations yet.

It would be an improvement of the resource assessment to include already existing shallow geothermal energy installations. However, due to the lack of data this has not been possible. The water registry of Vienna lists all open loop groundwater heat exchangers, but only the permitted pumping rate is mentioned. Information about the actual volume of water and heat extracted/injected is missing. The same can be said for closed loop borehole heat exchangers. Here even the location of the installations in the most Western part of the city is unknown, because licenses are not mandatory.

Table 2.8.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Vienna.

Permitting and licensing procedures	**3**
Local environmental, energy and climate mitigation strategies	**4**
Spatial planning including energy plans	**5**
Investment decisions by public or private entities	**4**
Local (web based) information systems	**5**
Other aspects – *please specify*	**-**

2.8.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

We applied the workflows from the project ”GEL-SEP” in the MUSE pilot area as planned.

2. Performance of field measurements in comparison to the initial plans

The field measurements started according to plan. Within the year 2020 we could not check our data loggers monthly as originally planned, due to the COVID-19 pandemic. Hence the batteries in some of the loggers ran out, resulting in data loss of a couple of weeks. With the project prolongation we were able to extend the field measurements up until the end of March 2021.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

The largest surprise from the data analysis was that there was no impact on the groundwater temperature downstream at borehole 2-34 at a distance of 700 m from the large GWHE (150 l/s) at Vienna University of Economics and Business, located in the Prater area. This could be partly due to the injected water flowing in parallel past borehole and due to an interference with the second GWHE in this area, which is also located downstream.

The greatest non-hydrogeological surprise during the field measurements was small animals that inhabited two boreholes. Aside from spiders we met fast-running crickets in the round space around the underfloor borehole pipe.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

Within the year 2020 we could not check our data loggers monthly as originally planned, due to the COVID-19 pandemic. In order to increase the amount of collected data, the field measurements were prolonged until end of March 2021.

In February 2021 it was exceptionally cold in Vienna. During our field trip in this month we were not able to open four of the boreholes because the caps were frozen. Therefore, no check of the data loggers was possible and the next check was performed a month later.

At borehole ‘2260 T’ the first troubles occurred in July 2020, where a high moisture content was found inside the borehole. After cleaning the logger and lacquering it, it was placed back into the borehole. However, the batteries never lasted long (not even a month) from that time on. It finally stopped working in November 2020 and was beyond repair. We assume the high number of temperature sensors (x10) attached to a longer cable than at the other locations, together with the high moisture content inside the borehole, was too much for both the data logger and the sensors themselves. The cables or the attached sensors appeared to be damaged. This was also the case at borehole ‘2295 T’, where we, together with ‘2260 T’, installed the longest cable of around ~36 m with also 10 temperature sensors. Here the logger stopped storing temperature measurements at the end of December 2020. It took some time to find this out and by the time we did, there were only 3 months left for the field measurements. Therefore we decided against the construction of a new measurement device and instead measured the temperature manually during the monthly field trips to check the other loggers.

About the data preparation, we originally did not plan to submit maps about heat transfer rate and specific annual thermal load for closed-loop systems. However, since we have developed a workflow for those parameters in the previous mentioned project ‘GEL-SEP’, we were able to provide these data sets as well, which was a bonus.

Originally, it was planned to simulate summation effects of existing groundwater heat exchangers within a numerical 3D model to be able to consider their impact on the resources. However, due to a shift of budget to other important tasks, we did not go through with this idea. It will be picked up in the future project ‘Heat below the city’.

2.8.6 Outlook

The project ‘Heat below the city’, which is funded by the Vienna Science and Technology fund and has an entire project duration of 3 years until 2024, aims to improve the groundwater temperature maps from MUSE. The maps from MUSE will be used as starting point to identify possible areas of urban heat islands. With measurements in additional boreholes, specifically in areas with expected urban heat islands, they can be better delimitated and in general the resolution for the temperature map can be increased.

In ‘Heat below the city’ it is also planned to develop a numerical 3D model for the pilot area of Vienna in order to simulate groundwater flow and characterise thermal parameters for the coupled groundwater flow and heat transport simulation. The data gathered within MUSE will serve as important input parameters for the model.

2.9 City of Cardiff (Wales, UK)

British Geological Survey

David Boon, Gareth Farr, Ashley Patton, Corinna Abesser, Johanna Scheidegger, Jon Busby, Laura Williams, Alan Holden, Steve Thorpe, Andy Butcher, Barry Townsend, Mark Woods

British Geological Survey

2.9.1 Focus of activities inside GeoERA-MUSE

The MUSE project (2018-2021) covered a time period of accelerating energy transition and climate change policy shift in the UK. In 2018 the UK (Westminster) government legislated to cut its CO2 emissions to Net Zero by 2050 to limit global warming to below 1.5°C. Nearly half of these carbon emissions reductions will need to come from the heating and cooling sectors and the majority of the heat/cold demand is in urban areas. 85% of UK homes (around 27M) have natural gas boilers that will need replacing with low carbon technologies. In December 2020, the UK government published an Energy White Paper (HM Government, 2020) that set an ambitious target to install 600 000 heat pumps a year by 2028. Of these, we anticipate 10 to 20% (120 000 to 60 000) to be GSHP/WSHP, with around 90% (100 000 – 50 000) of these being Closed loop type and around 10% (6,000 – 12,000) being Open loop type systems. To put this challenge into context, we must remember that the UK ground source heat pump market is still relatively immature, with an estimated 38,000 GSHP systems installed in the UK (up to 2020) and a rate of around 3 000 to 4 000 new GSHP systems being installed per year in 2019, and so it is important for industry designers, installers and energy planners to have the best available geological, hydrogeological and thermogeological information at their disposal.

Given this future energy policy landscape, we expect a high density of single and shared ground loop arrays to be deployed in urban and sub-urban areas, augmented with large (several MW) GSHP or WSHP schemes supplying public and industrial buildings and augmenting 4th and 5th generation low temperature district heating (and cooling) networks. Underground heat storage systems (BTES and ATES) will also play an increasing role in interseasonal heat storage.

Current market analysis showed that Cardiff city, with its population of around 350 000, has fewer than 10 known GSHP schemes (in 2021) and it can be assumed that homes are using gas boilers. Therefore, we expect very rapid uptake of vertical closed loop ground source heat pumps in the city, and moderate to high potential for subsurface thermal interactions as closed loop BHE are not currently regulated in the UK, and some will be installed in close proximity to other schemes and will partly be installed in the shallow gravel aquifer where heat advection will be a dominant process.

As such, the work undertaken by the BGS-UKRI in MUSE mainly focused on improving knowledge of location and impacts of existing GSHP systems, the thermo-geology of the Triassic sedimentary bedrock deposits in the Cardiff-Newport area, and the hydrogeology and geothermal resource potential of the shallow gravel aquifer under Cardiff.

Planned activities for March 2019 – March 2021 MUSE ‘monitoring period’ included:

- Investigation of aquifer properties and baseline temperature monitoring
- Open Loop GSHP scheme monitoring to study impacts
- Mapping installed systems and potential conflicts of use (Link to WP5)
- Geophysical Investigations (BGS-TNO collaborations)
- Thermal Response Test (TRT) (BGS-GBA collaborations)
- Pumping test on gravel aquifer
- Thermal conductivity measurements (field and lab/core)
- Heat flow or Hydrogeological models (city scale)
- Governance: Review of regulation (link to WP2 & 3)
- Social Science: Stakeholder questionnaires & Public engagement, Installer questionnaires (link to WP2, 3 and 5)

2.9.2 Outcomes of field measurements

The outbreak of the COVID-19 public health pandemic in the UK in March 2019 resulted in a string of national and local 'lockdowns' which severely affected field work logistics. As a result, the planned geophysics in Cardiff, pumping tests and TRT did not take place. Despite the challenges with COVID the activities successfully performed included:

- Baseline monitoring of aquifer groundwater temperature in 59 boreholes across the Cardiff Urban Geo-Observatory (Farr et 2019a &b; Patton et al 2020). The groundwater temperature data collected in MUSE is summarised in Figure 18 and includes 1.73 million new temperature measurements (time series) from 57 sensors deployed at depths of between 1.5 m to 18.9 m below ground level.
- Monitoring of the environmental impacts and energy performance at a small (22kW capacity) shallow Open loop GSHP scheme heating a school building. Outputs included a research paper (Boon et al 2019), several stakeholder presentations, and cross-cutting (WP6) dissemination with the IEA's Heat Pump Technologies Annex 52 international experts group. GSHP monitoring approaches were also discussed in a joint MUSE Blog.
- Investigations into aquifer water quality and microbiology around the Open loop GSHP scheme and control wells. Table 2.9.2-1 summarises aquifer water chemistry / quality results obtained during MUSE field work. A paper (Farr et al 2021) is also being prepared for a Special Issue *of 'Groundwater'.*
- Geophysical Investigations: The aim of the geophysical surveys was to demonstrate application of rapid passive seismic H/V methods and well logging techniques in urban environments for supporting characterisation of shallow geothermal resources/reservoirs. The geophysical survey work was initially planned for Cardiff City but due to the COVID-19 situation and timing/delays of 3rd party BHE installations, we were forced to move the fieldwork aspect to another UK city where we could access deep thermal wells. Downhole geophysical logging surveys and H/V microtremor surveys took place in February 2020 at a large (800kW output) Open-loop GSHP scheme under development in the town of Colchester (Essex, England). The results are reported in an open report (Boon et al 2020a) and are discussed in a MUSE Blog. The work provides a 'best practice' example of the value of undertaking rapid geophysical surveys to compliment 'traditional' hydrogeological investigations (pump tests) for characterising the geology (litho-stratigraphy) of shallow geothermal reservoirs –

in this case a Cretaceous chalk bedrock aquifer overlain by lightly-overconsolidated Palaeogene (London Basin) sediments. The feedback from the developer (Colchester Amphora Energy Ltd) was that the Gamma log and OPTV data helped to de-risk the planned geothermal scheme by confirming ‘as-built’ borehole construction details. The interpretation of this data enabling improvements to the site geological and hydrogeological models, and this knowledge was transferred into an initial numerical simulations of the long-term sustainability of the scheme undertaken by our academic collaborators at Surrey University (Sezer et al 2021). The groundwater temperature data and electrical conductivity profiles collected between 0-190m depth provide a useful comparison between the other MUSE pilot area sites in Scotland (Glasgow) and Wales (Cardiff), and with other MUSE pilot areas in Europe, and will be incorporated into future updates to the UK subsurface temperature maps.

- Thermal conductivity analysis: A *C-THERM* conductivity analyser was acquired during the MUSE project and measurements were made on 29 representative bedrock core samples of Triassic Mercia Mudstone Group (MMG, is the surface bedrock unit under most of Cardiff, and much of England). The new data, which includes data for the Sherwood Sandstone (Bunter) Group, enhances the UK thermal properties database. The early data from MUSE is published in the *EAGE GET21* conference (Boon et al 2021). The measured (core) thermal conductivity of 5 fresh Triassic Mercia Mudstone bedrock samples (argillaceous facies/red mudstone) is 2.7 W/mK, thermal diffusivity of 0.10 m2/day, Volumetric heat capacity of 1.9 MJ/m3/K at ave. NMC of 7.3%. (Boon et al. 2021). The range of all 23 MMG & MMF core samples was 1.5–3.6 W/mK, mean average value of 2.3 W/mK. For comparison, in-field TRT tests (type II) in 60-115m deep GSH test boreholes in 17m of Quaternary silt, sand and gravel deposits on 82m of MMG argillaceous facies (‘red mudstone’) and 19m of basal sandstone (probably Marginal Marine Facies, MMF), undertaken during the construction of the Senedd building in Cardiff Bay, returned average effective ground TC of 2.5 W/mK, (Groenholland BV, 2001). Furthermore, the collaboration in MUSE between BGS and the Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium (using their optical thermal conductivity scanner on our samples) also supported publication of a peer-reviewed research paper on thermal properties of Triassic Mercia Mudstone Group lithologies (Parkes et al 2020, *QJEGH*).
- A city-scale hydrogeological model was produced, including a water balance model, shown in Figure 19, including consideration of gains/losses from leaky sewers and leaking water pipes (building on work by Scheidegger et al 2017).
- Stakeholder engagement and creation of a database of existing known GSHP installations and preparation of GIS map layers for integration with the EGDI platform (WP5).
- Map of ’Shallow Geothermal Opportunities’ produced for European Geophysical Union conference session (Boon et al 2020b - EGU2020-19146). The map, based on Figure 20, depicts ‘traffic light’ style ’zones’ showing areas suitable for open and closed loop GSHP and incorporates aquifer thickness data from the BGS’ 3D Quaternary geological model (Kendall et al 2020). The data was shared during MUSE with the local municipal authority (Cardiff Council) and Welsh Government officers to support energy master planning and spatial planning.

- A review of geothermal energy regulation was carried out (linked with WP3), with questionnaires completed that contributed to a research paper published in *Energy Policy* (Garcia Gill et al., 2020). Discussions about pros' and cons for shallow geothermal regulation in the UK were had with key stakeholders from the UK Government and the UK heat pump industry (HPF, GSHPA).

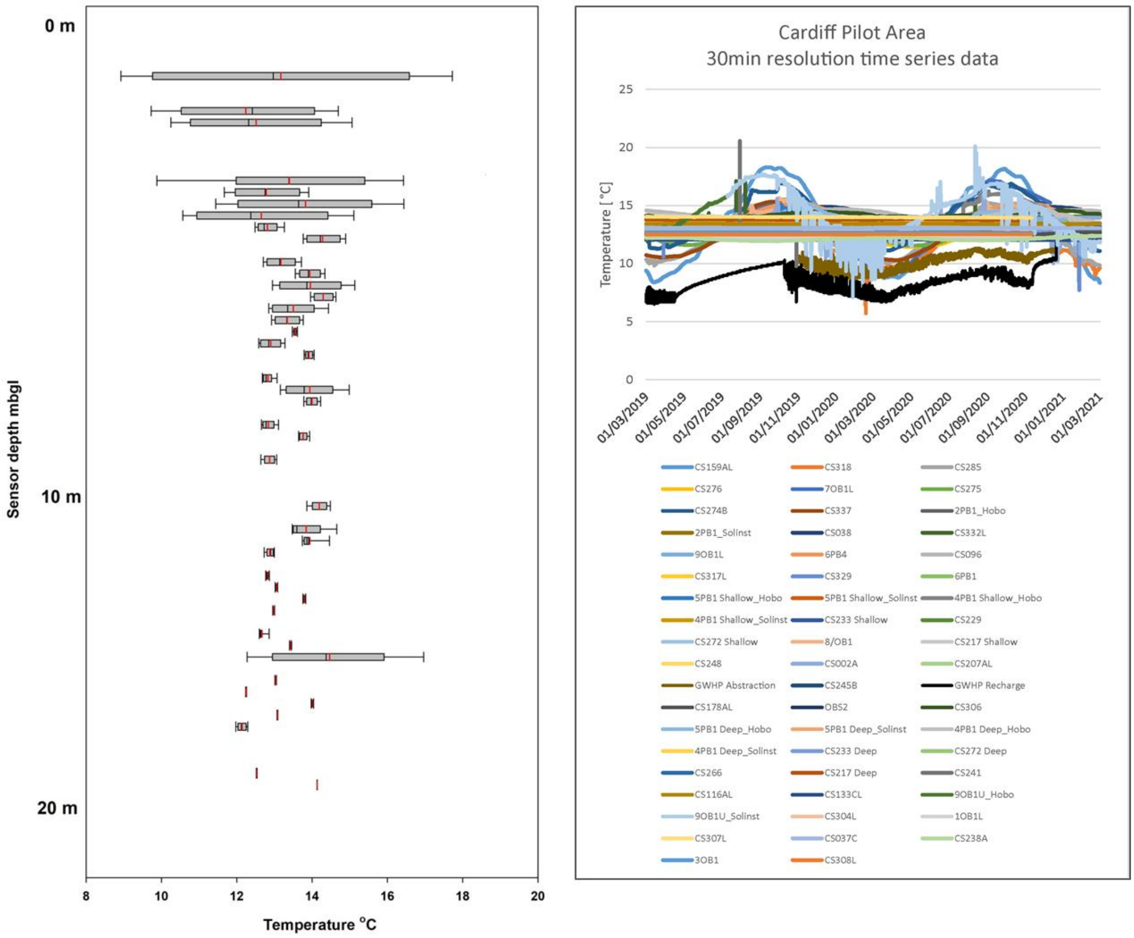

Figure 18. Image on the left shows box-and-whisker plots summarising 30min resolution groundwater temperature data measured continuously between March 1st 2018 and March 31st 2021 in 42 boreholes located across Cardiff City. The plot on the right shows the Cardiff borehole temperature data presented as a time series. The thick black and red lines are amongst the coldest temperatures, and are the insitu injection (recharge) and production (abstraction) well temperatures, respectively, at a small open loop GSHP heating scheme. (BGS-UKRI, 2021).

Table 2.9.2-1. Inorganic water chemistry from an operational GWHP well doublet and key observation wells distributed in the Cardiff Quaternary sand and gravel aquifer. Data from wells in the bedrock (Triassic Mercia Mudstone) and local surface water bodies (summer) are also included for comparison. (BGS, UKRI 2021).

Sample Point / Source	Easting OSGB (NGR)	Northing	Temp °C	pH	EC µS cm^{-1}	DO_2 mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cl^- mg/l	SO_4^{2-} mg/l	HCO_3^- mg/l	NO_3^- mg/l	Mn µg l	Total Fe µg l
Ground Source Heat Pump: Sand & Gravel Aquifer																
Abstraction borehole	318104	174495	11.6	7.4	1510	n.a	46	48	174	30	204	<0.25	nd	<0.15	867	6426
Recahrge borehole	318120	174502	11.6	7.7	1300	n.a	46	48	174	30	198	<0.25	nd	<0.15	979	4002
Quaternary: Sand & Gravel Aquifer																
CS134A	315616	177038	12.4	7.1	681	1.65	88	26	15	1.9	23	25	311	11	0.3	3
CS074AL	315834	175882	13.6	6.8	1193	0.01	91	61	46	18	27	25	713	0.2	369	4
CS322L	316614	175217	12.8	6.9	1988	0.06	110	74	208	25	195	56	866	<0.3	5789	2286
CS317L	318139	174388	13.5	7.6	1689	0.04	22	32	262	29	234	<2.5	620	<1.5	270	2589
CS278	318002	173967	15.4	6.9	9270	0.04	78	139	1627	65	2665	327	621	<3	576	3597
CS241	317980	174445	13.8	7.9	2660	0.11	10	17	550	22	440	19	811	<0.3	60	900
CS327L	318850	174553	13.9	7.8	3890	0.09	22	31	741	24	1150	245	462	6	130	11
CS308L	319448	174447	13.4	7.7	5730	0.06	53	97	964	46	1624	200	421	<1.5	104	810
4PB2	317973	174828	14.1	7.5	7980	0.04	33	61	1249	41	1412	316	931	<3	144	582
Bedrock: Triassic Mercia Mudstone Aquifer																
Techniquest 30m bgl	318984	174410	nd	7.8	6540	nd	164	135	938	20	2006	369	122	5	11	33
Techniquest 60m bgl	318984	174410	nd	6.7	>20,000	nd	3927	1439	13149	134	34589	1598	24	<30	737	2301
Brains Brewery 60m bgl	318115	175725	nd	6.5	5660	nd	338	81	756	17	1623	27	820	<3	718	68788
Surface Water																
River Taff	318206	174355	18.8	8.0	405 (?)	9.29	37	14	34	7.3	79	47	171	5	21	89
Roath Dock	319911	174647	19.0	8.3	12930	5.60	111	271	2247	84	4179	576	137	<3	9	11
Atlantic Wharf (Bute East Dock)	319419	175139	21.3	9.1	320	nd	21	11	29	5.3	29	34	123	<0.03	6	21
River Ely	315913	175247	16.3	7.3	498	nd	55	11	25	5.6	38	35	184	10	27	95
Bute Park (Dock Feeder Canal)	317809	177081	16.0	7.9	393	nd	34	12	25	6.0	21	38	152	7	9	96

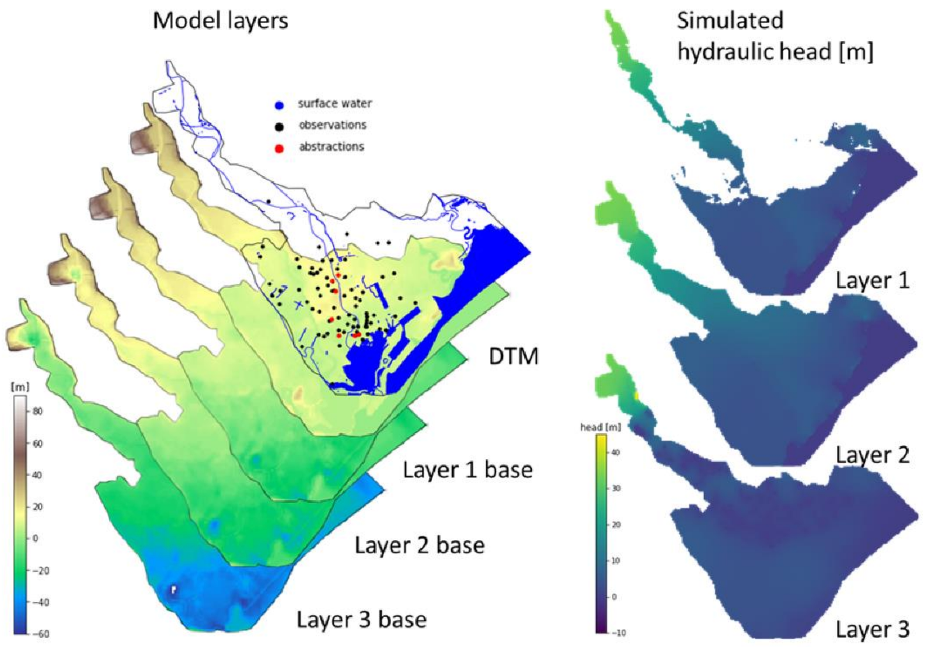

Figure 19. Outputs from the Cardiff groundwater model depicting shallow gravel aquifer body geometry (left) and modelled hydraulic heads (right). (BGS, UKRI 2021)

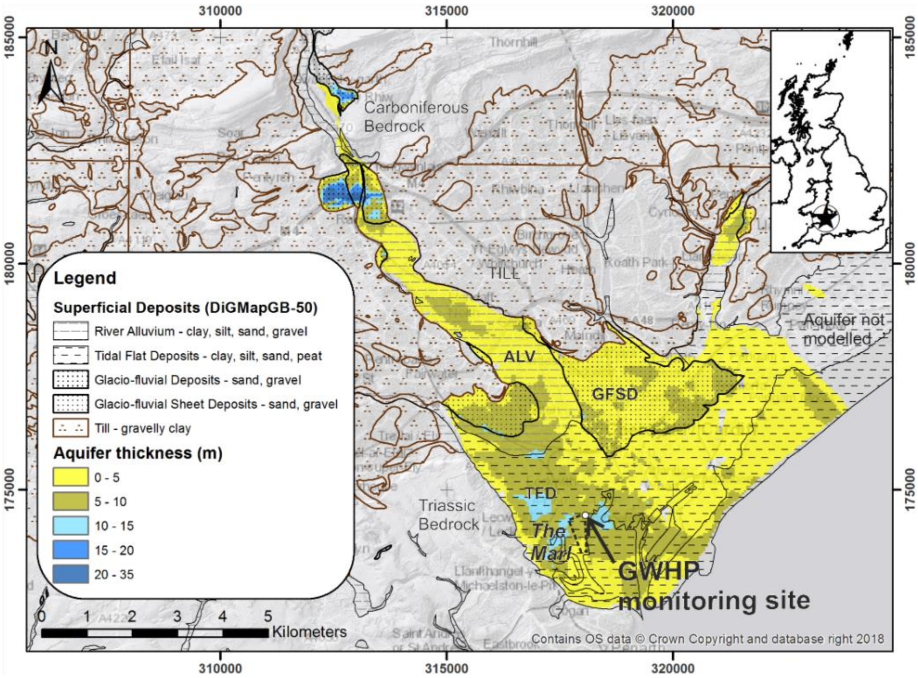

Figure 20. Map showing estimated thickness of Quaternary gravel aquifer and location of a GWHP monitoing site at Grangetown Nursery School (adapted from Boon et al 2019; thickness grid based on 3D geo-model by Kendall et al (2020)).

2.9.3 Outcomes of GIS datasets delivered to EGDI

The data sets prepared for the EGDI web viewer include:

1. **Existing GSHP installations –** collated through local stakeholder engagement. (Not exhaustive list but the schemes we knew about in 2020).
2. **Extent of groundwater body or aquifer** (Quaternary gravel aquifer).
3. **Quaternary gravel aquifer thickness** (Figure 20). 50m horizontal grid size.
4. **Depth to gravel aquifer –** essentially representing minimum drilling depth for open loop heat groundwater source pump and minimum drill casing depth.
5. **Elevation of top of gravel aquifer** (as above).
6. **Gravel aquifer and river water chemistry** summary table.
7. **Depth to bedrock (m).**
8. **Elevation of bedrock (m asl).**
9. **Thermal conductivity of bedrock** (estimated for Triassic Mercia Mudstone Group lithologies based on core measurements; Boon et al 2021)
10. **Cross sections** derived from the Quaternary 3D geological model (extracted from Kendall et al 2020).

These parameters, described in more detail in report D4.3, are seen as the most useful for local energy planners / stakeholders as they are interested, usually at the technical feasibility stage to understand: Can I use heat pumps?; Can I use open loop GSHP?; Is there a source of groundwater and what is its temperature?; How deep do I have to drill (and what is the rough cost) to access the groundwater?; How deep is the bedrock below unconsolidated deposits (that will need drill casing); What is its estimated bulk thermal conductivity in the upper 100m? The TC values discussed in this report provide an indication of conditions only, and should not be used for detailed design purposes where a TRT test(s) should be performed.

2.9.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Yes. The raw groundwater temperature data and 3D geological model data and 'opportunity maps' were shared (as .pdf and GIS layers .shp) with key stakeholders at the Council and supported enquiries from local and Government officers exploring the possibility of using shallow geothermal energy to decarbonise buildings in the city (Cardiff University, Cardiff Community Energy, Welsh Government Energy Service, Kensa Heat Pumps). The geo-observatory and GSHP's were mentioned in the Councils Energy Action Plan (One Planet Cardiff). It is too early to gauge the full impact of MUSE results as they will take time to disseminate and implement in other organisations information systems.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Yes. Plan is to share database on existing GSHP and ongoing GIS data sharing on geology and aquifer thickness to support Municipal authority land use and resource planning strategies. The 3D geological model data outputs have already been shared with Cardiff Council to help them understand ground conditions across the city as they construct new infrastructure such as district heat networks and other infrastructure. The hydrogeological model will be shared with the public water supply company (Welsh Water) who want to understand risks from groundwater levels on their subsurface infrastructure. The data is also being shared with UK university academics and students to benefit their research and training (e.g. Kreitmair et al 2020; and engineering PhD student from Leeds University).

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Yes. The geological model, experience and understanding of the aquifer and its physical response to thermal perturbation is being fed back to key stakeholders, including the Environmental Regulator (e.g. National Resources Wales), local Council officers, water companies, energy consultants, universities, Welsh Government. There will be some follow- up work to provide (and licence) the GIS and 3D model data in data formats that can be ingested and used by those organisations. The data sets will also feed into a planned Digital Twin project.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

Yes. The datasets (3D model derivatives) have been shared with Cardiff Council who may choose to use the information to plan new infrastructure (District Heat Network, Metro, GSHP). The geological model and groundwater temperature data has also been used by Rhondda Cynon Taff Council who are constructing a water source HP scheme using thermal spring waters from Taffs Well. It is expected installers in Cardiff and Newport will use the bedrock thermal conductivity data (Boon et al 2021) as a reference/sense check for outline GSHP designs, and the geological models for desk studies and planning site investigation works.

The data collected from the Colchester Open loop boreholes was delivered in a publicly available report (Boon et al 2020) and reduced the technical risk of their scheme. The collaboration encouraged them to consider options and benefits of long-term temperature monitoring of their geothermal wells, as part of an integrated sustainable management practice for their scheme and future GSHP schemes.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Not directly. Local authorities are not responsible for permitting as this is the responsibility of the environmental Regulators (NRW in Wales, EA in England, SEPA in Scotland). The NRW will have access to the datasets and may choose to consult this information in their assessments. Currently only Open-loop systems with groundwater abstractions of >30m3 per day are regulated. There is no permitting for Closed-loop geothermal systems in the UK. NRW and the EA (England) will probably use the BGS' baseline datasets and existing systems database for risk assessing new schemes in the future.

6. Will the datasets produced for your pilot areas be available in a local (web based) information system or data repository? If yes, please provide a brief explanation

Yes. Some of the data may be displayed in the GeoIndex web map viewer, such as 3D geological model derivatives, locations of existing GSHP schemes and all the data will be accessible from the UKGEOS Cardiff (www.ukgeos.ac.uk/) or another BGS-NERC data repository (e.g. NORA and the BGS 'GeoIndex').

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

Public sector organisations in the UK use a variety of GIS platforms and IT/Internet security policies mean they cannot access some web-based information systems. Therefore, integration of datasets into their local IT systems and networks/servers is important to realise the value of the data. Open access data is the preferred method, as many local authorities have limited IT funding and capability and can't always afford to licence GIS data.

Table 2.9.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Cardiff.

Permitting and licensing procedures	**3**
Local environmental, energy and climate mitigation strategies	**2**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**3**
Other aspects – ***Regulation***	**2**

2.9.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Workflows on adaptive management concepts need to be tailored to local legal and regulatory conditions. Uptake will take many years, if not decades, but the presence of a framework is a good starting point for influencing local policy makers to set targets for and sustainability criteria.

2. Performance of field measurements in comparison to the initial plans

Field measurements (temperature sensors) performed well throughout the monitoring period, however COVID-19 delayed access to download many of the sensors and some ran out of battery or data storage during the monitoring period resulting in minor data losses. Telemetry systems at the GSHP monitoring site also incurred some data losses - not helped by the fact we could not access the school to diagnose faults due to national and local COVID travel restrictions. The heat pumps were turned off in Nov 2020 and this cut the power to the telemetry so we lost much data about the heat pump, though fortunately we have some back up loggers installed alongside the telemetry sensors in the aquifer /boreholes.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

COVID-19 pandemic. We had data losses as we had deployed data loggers in the aquifer but could not return to the field to download them before the internal memory ran out. The telemetered systems did not suffer this problem but other problems were power cuts and difficulty accessing the heat pump monitoring site to manually read heat pump system consumption loggers. Having more online meetings was actually an efficient way to share results and discuss preparation of data sets as the team is based across several offices.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

COVID-19 caused a major deviation to our planned download of the temperature sensors and some of the proposed fieldwork. However, most of the sensors continued to monitor temperatures and other data (e.g. Geochemical data) was collected during periods where lockdown restrictions were eased and data set were prepared as planned. Deviation of geophysics field work to a site in England was unplanned, but we were still able to demonstrate the benefits of geological and geophysical data collection and for promoting application of 'good practice' in the industry.

2.9.6 Outlook

The Cardiff Urban Geo-Observatory will next develop a digital twin platform and undertake further modelling research into thermal interactions between shallow geothermal energy systems in urban aquifers. We hope to develop planning tools to support optimisation of geothermal scheme locations and to support in sustainable planning. The new data will feed into the UK knowledge base and will be disseminated actively to stakeholders beyond the life of MUSE.

2.10 City of Glasgow (Scotland, UK)

Alison Monaghan, Kirsty Shorter, David Boon

British Geological Survey

2.10.1 Focus of activities inside GeoERA-MUSE

The motivation for a pilot area in Glasgow is that the city is Scotland's largest, with a post-industrial landscape with a rich social and economic history bound to subsurface coal mining and heavy industry. The regeneration of the city and decarbonisation of old and new building stock can benefit from re-use of flooded, abandoned coal mines for low carbon heating and can be integrated with new district heating schemes.

Inclusion of the UK Geonergy Observatory in Glasgow brings an example of shallow coal mine geothermal energy to the MUSE project portfolio. The development of a geo-observatory in eastern Glasgow is providing a field scale geothermal energy research and innovation infrastructure. It will de-risk geothermal energy solutions in urban areas that have access to groundwater stored in coal mines. The planned field measurements and planned GIS layers include baseline groundwater and surface water monitoring, fibre-optic distributed temperature sensing (FO-DTS) temperature and electrical resistivity tomography (ERT) measurements, ground gas, soil chemistry, seismic monitoring and ground motion.

2.10.2 Outcomes of field measurements

The activities performed between March 2019 and March 2021 include drilling of research boreholes, instumentation, baseline environmental monitoring, including DTS temperature profiles (Figure 21 and Figure 22), borehole test pumping. The results are openly avalaible via the UKGEOS website with data downloads and more information on the FO-DTS is avalible in UKGEOS project blog and MUSE blog.

The Glasgow Observatory is open for access from 2021 to UK and international researchers and industry. Rock core, chippings, geomicrobiology and water samples have been made available for academic research.

Figure 21. Installation of DTS (thin black) and ERT cables (red electrode) in a mine water geothermal research borehole (Monaghan et al. 2021)

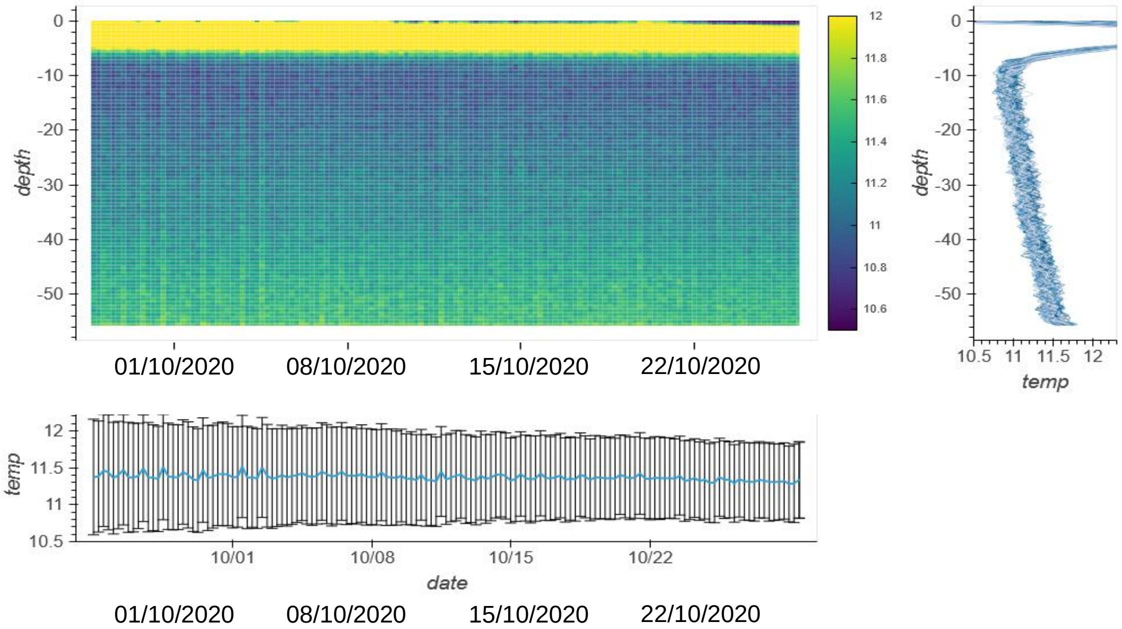

Figure 22.Top left: Time series image of FO-DTS downhole temperature variation in borehole GGA07 throughout October 2020. Top right: downhole temperature plots for October 2020. Bottom: daily range and means of temperatures.(image source: UKGEOS website).

2.10.3 Outcomes of GIS datasets delivered to EGDI

The layer provided to EGDI includes *geological cross sections* through the study area. The cross-section output was chosen as an example of a litho-stratigraphic model as part of developing and testing geothermal 'ground models'.

2.10.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Yes – the Glasgow Observatory has provided a facility for research and attracted funding for academic research into shallow geothermal energy. Stakeholder events have engaged local communities and authorities.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Yes – the datasets produced by UK Geoenergy Observatories during the MUSE project period are open access and are being used by and published on by academic researchers: Walls et al. 2021, Watson el al, 2019, Chambers at al. 2019, Kuras et al 2021 AGU abstract - submitted.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Yes – data and learnings will contribute to local energy action plans for Glasgow and other coal mine communities.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

It's too early to say what the impact has been on local management and energy strategies as the technology application is still considered novel for the UK. The establishment of a geo-observatory has highlighted the need for subsurface research into environmental and geotechnical impacts of geothermal energy use to stakeholders and policy makers and will provide a platform to investigate, de-risk, and manage these issues in future underground heat storage schemes.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Not immediately or directly. However, the data will be used to increase the evidence base for aspects such as ongoing baseline environmental change in the groundwater and surface water environment, impacts of pumping, scale of temperature variations, size of thermal resource and sustainability. These aspects will inform permitting and licensing of mine water thermal resources.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

Yes all data collected is published on the UK Geoenergy Observatories project website.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

No

Table 2.10.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Glasgow.

Permitting and licensing procedures	**3**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**2**
Investment decisions by public or private entities	**1**
Local (web based) information systems	**1**
Other aspects – please specify	**-**

2.10.5 Lessons learned in the pilot area

Details of lessons learnt for drilling into mine workings for heat are given in Monaghan et al. 2021. More detailed technical observations on the workflow, borehole construction, cleaning and testing are given in Starcher et al. (2021; NORA ref)

1. Applicability of workflows and the elaboration of output data sets

The workflows produced in MUSE were not directly used in the Glagow pilot area due to the timing of the project.

2. Performance of field measurements in comparison to the initial plans

COVID restrictions caused difficulty and delay to fieldwork, equipment installation, sampling and surveys. The DTS sensor data experienced technical challenges with remote communicatons and site security was compromised by vandalism in late 2020 resulting in loss of baseline data.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

The boreholes penetrated a range of mine water reservoir types, ideal for a research facility, the mine water chemistry and temperatures are fairly typical. The borehole test pumping was successful, indicating both high flow rates and responses in boreholes within the same mine working and overlying bedrock, such that research experiments are likely to provide measurable responses to characterise the system and its response to heat and flow perturbations.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

FO-DTS temparature measurments were disrupted by COVID-19 pandemic and vandalism at the field site. In the end, 3 months of continuous DTS temperature monitoring was achived from August through October 2020. The data is being prepared for delivery via the UK Geoenergy Observatories project web portal. A MUSE blog has been published that summarises the DTS monitoring, which is expaned on in a UKGEOS blog.

2.10.6 Outlook

The UK Geoenergy Observatory in Glasgow will be utilised by academic and commercial researchers and innovators over the next 15 years (up to 2035) for shallow mine water geothermal energy and heat storage research.

2.11 City of Bratislava (Slovakia)

Radovan Cernak and Jaromir Svasta
State Geological Institute of Dionýz Štúr

2.11.1 Focus of activities inside GeoERA-MUSE

Bratislava is in south-western Slovakia at the foot of the Little Carpathians, occupying both banks of the river Danube that is the source of the groundwater along with groundwater transfer from the Male Karpaty Mts. The share of geothermal energy use for heating and cooling is to a certain extent unknown, due to a lack of information about existing installations, utilization performance, and limited information about closed loop systems.

The aim of the field measurements was to review and interpret the recorded values of groundwater temperature in the relevant wells (Figure 23). The monitoring wells were chosen in the pilot area and in the city centre to evaluate the influence of factors which impact groundwater temperature in the study area. Variables that affect the groundwater temperature are surface water temperature (Danube River) and anthropogenic factors that result in urban heat island anomaly (UHI). Data were obtained by continuous measurements of groundwater level and groundwater temperature.

Field measurements, archive data from previous studies and accessible sources were used to create layers: land surface temperature, subsurface temperature, thermal conductivity and average interval subsurface temperature.

2.11.2 Outcomes of field measurements

To a greater or lesser extent, three main factors affect all wells – air temperature, Danube river temperature and urban development. A close relationship with the temperature of the Danube was expected and confirmed from the boreholes on the right and left bank of the Danube and in vicinity to the river (VN138-1, VN138-3) (Figure 23). Evidence of the influence of anthropogenic factors on the subsurface temperature is considered to be in wells with high values of groundwater temperature in places of maximum urban development. The higher temperatures are more likely caused by direct utilization of groundwater in open loop systems used preferably for cooling of the buildings in newly developed area (City centre, wells VN4-2, VN5-7). Marginal areas are influenced by air temperature through paved surfaces or subsurface infrastructure installations. The latest mentioned can be assumed to be in higher density the centre than in the surroundings and also influence subsurface temperature anomalies.

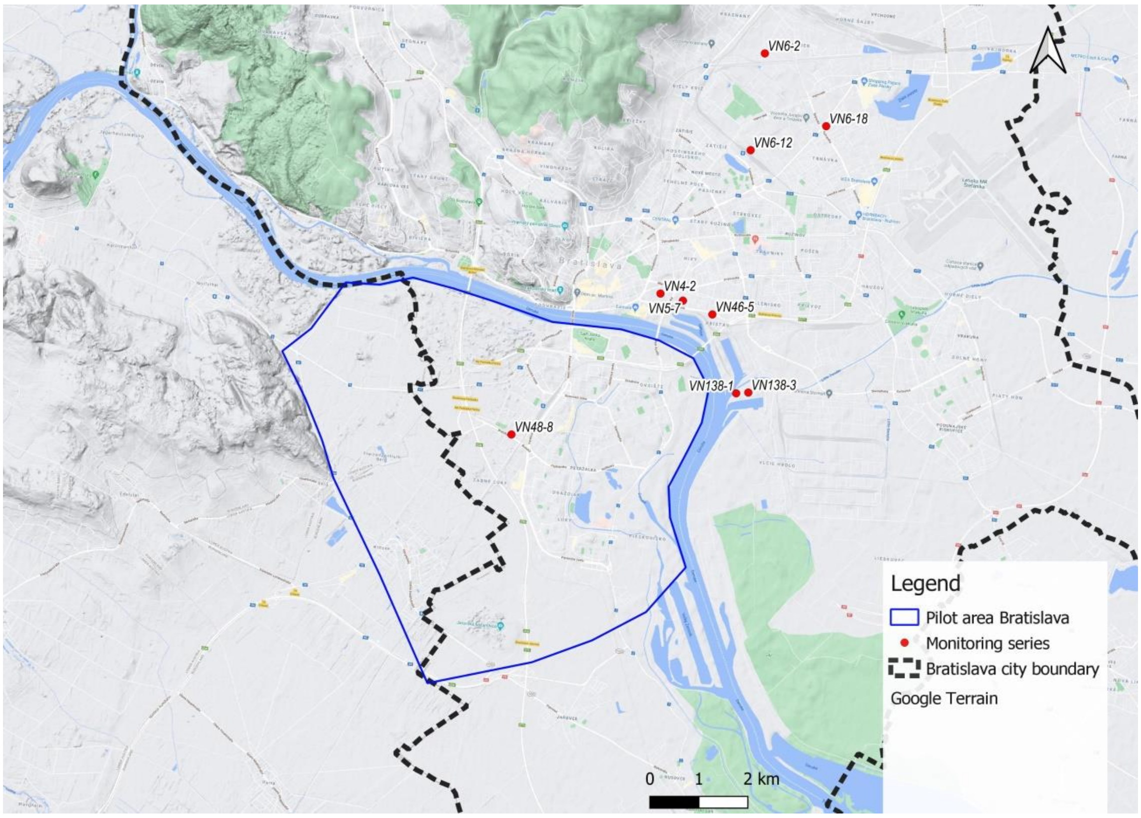

Figure 23. Monitoring network of Bratislava pilot area. Nine groundwater monitoring points, where groundwater temperature and water level was monitored between 2018 and 2021.

2.11.3 Outcomes of GIS datasets delivered to EGDI

Delivered GIS layers prepared for EGDI provided information about geological and hydraulic conditions of the subsurface environment and restrictions of the area due to its utilization or environmental burdens. Measurements of groundwater level and temperature were used to define average interval of the subsurface temperature, groundwater depth/level and groundwater temperature.

List of GIS datasets provided to EGDI:

1. **Groundwater protection**. Layer delineating groundwater protection zones for drinking water sources. The dataset extends to Austria territory due to a presence of transboundary aquifers. Protection zones and adjacent areas were delineated to sustain safe drinking water supplies.
2. **Contaminated areas** - sites with confirmed or suspected waste, landfills and/or underground pollution generated from domestic, construction and/or industrial activities that may have an impact on the installation of shallow geothermal energy systems.
3. **Groundwater body suitable for open-loop systems**. Outline of near surface groundwater body (alluvial aquifer) generally suitable for open-loop systems. The

dataset extends over Slovakia and partly over Austria due to a presence of transboundary aquifers.

4. **Land surface temperature (degC)**. Raster dataset which represents the average annual surface temperature distribution in pilot area. It is derived from the MODIS Land Surface Temperature Dataset, at 250 m pixel resolution.
5. **Confined or artesian groundwater zones.** Layer outlines the areas with possibly confined or artesian confined groundwater in Neogene strata. The dataset extends over Slovakia and partly over Austria due to a presence of transboundary.
6. **Natural reserves** outlines protected area of importance for wildlife flora or fauna.
7. **Groundwater chemistry**. Zones inside groundwater bodies or groundwater bodies potentially leading to operational problems for shallow geothermal use due to a critical chemical composition. Layer delivers outline of regions with unsuitable chemistry (e.g. with low oxygen content, corrosive, or posing a risk of scaling).
8. **Elevation of a geological boundary**. Contour map of the elevation of a defined geological boundary relevant for the use of shallow geothermal energy (e.g. bedrock surface). In case of Bratislava pilot area elevation of the top of Neogene bedrock, underlying the Quaternary aquifer is outlined. The boundary is relevant for the use of shallow geothermal energy.
9. **Average subsurface temperature (degC)** is a raster dataset which represents the estimated annual average subsurface temperature for a 0 – 100 m depth interval.
10. **Average interval bulk thermal conductivity** (W/m/K) is a raster dataset which represents the average ground thermal conductivity in the pilot area from 0 – 100 m depth interval. Average thermal conductivity (including unsaturated zone) for a specific depth interval is not accounting for advective effects caused by groundwater.

2.11.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Shallow geothermal energy is still a developing sector. The data about the utilization are mainly connected to the permitting process that is applied for open loop systems. However data about the installed capacities for closed loop systems are missing. The MUSE project contributes to dissemination of knowledge on SGE and to promotion of SGE resources utilization.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

The outputs of the project and connection to stakeholders will be further developed in a planned project that will be dedicated to urban geology and information systems connected to subsurface data.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

The datasets and information provided within the project will be accessible in EGDI platform. The implementation to the environmental planning instruments will be reachable for strategies and action plans.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

The data provided are meant as support information, not decision making information.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Permitting procedures are case by case studies based on investigation that is bound to the well/source of the groundwater on open loop systems. For closed loop systems the procedures are due to reporting obligation.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

Datasets provided are available on the EDGI platform. Datasets are referenced to SGIDS and can be provided to local authorities upon request.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

No.

Table 2.11.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Bratislava.

Permitting and licensing procedures	**1**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**2**
Investment decisions by public or private entities	**2**

Local (web based) information systems	**3**
Other aspects – *please specify*	**-**

2.11.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Workflows applied enabled standardized data publishing for project partner countries.

2. Performance of field measurements in comparison to the initial plans

Continuous measurements were planned in wells that are in ownership of SGIDS due to previous installations. This way the continuity of measurements could be ensured. The delineation of the project area was during the project modified with respect to the Quaternary aquifer on the right bank of the Danube River. Documentation of the different types of groundwater regime is delivered through originally planned monitoring scheme.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

Over the last decade the city development was focused on historical industrial zones (grey areas or brownfield). Some of the locations are in the vicinity of the environmental burdens, where temperature change of the groundwater regime was documented. All contaminated sites went under the remediation process, though higher groundwater temperatures could influence so far not documented processes in the aquifer. This topic should be investigated in future.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

There were no major deviations in field work and the preparation of output data sets. All selected and delivered output datasets were prepared based on the measured data.

2.11.6 Outlook

Knowledge and results of the monitoring and field works will be used in compilation of the project focused on urban geology information system. The base and network of the partners will be a good base for future knowledge sharing and consultations.

2.12 City of Cork (Ireland)

Sarah Blake, Harrison Bishop, Taly Hunter Williams, Max Meakins, Alasdair Pilmer, Ross Mowbray

Geological Survey of Ireland

2.12.1 Focus of activities inside GeoERA-MUSE

The pilot area encompasses Cork City and some of its environs (Figure 24). Cork was chosen as it has a long history of ground source heat use and more readily available data than other parts of Ireland.

The primary motivation for the project is to improve our knowledge and understanding of the hydrogeology, geology, geothermal potential, groundwater chemistry, and management of shallow geothermal resources. Specifically, we developed and added to databases on groundwater temperatures, water levels, hydrochemistry, and borehole/monitoring point networks, and gathered additional data on ground source heat pump (GSHP) heating and cooling installations. Additionally, we aimed to build and develop relationships with stakeholders, local authorities, organisations and citizens.

Cork City has shallow groundwater temperatures that are elevated with respect to the national average, productive aquifers beneath the centre of the city and a long history of ground source heat use. Notable SGE installations include public and municipal buildings such as the Lewis Glucksman Gallery in University College Cork. As a thriving urban settlement, Cork now faces the challenge of decarbonising its heat sector, and geothermal energy can play a role in increasing the share of renewable heat.

Cork City Council's Sustainable Energy and Climate Action Plan (SECAP) was prepared and adopted by the City Council in January 2018 and identifies ways to reduce energy related greenhouse gas emissions by 43.7% by 2030. Geothermal energy was not included in the specific actions of the SECAP, however energy efficiency in buildings and heat/cold production were specifically mentioned as themes in the report.

Geological Survey Ireland produced an assessment of geothermal district heating in Ireland in 2020 (available here), and while this assessment focussed on deep geothermal resources (> 2 km) it serves to highlight the significant potential for deep geothermal energy in the south of Ireland. The Department for the Environment, Climate and Communications are committed to developing a policy framework for geothermal energy over the next few years, and it is anticipated that this regulatory and legislatory structure will encourage investment in the geothermal industry in the near future.

The inclusion of Cork City as a pilot in MUSE will serve to increase awareness of its shallow geothermal resources, highlight existing research findings and new data collected by Geological Survey Ireland, and enable city planners and policy makers to assess the possibilities for SGEs to contribute to the ambitious climate change mitigation targets set by the local authorities.

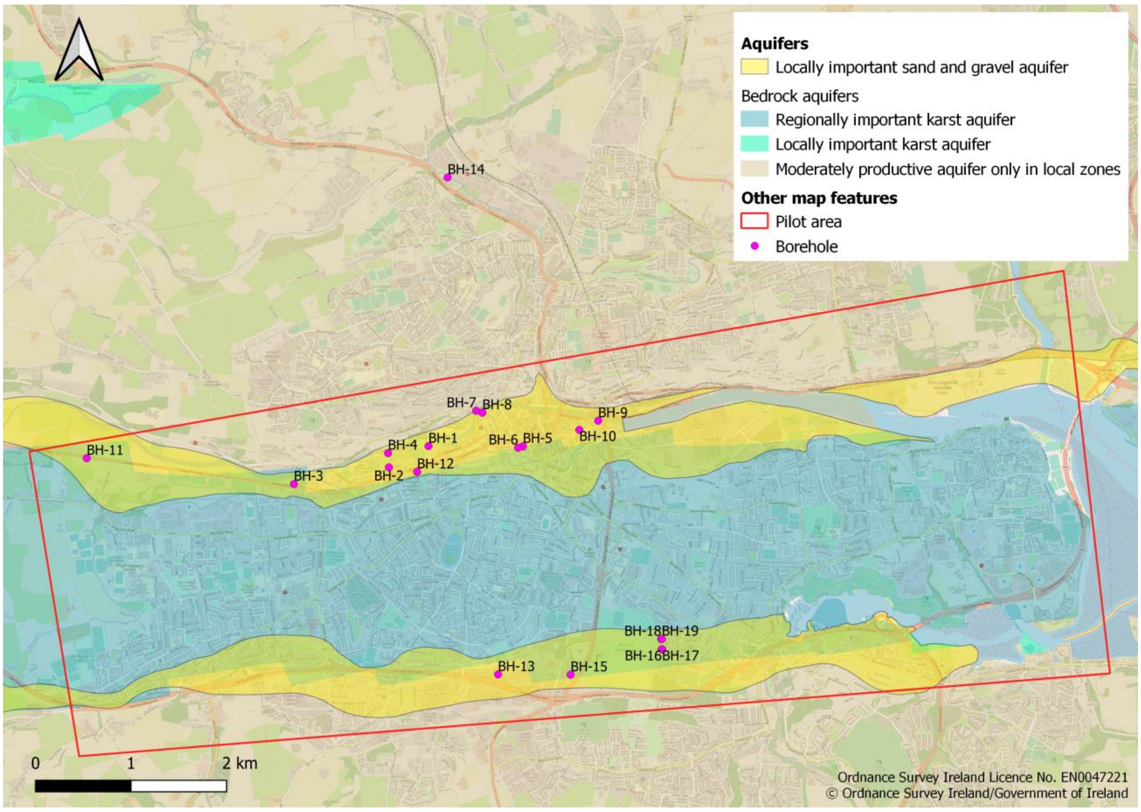

Figure 24.Cork City pilot area map displaying aquifer types and the location of boreholes sampled during fieldwork.

Planned field measurements

The following field measurements were planned at the outset of the project: (1) static water levels collected from boreholes using a dip-meter; (2) temperature profiles collected from boreholes using a temperature probe and a fibre optic distributed temperature sensor (DTS); and (3) water samples for hydrochemical analysis.

Planned GIS datasets

Geographical information system (GIS) datasets have been developed to provide information to support the implementation and management of SGE installations, highlighting any potential impacts to development or maintenance.

Geological Survey Ireland (GSI) planned to produce the following GIS datasets: existing shallow geothermal energy installations, other groundwater uses within the pilot area, karstified zones, contaminated areas, flood risk, surface temperature, groundwater bodies suitable for open loop systems, hydraulic conductivity, net aquifer thickness, compressible ground, borehole hydraulic specific capacities, ground instability problems, subsurface infrastructure, groundwater chemistry, faults, elevation of existing geological boundaries, existing geological profiles and cross-sections, measured subsurface temperature profiles, thermal conductivity of hardrock samples, and measured electrical conductivity.

2.12.2 Outcomes of field measurements

Fieldwork activities performed

Field measurements were collected during three fieldwork campaigns in April and November 2019, and August 2020. Various activities were performed throughout the fieldwork phase and are outlined below:

- Desk-based studies.
  - Identifying boreholes/monitoring points for sampling.
  - Contacting relevant organisations and companies to request access to boreholes.
  - Investigation and collation of information on the study area from existing databases, published research and academia.
- Field-based studies.
  - Well surveying.
  - Sample/data collection.
    - Static water levels collected from boreholes using a dip-meter (Figure 25).
    - Groundwater temperature profiles collected using a temperature probe attached to dip-metre and the distributed temperature sensor (DTS), which was used in several boreholes during the November 2019 field trip.
    - Water samples collected using a peristaltic pump.

Figure 25. Using the dip-metre to collect groundwater level and temperature measurements from a borehole.

Description of results

Temperature profiles

Discrete temperature profiles were collected from a total of 18 boreholes, 16 of which had multiple readings taken across the different fieldwork excursions.

Figure 26 displays several representative temperature profiles from boreholes in the pilot area. Boreholes with multiple temperature readings display one of two trends: (1) seasonal variation in the very shallow groundwater temperature < 4-5 m depth, below which groundwater temperatures equilibrate to approximately 12-13 ºC, or (2) some seasonal/temporal variation with no apparent equilibration (at least within the bounds of the borehole depth) and with groundwater temperatures varying from 4 to 10 ºC between the coolest and warmest readings.

Hydrochemistry

Water samples were collected from most boreholes in the study area at least once, and the samples were sent to a lab for hydrochemical analysis. Major ion concentrations were plotted using the ternary Piper plot method and are displayed in Figure 27.

The results show that little-to-no seasonal hydrochemical variation is observed at each borehole, with most boreholes that were sampled multiple times plotting in the same hydrochemical facies. The exceptions are borehole (BH) 5, which plotted as a mixed NaCl-$MgHCO_3$-$NaHCO_3$-type in April 2019 and as NaCl-type in August 2020, and BH-17 which plotted as NaCl-type (November 2019) and $MgHCO_3$-type (August 2020). Boreholes in closer proximity to the mouth of the River Lee (BHs 5 to 10) plotted as NaCl-type, indicating a marine influence on the groundwater. Boreholes located west of the City Centre (west of Mercy University Hospital) and in the south of the city, around Tramore Valley Park, plot as $MgHCO_3$-type water, which ties in with the karst limestone aquifer which underlies the gravels and much of the pilot area.

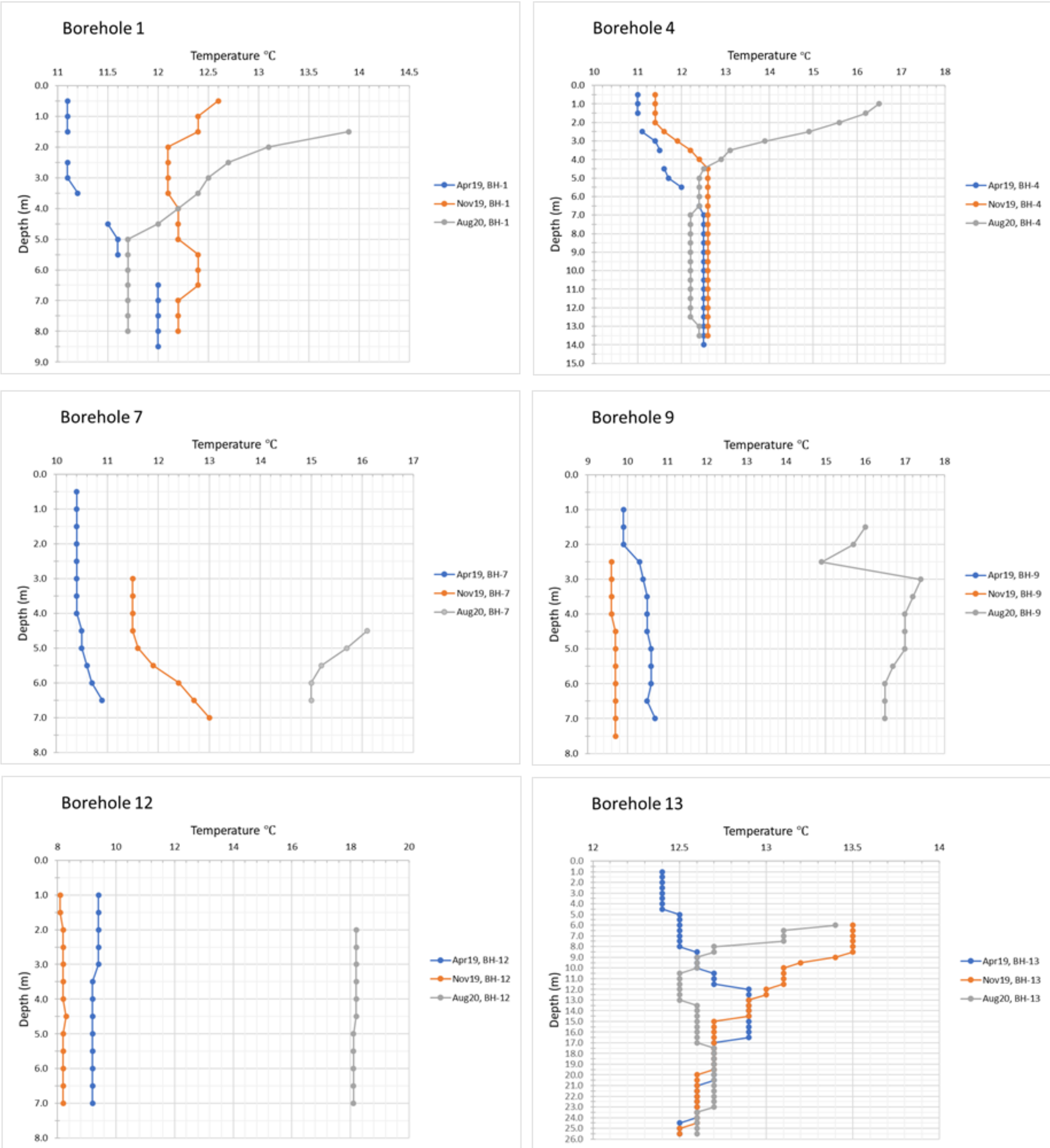

Figure 26. Temperature profiles collected from boreholes using a temperature probe and dip-metre. Blue = April 2019, orange = November 2019, and grey = August 2020.

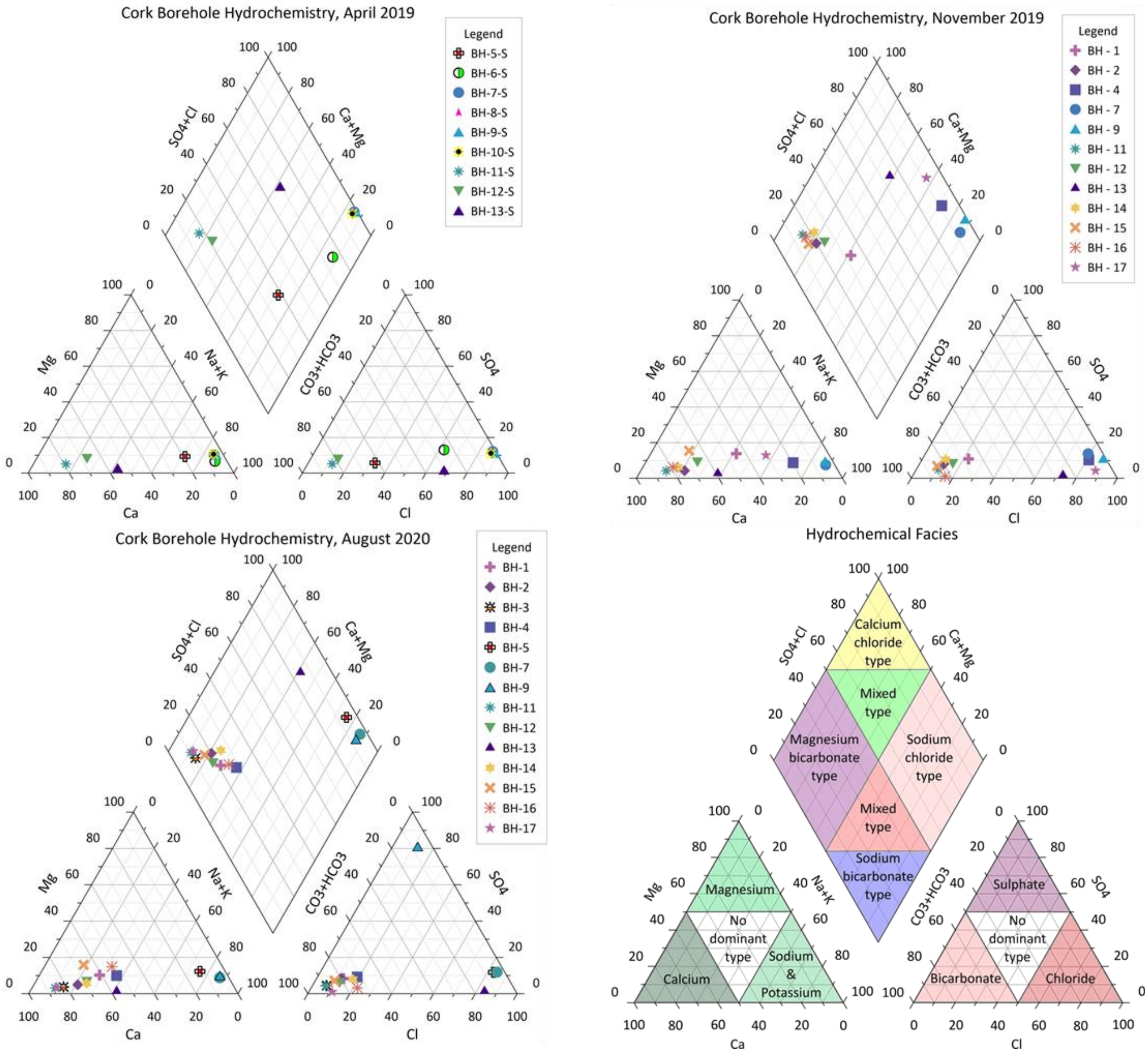

Figure 27.Piper plots displaying major cation concentrations of water samples collected from boreholes in the pilot area. Bottom right image displays hydrochemical facies modified from Hatari Labs (website last visited 02/06/2021, https://www.hatarilabs.com/ih-en

2.12.3 Outcomes of GIS datasets delivered to EGDI

The following GIS datasets have been prepared for EGDI:

1. **Existing shallow geothermal energy (SGE)** – location and type of existing SGE installations.
2. **Other groundwater use** – information on boreholes, wells, springs, and other uses of groundwater in the pilot area.
3. **Karstified zones**.

4. **Contaminated areas** – location and outline of landfill sites.
5. **Land surface temperature** – raster file displaying land surface temperature derived from EuoLST and Met Éireann datasets.
6. **Groundwater bodies suitable for open loop systems**.
7. **Hydraulic conductivity**.
8. **Net aquifer thickness**.
9. **Compressible ground** – a record of observed compressible ground/ground stability problems.
10. **Specific capacity** - modelled extracted water volume per hour and metre drawdown for a defined well diameter.
11. **Landslides** – areas susceptible to landslides.
12. **Subsurface infrastructure.**
13. **Groundwater chemistry.**
14. **Flood risk.**
15. **Faults.**
16. **Measured subsurface temperature profile.**
17. **Measured electrical conductivity.**
18. **Elevation of existing geological boundary.**
19. **Existing geological profiles and cross sections.**
20. **Thermal conductivity of hardrock sample.**

2.12.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

The MUSE datasets have yet to make a real impact with regards to raising awareness of the shallow geothermal energy potential beneath Cork City. We anticipate that the release of the final MUSE products will enable GSI to further advertise the potential of SGE in decarbonising urban heat.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Geological Survey Ireland are cooperating with local authority stakeholders in the pilot area (Cork City Council and Cork City Energy Agency) to disseminate the results of MUSE.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

As mentioned above, Cork City Council's Sustainable Energy and Climate Action Plan 2018 (SECAP) identifies ways to reduce energy related greenhouse gas emissions by

43.7% by 2030. Geothermal energy was not included in the specific actions of the SECAP, however energy efficiency in buildings and heat/cold production were specifically mentioned as themes in the report. There is significant potential for SGE use wherever low carbon heat is required. Through our engagement with local authority stakeholders, we anticipate that SGE will be included in future iterations of the SECAP.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

Not yet, to our knowledge.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Not yet, to our knowledge.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

Yes. The MUSE datasets will be made freely available to view or download on GSI's public web viewer platform.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

Despite the development of new datasets for Cork City under the MUSE project, a significant barrier to SGE uptake in Cork City is still a lack of subsurface knowledge. This is clear when assessing Cork City pilot area against the more developed pilot areas within MUSE. There is no centralised local or national database of GSHPs and collector systems, which would provide valuable information for planning and managing geothermal resources.

Table 2.12.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Cork.

Permitting and licensing procedures	**1**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**4-5**
Other aspects – *please specify*	**-**

2.12.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

The provided workflows were applicable to most of the GIS datasets produced by the GSI. Some workflows were not applicable and this is due a lack of available data and oftentimes the dataset requiring a modelled raster file as an output. These workflows either had to be modified to suit the available data or not produced at all. For example, the groundwater chemistry dataset required highlighting areas as different coloured polygons with no risk or susceptible to one or multiple risks. Given the dynamic nature of groundwater conditions, low density and count of our groundwater chemistry data, the GSI did not feel comfortable sectioning areas into risk-based polygons. Instead, this dataset is presented as point data.

2. Performance of field measurements in comparison to the initial plans

The field measurements have provided a solid foundation of quantitative data, helped identify knowledge gaps and areas which need further research — details of which will be outlined below in section 2.12.6.

Preliminary analysis and interpretation of the data has highlighted the temporal and spatial variability of shallow groundwater temperatures and groundwater chemistry within the pilot area. However, sample collection is limited to areas with pre-existing boreholes which the GSI have permission to access. This network of boreholes were previously used as flood monitoring points by The Office for Public Works (OPW) and, therefore, are in relatively close proximity to the Rivers Lee and Tramore are located in the north and south of the pilot area, respectively. As a result, there is a lack of data collected from the central part of the pilot area.

The GSI were unable to collect field data for a couple of key parameters used in the groundwater chemistry risk assessments: dissolved O_2 and CO_2. This is due to the required equipment being unavailable for use during fieldwork.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

Initially it was thought that there was little seasonal effect on shallow groundwater temperatures in Cork City below the temperature equilibration depth (approximately 4-5 m below ground level). Although this remains true in some cases, fieldwork has revealed that certain areas do display seasonal variation in shallow groundwater temperatures, with differences of 4 to 10 ºC between the coolest and warmest readings.

The method for assessing the risk of carbonate scaling, the Ryzner Stability Index (RSI), showed that none of the groundwaters from the boreholes displayed a risk of carbonate scaling (RSI < 6.0), which is surprising given that the area is underlain by limestone.

Sampling from boreholes in a busy city had its challenges. Some boreholes were inaccessible due vehicles blocking access or, in the case of boreholes 5 and 6 (November 2019), a Christmas market located on top of them.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

Deviations from fieldwork and the preparation of output datasets include the following:

- Initially used the DTS to collect continuous temperature measurements from some boreholes but realised it was not practical due to the nature of installations (located in a busy city with restricted access) or extremely shallow boreholes.
- Thermal response tests were planned but none executed due to limited time and funding.
- Unable to get data from existing installations.

2.12.6 Outlook

Time spent on the project has been invaluable; helping to collate, develop and build databases on SGE and highlighting knowledge gaps. As a result, the GSI has the following activities planned for the future:

- Deployment of data loggers to continuously monitor groundwater temperature and levels.
- Collect dissolved O_2 and CO_2 data in the field which will feed into the following groundwater chemistry risk assessments.
    - Risk of concrete corrosion.
    - Risk of Fe and Mn scaling.
    - Risk of metal corrosion.
- Targeted outreach campaign to local decision makers in Cork City and potentially decision makers in Dublin or other cities with shallow geothermal energy potential.

2.13 City of Brussels (Belgium)

Pierre-Yves Declercq and Estelle Petitclerc, ***Geological Survey of Belgium***

Stefan Carpentier and Vincent Vandeweijer, ***Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO***

2.13.1 Focus of activities inside GeoERA-MUSE

Europe is working hard to meet its first climate goals. Combatting CO2 emissions and making the European energy mix more sustainable are part of this. The means to achieve this include CO2 capture and underground storage (CCS) and increased production of sustainable energy like wind, solar and geothermal energy. In order to make efficient use of sustainable energy, buffering of the produced energy has proven paramount. With High Temperature Aquifer Thermal Energy Storage (HT-ATES) large quantities of energy can be stored in the subsurface in the form of heat. A drawback for HT-ATES is that exploration for the right subsurface conditions often must happen in urban environments, close to where the energy demand is. It is important that a site is characterised well as leakage from the reservoir would degrade the efficiency of the system, and could also endanger potable water supplies.

Geophysical survey

Exploring the subsurface of urban environments in high resolution poses new geophysical challenges, these are: 1) The conflicting and interfering subsurface usage by infrastructure, pipes, cables and ground stability reinforcements complicates surveying, drilling and system design. 2) The uncertain depth of the interface between sediment cover and basement poses high risks on the drilling operations. 3) For HT-ATES systems it is of paramount importance that the injected water with ultra-high temperatures of +100 °C is properly insulated from potable water by sufficiently thick sealing clay layers.

Seismic imaging is currently the method with the highest resolution and the largest de-risking capability for geothermal projects. It is a typical cross-over technology that profits from advancements made in oil, gas and mineral exploration. Innovations in seismic imaging are three-fold: advancements in seismic acquisition, seismic processing and seismic interpretation/analysis. This study pursues the use of fibre-optic distributed acoustic sensing (FO-DAS) technology in seismic acquisition to improve the de-risking ability of seismic data in urban HT-ATES settings.

Urban environments are typically the places where we expect HT-ATES systems to be rolled out. In 2019 TNO and GSB combined a dense surface based high resolution seismic survey with a FO-DAS survey (on the surface and downhole in a well, DAS-VSP) on a potential ATES site in the city of Brussels, Belgium. The combined survey took place on a narrow patch of land in a barely accessible, noisy urban environment in Anderlecht.

The objective was to test and demonstrate the possibility to acquire a high-resolution image of the shallow subsurface to de-risk (HT-)ATES systems in an urban environment in a cost-effective, low environmental impact way. Besides the technology demonstration, targets were aquifer and seal continuity and depth away from the well as well as acoustic velocity of the sediment overburden for H/V Spectral Ratio calibration.

Thermal interference survey at Tour&Taxis

A master thesis was launched in collaboration with Liege University: “Groundwater interference modelling between different low temperature ATES systems in urban context.” Tour & Taxis is an old railway site located on the border of the Brussels-Charleroi Canal and close to the historical centre of Brussels. Since the decline of economic activities in the 1990s, many projects were considered for the rehabilitation of this site. Hosting buildings of great heritage value and surrounded by densely populated and lively neighbourhoods, the rehabilitation plan was carried out with particular attention to green spaces, active mobility, diversity, heritage enhancement and durability. In this context, several buildings were built or renovated, with a decision for some of them to switch to sustainable energy production methods and more particularly ATES systems. The location of the concerned buildings is shown in Figure 28 and Figure 29.

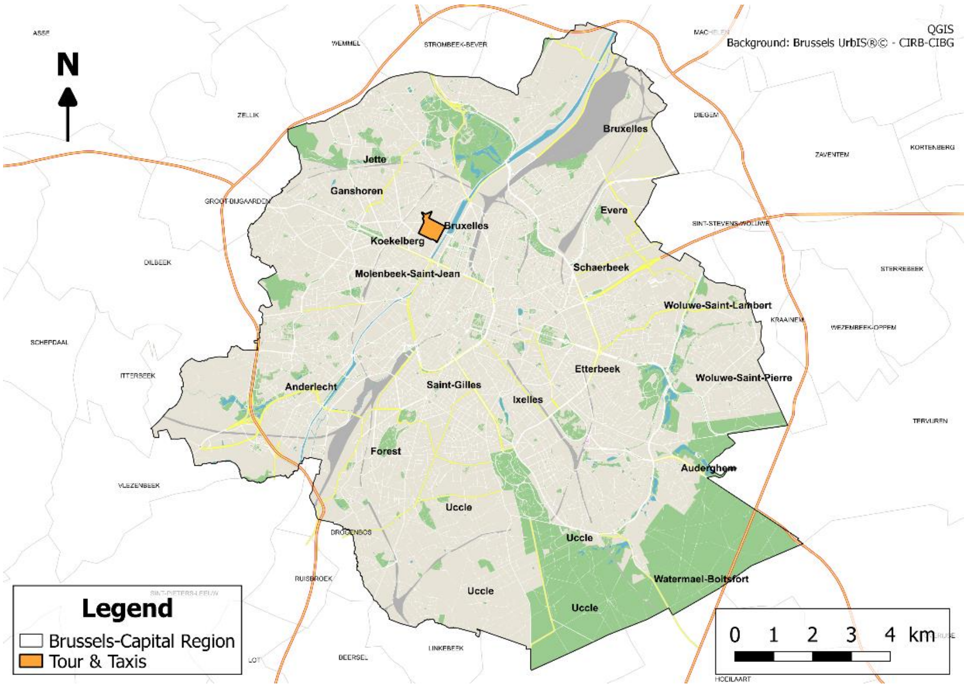

Figure 28. Tour & Taxis is located in the northern part of the Brussels-Capital Region in Belgium.

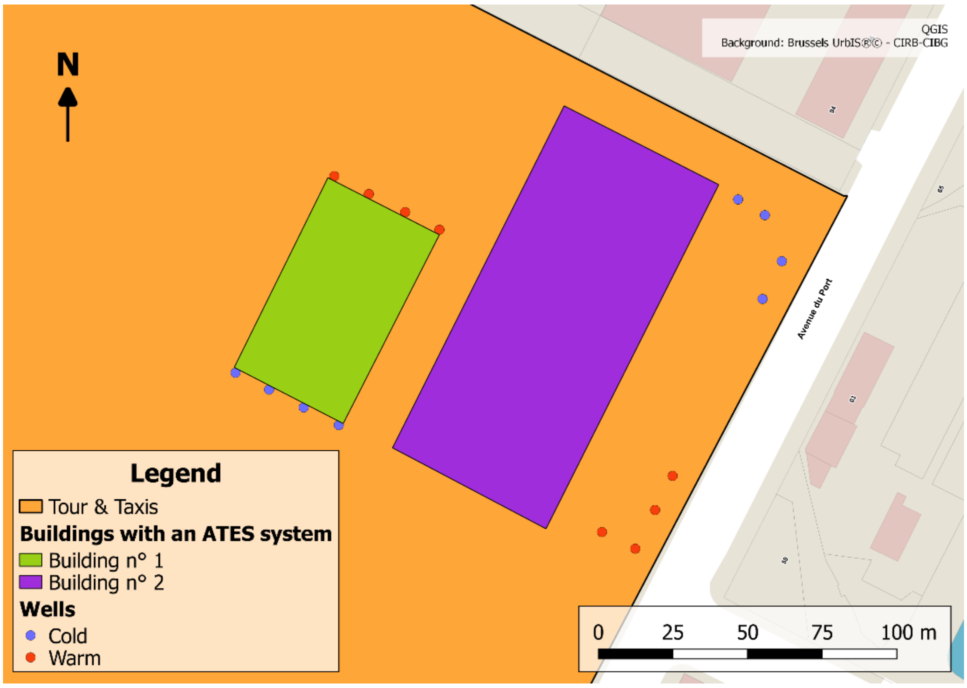

Figure 29. Location of the wells of Building n° 1 and n° 2 at the Tour & Taxis study site. Now that Building n° 1 and n° 2 have been heated and cooled by their respective ATES system for a few years in the same aquifer, it is interesting to develop a new hydrogeological model and to use field measurements to assess real interactions between the two buildings.

In the Brussels Region and the surrounding areas, soft sedimentary rocks deposited during the Tertiary overlie hard and massive rocks belonging to the Cambrian (Paleozoic) series of the Brabant Massif. The Cambrian bedrock is: i) highly heterogeneous (i.e. interstratified quartzite, sandstone, and shale layers), ii) is strongly folded and faulted, and iii) the intense weathering and deformation episodes have affected the upper part of the basement with extremely high fracturation zones and weathering modifications of the rocks. Most of the existing shallow geothermal systems were stopped at the contact between Tertiary/Mesozoic soft rocks and the Cambrian hard rocks due to the lack of geological and hydrogeological knowledge on the bedrock. Nevertheless, some recent explorations have shown the probable high potential of the Cambrian layers (high thermal conductivity, large groundwater flow) suggesting an interesting and previously overlooked groundwater reservoir. One of the objectives in the pilot area of Brussels was also to increase the knowledge of the Brabant Massif thanks to the new acquisitions of hydrogeological (pumping tests) and geological data (samples and thermal conductivity measurements). More than 8 geothermal drillings in the Brabant Massif were followed by the GSB during the project, including the prefeasibility study at the PHS-EU parliament building.

In Anderlecht, a newly developed home-made temperature sensor (Niphargus) was installed and tested for 2 years in a piezometer well at 100 m depth.

2.13.2 Outcomes of field measurements

- *Anderlecht Geophysical survey (TNO and GSB-RBINS)*

The Brussels ATES well at Anderlecht was installed by the Geological Survey of Belgium (GSB). A commercial DAS system was used in the DAS survey at the Anderlecht site. The Brussels DAS VSP survey was combined with a high-res 2D seismic survey using entrenched DAS, 3-component (3C) accelerometers, conventional geophones and active surface-based sources at short offsets. The intermediate result indicates that with FO-DAS it is possible to image the subsurface relatively easily, rapidly, and at low cost and with low environmental impact, even in busy seismically 'noisy' urban areas.

At the Anderlecht site, TNO and GSB personnel performed seismic measurements with surface-based seismic sensors (geophones and 3C accelerometers) and FO-DAS measurements. The fibre optic cables consisted of a multimode (MM) cable along the casing of the well for VSP as well as entrenched single mode (SM) fibre-optic cables. Figure 29 shows the well schematic including the duplex multimode FO cable as well as the field layout of the receiver lines. The DAS survey setup had 1 meter spaced virtual receiver points with a DAS gauge length of 10 meters on the entrenched and downhole FO cables. Geophones were spaced 1 meter along the three major receiver lines as well as the 3C sensors. As a seismic source, a small mobile P- and S- vibroseis device was used with 10 second long 16-160 Hz linear sweep. Source positions were every 0.5 meters along the three major receiver lines. The surface seismic lines were acquired separately from the DAS VSP survey, as simultaneous recording on the single mode and multimode FO cables was not possible.

Data processing of the DAS VSP survey is quite basic at this moment while a more advance processing flow is currently being developed. Current data processing consists of 1) loading the raw DAS data traces, 2) performing a low-pass filter with high-limit of 700-1000 Hz, 3) downsampling the data to 0.5 ms, 4) converting the data to SEG-Y format, 5) adding geometry and coordinates, 6) correlating the data with the vibroseis pilot sweep and stacking the duplex DAS traces per shot for better S/N, 7) picking first breaks and flattening downgoing waves, 8) supressing downgoing waves with subtractive running median filter, 9) NMO correction for flattening upgoing wave reflections, 10) summing NMO corrected reflections into a corridor stack.

In this study only the acquisition and intermediate processing result of the DAS VSP survey are discussed. Figure 30 displays processing results on one DAS VSP shot of a P-vibroseis source located at the wellhead. The data has experienced all the processing steps (1-9) from the 'Methods' section except the corridor stack. One can see that the suppression of the downgoing energy reveals quite some upgoing reflections, aligned after the NMO correction. Further processing of more shots will result with certainty in coherently stacking events. The TWT window of 150 ms, ~120 m depth, contains apparent reflections that may represent target internal sediment interfaces and the anticipated sediment-bedrock interface. Later arrivals up to 450 ms are visible, but these may also represent multiples.

- *Tour&Taxis interference test-site*

The simulations performed for the different scenarios made it possible to better understand the behaviour of the heat plumes produced by the two ATES systems of interest. The temperature observed in warm and cold wells of Building n° 1 increased over time because the amount of warm water injected in the subsurface during the summer cooling season was more important than the amount of cold water injected during the winter heating season. This imbalance led to an increase in the size of the heat plume which finally reached the cold wells of the same system. The heat storage is efficient as the temperature around warm wells increases over time. However, the cold storage is not-existent and the situation is getting worse as the temperature in cold wells is now higher than the undisturbed ground temperature and keeps increasing. This increase in the temperature (gradual overheating) leads to a lower efficiency of the cooling system year after year and a higher energy consumption for the production of cold water.

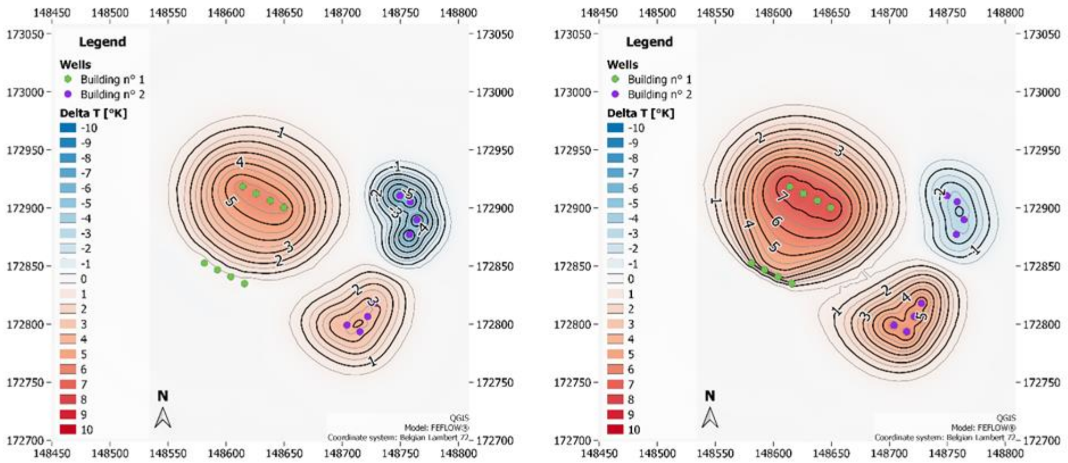

Figure 30. Temperature difference from the initial state in March 17, 2019 (left) and November 3, 2019 (right)

The management of the 2 ATES systems should therefore be changed quickly to rebalance the heat and cold storage. This would help limit interference between wells in the same system and/or the adjacent system and improve their efficiency in the short and long term. This is especially true for Building n° 1 since the ATES system in Building n° 2 has been in operation for less than 3 years and no imbalance in heat and cold storage has been observed yet. To balance the amount of heat stored in the subsurface, less warm water or more cold water should be injected. In this case, the best option would be to reduce the injection of heat to limit as much as possible interferences with the adjacent building. Methods exist to balance the amount of heat and cold injected in the subsurface such as direct compensation, compensation from a heat pump or night ventilation. In the same order of ideas, some measures will be taken soon about solar protections in Building n° 1. These later should reduce the solar energy gains in the building during warm days and therefore reduce the needs for cooling.

- *Brabant Massif knowledge*

Eight different sites with a total of 22 destructive boreholes (up to 252 m depth) have been analysed in collaboration with the GeoCamb project. 6 sites are located in the Brussels Capital Region and one in both Walloon- and Flemish-Brabant. The lithology, mineralogy, geophysical and thermal characteristics of the encountered Cambrian basement and its weathered/eroded top were investigated. Before encountering siltstones and (quartzitic) sandstones with some quartz-rich layers of the Tubize Formation a few meters up to more than 20 meters of weathered layer is observed in almost all sites. This weathering zone consists of clay, silt, sand, weathered siltstone and sandstone, (large) quartz veins, faults and cavities which can have serious implications on the design, budget and risks of exploration drillings. To have a better understanding of the Cambrian basement and to de-risk geothermal feasibility studies in the future, not only the top of the basement should be investigated but also the thickness and lithology of the weathered zone, which is not considered as a separate layer in existing geological models (Brugeo, DOV).

- *Sensors*

The temperature sensor (Niphargus) installed in Anderlecht was unfortunately not sealed enough and its components were flooded.

2.13.3 Outcomes of GIS datasets delivered to EGDI

The GIS datasets delivered to EGDI consist of:

1. **Groundwater protection zones** corresponding to area where the installation of shallow geothermal systems is restricted or prohibited due to the use of the groundwater for drinking or curative water supply. For Brussels, the area around the drainage galleries in the “Bois de la Cambre”.
2. **Location of active wells** used for other purposes than shallow geothermal energy, which might restrict the installation of shallow geothermal energy systems.
3. **Existing shallow geothermal energy installations** that enable the use of the energy stored underground in a depth of up to 200 to 300 meters.
4. **Surface temperature** that is equal to the average annual surface temperature derived from infrared satellite data. If available, these datasets are calibrated and validated by soil temperature measurements.
5. **Confined or artesian groundwater** zones
6. **Extent of the Pilot Area** that correspons to the Region of Brussels
7. **Average thermal conductivity** map at 100 m.

From the 2D seismic field survey, no GIS datasets could be delivered to EGDI, since the bedrock mapping results are still preliminary.

2.13.4 Impact of the achieved results on local management and energy strategies

In this study, we claim to have demonstrated that with current seismic acquisition technology it is possible to acquire a high resolution seismic image at low environmental impact, at low cost under challenging, noisy urban conditions. These conditions we expect to be typical for future HT-ATES systems. This high resolution image can subsequently be used to identify and asses the geometry and properties of reservoirs and seals, creating an image at and around a potential HT-ATES site. Combined with subsequent DAS time-lapse imaging, the development and safe operation of the site are de-risked.

At Tour&Taxis, the study highlighted the importance of existing ATES systems monitoring and the necessity to identify as soon as possible the potential unbalanced geothermal installations in an urban context which can have serious impacts on environmental and resource management.

The malfunction of the ATES system of Building n° 1 is therefore not due to thermal interferences with the adjacent building but to thermal interferences between its own heat plume and cold wells. The growth of this heat plume is due to thermal imbalances, i.e. unequal demand in heating and cooling. Indeed, until today, the amount of energy derived from groundwater by the ATES system of Building n° 1 has been more important for cooling than for heating. The cooling seasons have also been longer than the heating seasons. The temperature around the cold wells of Building n° 1 has to be reduced to rebalance the system and increase its efficiency. Furthermore, if the heat plume continues to grow, it will continue to affect not only the efficiency of its own system but also the one of the adjacent building. If the ATES system of Building n° 2 did not have a negative impact on the system of Building n° 1 during its first 2 years of operation, thermal interferences between the 2 systems could still be observed. Indeed, the heat plumes of the 2 systems already came into contact.

1. Did the datasets created for your area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Yes, it will certainly help since thanks to the data produced new collaborations with drillers/ geothermal installers were set up as well as a fair exchange of data. The newly acquired datasets were also used into two others Regional and Federal projects and are complementary to the existing datasets of those projects. It also increased the involved networks of actors involved in geothermal energy.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Yes a new collaboration agreement was decided between the Geological Survey of Belgium and Brussels Environment of which several datasets were used and transformed as products for this project.

A meeting is planned in September 2021 with the Energy Minister of Brussels Region to evaluate the perspectives of shallow geothermal energy and makes it more visible in the Regional Energy Action Plan.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

Yes, since a new collaboration agreement was decided between the Geological Survey of Belgium and Brussels Environment who is responsible for the green energy planning of the Region.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

Yes, the data produced and easily accessible via the EGDI platform together with *BrugeoTool* will help consulting companies to propose geothermal solutions.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

Thanks to the agreement made between Brussels Environment and the Geological Survey of Belgium for this specific project, the local authority has access to a set of new datasets that will help them in the decision making process. For example, in Tour&Taxis, the data revealing a strong influence between the installed systems at this location is having a strong impact on the future installations. This raises awareness to better evaluate the common impact of installations at short distance and will conduct to improve the current legal framework (permitting).

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

No directly since the product made here were realised specifically for this project. But derivative datasets will be incorporated into the webgis system of the Geological Survey of Belgium.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

Often the quantity and the quality of the available data that decreases very fast together with an increasing depth make it questionable to release the information to a large audience. The aquifer temperature data were deeply analysed. This study revealed that those data are punctual, sparse in time and space that makes them very hard to exploit in the framework of this project. Despite the fact that a map of the aquifer temperature in Brussels is of great interest for the development of the geothermal energy use and resource management.

Table 2.13.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Brussels.

Permitting and licensing procedures	**2**
Local environmental, energy and climate mitigation strategies	**4**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**2**
Other aspects – *please specify*	**-**

2.13.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

Since a majority of the required data is coming from previous projects or local databases the elaboration of the required output was not too demanding. However some data although available in digital format were not initially made for this purpose and required when possible extensive editing.

2. Performance of field measurements in comparison to the initial plans

- Poor coupling of the fibre-optic cable to the well casing/cement can sometimes be forgiving, but can also stop the show
- Need for better protocol in the field for obtaining geometry and layout of DAS array that goes beyond tap tests
- The Thermal sensor (Niphargus) installed in Anderlecht at 100 m depth failed to support the long immersion.
- At Tour&Taxis only the interference between two buildings was evaluated due to the difficulties to access and process the exploitation data of the two open geothermal systems.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

- In spite of the difficult urban and operational conditions, the DAS VSP survey was a partial success.
- High (urban) noise levels, small offsets, limited source strength proved challenges to good signal.
- The drillings sampling realised during the MUSE project provide new insights in terms of structure, composition and development of the altered part of the Brabant Massif.

The unexpected size of thermal plume modelled thanks to the installation of the thermal loggers at Tour&Taxis allowed the managers to adapt their exploitation plans. Solutions are currently evaluated to limit the impact of this hot plume mainly due to the cooling demand being 5 times higher than the heat demand of the building.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

- We conclude that the use of a small vibroseis source is not recommended as there is too much 1) overall attenuation, 2) uncoherent dissipation of especially high frequencies 3) other near surface effects. Impulsive source is better.
- The Covid situation has impacted the number of field campaigns and the possible interaction with some local actors. For example, it was not possible to install in time the thermal sensors (Niphargus) at several places.

2.13.6 Outlook

Thanks for the work initiated in MUSE, new contacts were made with local high level Policy makers and Brussels Environment. The management strategies report provided by each partner in the WP3 will serve as a basis for the future improvements of the Brussels resources management strategies. It is also expected to contact the local government to report on the actions carried out and promote joint activities to disseminate and promote the use of these technologies.

2.14 City of Warsaw (Poland)

Maciej R. Kłonowski, Jacek Kocyła, Mateusz Żeruń

Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy

2.14.1 Focus of activities inside GeoERA-MUSE

Field and laboratory activities undertaken in the Warsaw pilot area under the framework of the MUSE project focused on measuring the thermal properties of the soil and rock samples including performance of the in situ and laboratory measurements of thermal conductivity and resistivity as well as TRT tests and geoelectric sounding. The results of these studies have been applied to parameterization of a 3D geoscientific model of Warsaw agglomeration, including production of GIS map (data) layers. Described measurements were performed in order to support research on application of closed-loop systems.

2.14.2 Outcomes of field measurements

In April and May 2020 the thermal properties of Quaternary soils and rocks were measured in situ in the outcrops and in the laboratory. Those covered such properties, as thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity and were performed with use of KD2 Pro Thermal Properties Analyzer and TK04 thermal conductivity meter. The measurements were taken all over the city and focused on undisturbed and non-weathered outcrops. Measurements of samples of consolidated deposits such as clays will be completed at a later stage in the laboratory. The results of measurements of thermal properties enabled correlation between lithological properties of the rocks and their thermal parameters and support parameterisation of the geothermal models and maps.

The geoelectric resistivity method was used to investigate geological and hydrogeological settings of the studied area with special focus on the structure of the present Vistula River valley. The results of geoelectric resistivity sounding improved construction of the standard geological profile. Investigations contributed to MUSE by improving our understanding of local geology, hydrogeology and geothermal potential and were also used for geological modelling and mapping of low-temperature geothermal potential and suitability for shallow geothermal energy systems.

In April 2021 drilling of a 99 metre deep borehole and installation of BHE in Halinów, in the Warsaw pilot area, took place. During the drilling soil samples were taken for further laboratory tests with the use of a KD2 Pro Thermal Properties Analyzer and TK04 thermal conductivity meter. In the second half of April 2021, a TRT was performed on the borehole installation in Halinów. The test results are currently being evaluated.

2.14.3 Outcomes of GIS datasets delivered to EGDI

In the Warsaw project pilot area several types of data (layers showing the selected parameters) have been prepared to determine shallow geothermal potential and suitability conditions for location of closed loop systems installation (conflict mapping - traffic light map)

List of layers (conflicts) prepared and delivered to EDGI:

1. **Other groundwater use** - the vector dataset (point layer) representing hydrogeological objects for specified groundwater use: drinking water supply, exploitation and observation wells
2. **Shallow geothermal energy systems** - the vector dataset (point layer) representing of borehole heat exchanger installation (closed loop system)
3. **Subsurface infrastructure** - the vector dataset (line layer) representing subsurface infrastructure of city of Warsaw and vicinities (district heating zone, gas lines, sewage and tunnels)
4. **Flood risk** - the vector dataset (polygon layer) representing the extent of flooded area in a 100-year flood
5. **Mining area** - the vector dataset (polygon layer) representing mining activities - exploitation of gravels, sands and clays
6. **Landslides** - the vector dataset (polygon layer) representing areas susceptible for landslides
7. **Groundwater protection** - the vector dataset (polygon layer) representing water intakes' protection zones
8. **Contaminated area** - the vector dataset (polygon layer) representing landfill sites (after reclamation and active)
9. **Extent of confined artesian and subartesian aquifers**- the vector dataset (polygon layer) representing evaluated extent of artesian waters (the outer polygon represents subartesian water conditions)
10. **Natural reserves** - the vector dataset (polygon layer) representing national reserves and nationals park location.

2.14.4 Impact of the achieved results on local management and energy strategies

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

SGE is still under development in Poland including the Warsaw agglomeration. There is an urgent need for reliable information on applicability and efficiency of the SGE technology in our country. The results of the MUSE project helped to disseminate information on application of SGE with respect to closed-loop GSHP systems as well as its ecological effect and economic advantages.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Under the terms of MUSE and the previous national and international projects PIG-PIB has established good relations with the representatives of the major stakeholders of SGE technologies in the country, including the producers and designers of the installations as well as the administration. Based on these contacts the results of the MUSE project are and will be still disseminated even after the project end. PIG-PIB would like especially focus on spreading information on effectiveness of SGE and on assurance of application of best practices.

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation

The Polish Energy Policy until 2040 was published in February 2021. PIG-PIB plays a consultancy role during its elaboration and has some influence on practical aspects of implementation and future evaluation. PIG-PIB, based on the results of research completed in several projects, including MUSE, emphasizes the importance of SGE technologies. The results of the MUSE project, as well as other research are, and will be still presented on diverse types of conferences, seminars, etc., on the national, regional and local levels in Poland.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation

The MUSE datasets elaborated for the Warsaw pilot project area will be available for diverse users, including regional and local administration as well as the private sector. As a matter of the fact in case no investment resulting from the MUSE project is foreseen. Nonetheless, the PIG-PIB will be willing to disseminate further information of SGE potential in the studied area as well assure its safe use.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

In Poland the permitting procedures for SGE are developed on the national level, therefore the results of the MUSE project are not expected to influence those.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

The PIG-PIB runs the national database and geoportal on diverse types of geo-data, including borehole data, maps, hydrogeological data, geoenvironmental data, mineral resources, etc. Geothermal data layers are still under development. It will be considered to include the MUSE datasets into the PIG-PIB geoportal.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

No further barriers are foreseen.

Table 2.14.4-1. Impact of the work performed in MUSE (1- very low to 5- very strong) in City of Warsaw.

Permitting and licensing procedures	**3**
Local environmental, energy and climate mitigation strategies	**3**
Spatial planning including energy plans	**3**
Investment decisions by public or private entities	**3**
Local (web based) information systems	**3**
Other aspects – *please specify*	**-**

2.14.5 Lessons learned in the pilot area

1. Applicability of workflows and the elaboration of output data sets

The workflows elaborated for field and laboratory measurements have been successfully applied during the project. Some problematic points referring to technical issues or interpretation of data have been solved on an ongoing basis.

2. Performance of field measurements in comparison to the initial plans

The initial plans of the field measurements in the Warsaw project pilot area have been achieved in spite of the COVID-19 pandemic and limited possibility of travelling.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

As a matter of the fact there were no major surprises linked to field work and preparation of data under the MUSE project for the Warsaw project pilot area. Possible risk was mitigated and managed on an ongoing basis.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

There were no major deviations of the field work planned in the MUSE project for the Warsaw project pilot area. Some small delays have been noted.

2.14.6 Outlook

The follow-up activities include:

- profiling of groundwater temperature in the selected wells and piezometers;
- temperature profiling in the thermopiezometer in Halinów;
- seasonal TRT test in the thermopiezometer in Halinów;
- comparison of above TRT results with the results of upcoming boreholes in the studied area.

The follow-up activities will be carried out to complement and update the data layers elaborated in the effect of the MUSE project.

3 SUMMARY OF ACHIEVEMENTS IN THE PILOT AREAS

Between 2018 and 2021 possible conflicts of use associated with the use of shallow geothermal energy and key geoscientific subsurface data were studied in 14 European urban areas. A wide range of geo-scientific activities were undertaken in pilot areas in order to assess geothermal properties and resources and to prepare GIS based datasets, which were integrated in the web-based decision support and information tool on shallow geothermal energy use at the EGDI platform. Each pilot area was applying specific methods to obtain geoscientific field data, such as hydrogeological, geological and geophysical surveying, TRT, laboratory-based physical property analysis, 3D geological modelling, drone mapping, or desktop studies.

Hydrogeological surveying was the most common method which was applied in the pilot areas. For instance, baseline groundwater and surface water monitoring was done in Glasgow pilot area and automatic monitoring systems/networks/points with dataloggers were established in 6 out of 14 pilot areas: including Ljubljana, Zaragoza, Zagreb, Girona, Vienna and Cardiff. During the 2-year-long MUSE monitoring period dataloggers were collecting data about groundwater levels, temperature or electrical conductivity (only in Ljubljana). Furthermore manual measurements of groundwater temperature and level were also performed in Ljubljana, Zaragoza, Girona, Vienna, Bratislava and Cork. In the Glasgow mine water geothermal pilot areas pumping tests and baseline DTS were performed as well. DTS was also performed in Cork pilot area. These measurements in pilot areas allowed assessment of the thermal state of the groundwater system and investigation of factors which impact groundwater temperature, notably anthropogenic use and nearby geothermal use. Furthermore, groundwater chemistry was evaluated in Cork and Cardiff, with an interesting finding that the groundwater chemistry may be seasonally transient in coastal settings (Cork).

Thermal properties of the bedrock were assessed using geophysical, TRT and laboratory measurements. For instance in Linköping ground geophysical surveys with magnetometer and VLF combined with borehole investigations, geophysical wireline logging, thermal conductivity measurements were performed. In Warsaw pilot area thermal properties of the bedrock were measured in situ on outcrops using and in the laboratory. Thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity and were performed with use of KD2 Pro Thermal Properties Analyzer, TK04 thermal conductivity meter an applying geoelectric sounding. Furthermore both in Warsaw and Girona pilot areas thermal conductivity was measured with Thermal Response Tests.

In Glasgow and Brussels pilot areas seismic imaging was used. In Glasgow pilot area field measurements included fibre-optic distributed temperature sensing (FO-DTS) and electrical resistivity tomography (ERT) measurements, monitoring and ground motion. At Brussels pilot area, seismic measurements with surface-based seismic sensors (geophones and 3C accelerometers) and FO-DAS measurements were performed.

Most pilot areas located on aquifers utilised pre-existing groundwater monitoring wells to maximise data coverage and reduce project capital costs. During the MUSE monitoring period new boreholes were drilled in Girona, Warsaw and Glasgow. In the Girona pilot area 11 boreholes (100m deep) were drilled and in 5 of them TRT was performed. In

Warsaw one 99m deep borehole was drilled and a BHE installed for TRT testing. In Cardiff, previous TRT test data was collated and compared with lab-based thermal property measurements on stratigraphically analogous cores (same lithofacies).

Aarhus and Prague pilot areas did not carry out any field work, instead opting for extensive desktop studies and preparation of datasets for EGDI platform using available data. Nevertheless, research on historic data and literature review was an important part of work in all pilot areas. Data collected from field investigations and desktop studies were mostly processed using Excel and plotted in GIS mapping platforms. Additionally, 3D geological models were developed for Ljubljana and Girona urban areas, hydrogeological models were prepared for Cardiff and Aarhus pilot areas and integrated newly collected data and already available geological models.

The following table summarises GIS dataset which were prepared in each pilot area.

Parameter name	Pilot area
Annual thermal load - closed loop system	Girona
Areas suited for groundwater disposal to surface waters or municipal drains	Zaragoza
Average interval bulk thermal conductivity	Linkoping, Bratislava, Vienna, Brussels
Average subsurface temperature	Ljubljana, Girona, Bratislava, Vienna
Compressible ground	Cork
Confined or artesian groundwater zones	Bratislava, Brussels, Warsaw
Critical composition of groundwater	Cardiff, Bratislava, Cork
Decision support map for the use of shallow geothermal use	Vienna
Depth of a geological boundary	Linkoping, Cardiff
Elevation of a geological boundary	Cardiff, Bratislava, Cork
Existing geological profiles and cross-sections	Zaragoza, Zagreb, Glasgow, Cardiff, Cork
Faults	Linkoping, Prague, Cork
Flood hazard	Prague, Cork, Warsaw
Geomagnetic characterization	Linkoping
Groundwater body suitable for open-loop systems	Ljubljana, Cardiff, Bratislava, Cork, Vienna
Groundwater protection	Ljubljana, Linkoping, Zagreb, Aarhus, Prague, Bratislava, Warsaw , Vienna, Brussels
Heat transfer rate	Vienna
Hydraulic conductivity	Zaragoza, Cork
Hydraulic productivity	Vienna
Hydraulic transmissivity	Zaragoza, Girona, Cork
Surface temperature	Ljubljana, Linkoping, Zagreb, Girona, Prague, Bratislava, Cork, Vienna, Brussels

Parameter name	Pilot area
Landslide	Prague, Cork, Warsaw
Maximum groundwater temperature	Vienna
Measured electrical conductivity	Cork
Measured groundwater depth	Girona, Cardiff
Measured groundwater level	Zaragoza, Girona, Cardiff
Measured groundwater temperature	Zagreb, Girona, Vienna
Measured subsurface temperature profiles	Cork, Vienna
Minimum groundwater temperature	Vienna
Mining area	Prague, Warsaw
Natural reserves	Ljubljana, Zagreb, Prague, Bratislava, Warsaw, Vienna
Net aquifer thickness	Zaragoza, Aarhus, Girona, Cardiff, Cork, Vienna
Other groundwater use	Linkoping, Zaragoza, Aarhus, Prague, Cork, Brussels, Warsaw
Pilot areas	Brussels
Karstified zones	Prague, Cork
Shallow geothermal energy systems	Linkoping, Aarhus, Prague, Cardiff, Cork, Brussels, Warsaw , Zaragoza
Specific annual thermal load - closed loop systems	Vienna
Specific annual thermal load - open loop systems	Girona, Vienna
Specific thermal capacity - closed loop systems	Cork, Vienna
Specific capacity	Zaragoza, Aarhus, Cork
Subsurface infrastructure	Ljubljana, Cork, Warsaw
Thermal capacity - open loop systems	Girona
Thermal conductivity	Ljubljana, Cardiff, Linkoping
Thermal conductivity of hardrock samples	Cork, Cardiff
Traffic light map closed loop system	Aarhus, Vienna
Traffic light map open loop system	Aarhus, Vienna
Landfills or contaminated areas	Zagreb, Cork, Bratislava, Warsaw

4 CONCLUSIONS

4.1 The impact achieved in the pilot areas

1. Did the datasets created for your pilot area help to raise awareness towards the use of shallow geothermal energy? If yes, please provide a brief explanation

Most of the partners report that datasets created for pilot areas contributed to raising awareness and disseminate knowledge of shallow geothermal energy. For instance, the Croatian Geological Survey was collaborating with the users (system operators) and datasets created for the Zagreb pilot area helped to raise awareness in the installation-scale. Throughout the project the Geological Survey of Denmark and Greenland had an ongoing dialogue with the district heating company and their technical advisers and recently, the Aarhus municipality has received, read and acknowledged a comprehensive report describing the results from MUSE, Aarhus in Danish (Ditlefsen 2021). Partners from Girona and Cardiff pilot areas also had an opportunity to get in contact with local administrations, stakeholders and local organizations. These contacts contributed to spread knowledge about SGE and promote the utilisation of urban shallow geothermal resources. Furthermore, datasets from the Vienna pilot area were elaborated in cooperation with GEL-SEP “Green Energy Lab – Spatial Energy Planning” project and a MUSE workshop was held in summer 2021 on novel methods for calculation of shallow geothermal resources. Inside the energyATLAS, their results will be accompanied by other renewable energy resources like solar energy. They presume that the lesser known technology of shallow geothermal energy will benefit from this joint appearance.

Nevertheless, many partners agree that it is too early to gauge the full impact of MUSE and anticipate that the release of the final MUSE products will enable partners to further advertise the new data and potential of SGE in decarbonising urban heat. At last, in the Glasgow pilot area, the UKGEOS Glasgow Observatory has provided a facility for research and attracted funding for academic research into shallow geothermal energy and storage in abandoned coal mines. Stakeholder events have engaged local communities and authorities and are being presented at COP26.

2. Do you already have or plan to have a cooperation with local stakeholders in your pilot areas regarding the use of the datasets produced in MUSE? If yes, please provide a brief explanation

Regarding the cooperation with local stakeholders most partners report that they are already collaborating (Ljubljana, Zaragoza, Aarhus, Vienna, Cardiff, Cork, Brussels, Warsaw) or that produced datasets will help to reach out to potential stakeholders (Zagreb, Girona, Prague, Bratislava, Brussels) or that datasets have open access and academic researchers are already using data (Glasgow, Cardiff).

3. Do you expect that the datasets produced for your pilot area will feed into energy and environmental planning instruments and/or strategies? If yes, please provide a brief explanation.

The majority of pilot areas give a very positive feedback towards the implementation of produced datasets into energy and environmental planning instruments and/or strategies: (1) datasets are prepared in a way that can be feed into energy and environmental planning instruments and/or strategies (Ljubljana, Zaragoza, Glasgow), (2) have been already considered by local authorities or stakeholders (Aarhus, Cardiff, Warsaw), (3) datasets were used to update local geological maps and in that respect it will provide a better basis for future SGEs (Linkoping). Interestingly, partners from the Girona and Cork pilot areas address that shallow geothermal energy was not considered as an alternative to fossil fuels and was not included into government energy plans whereas now it is anticipated that produced datasets will make an impact and SGE will be introduced as an energy alternative for decarbonisation of urban areas.

This success partly reflects the introduction over the last few years of more urgent renewable energy targets (e.g. NetZero2050), declared ‘Climate Emergency’, and push on renewable energy production and electrification of heat on local, national and EU levels, and in this respect, the MUSE project was well conceived and timed to enable geological survey organisations to inform this conversation with scientific evidence.

4. Will the datasets produced for your pilot area be used for any investment or other decision by local stakeholders? If yes, please provide a brief explanation.

The datasets and information produced in Ljubljana pilot area have been used in two SGE projects in the area of Municipality of Ljubljana: for the planning of the heating and cooling of the planned Science Centre and for the construction of open-loop system for the heating of the primary school. In the pilot areas of Zaragoza, Aarhus, Girona, Prague, Vienna, Cardiff, Brussels and Warsaw it is anticipated that datasets will make an impact in the future. Whereas, in pilot areas of Linkoping, Zagreb, Bratislava produced datasets will not be immediately used as a foundation for any investment or other decision by local stakeholders.

5. Are or will the datasets produced for your pilot areas be used by local authorities for permitting procedures?

In most pilot areas datasets will not be used by local authorities for permitting procedures (Ljubljana, Linkoping, Zagreb, Prague, Vienna, Cardiff, Glasgow, Bratislava, Cork, and Warsaw). In Zaragoza pilot area the data are useful for the CHE (agency which authorise groundwater exploitation and the emission of thermal discharges), but requests the support of the IGME for its interpretation and for the assessment of the suitability of geothermal exploitations of groundwater. In the Aarhus pilot area, it is expected that the datasets will be used by local and national authorities for environmental impact assessments as part of coming permitting procedures. In Girona pilot area and in Catalonia in general, permitting procedures are developed and regulated by the Catalan and Spanish governments. So, the impact of the datasets in that area is expected to take place in a long-term. Finally, due to the agreement made between Brussels Environment and the Geological Survey of Belgium, the local authorities has access to a set of new datasets that will help them in the decision making process.

6. Will the datasets produced for your pilot areas be available in local (web based) information system or data repository? If yes, please provide a brief explanation

All datasets listed in this report are available on EGDI platform; furthermore, most of the datasets from each pilot area will be also available in local information systems.

7. Are there any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management and in your pilot area? If yes, please provide a brief explanation

In the most of the pilot areas there are any remaining barriers concerning the assessment and provision of datasets relevant for shallow geothermal energy planning or management. Some pilot areas (Aarhus, Prague, Vienna, Cardiff, Cork and Brussels) report that there are some remaining barriers, but all these barriers are site specific. All pilot areas admit there is a need for further research into geothermal properties and potential in their urban areas and nationally, and further funding needs to be made available to support this endeavour.

All partners evaluated the impact of the work performed in MUSE on the 5 listed aspects (1- very low impact to 5- very strong impact): 1) Permitting and licensing procedures, 2) Local environmental, energy and climate mitigation strategies, 3) Spatial planning including energy plans, 4) Investment decisions by public or private entities, 5) Local (web based) information systems and 6) Other aspects (specified by the partner). Their answers were summarised in the Table 2.14.6-1.

Table 2.14.6-1. Impact of the work performed in MUSE (1- very low to 5- very strong) on: 1) Permitting and licensing procedures, 2) Local environmental, energy and climate mitigation strategies, 3) Spatial planning including energy plans, 4) Investment decisions by public or private entities, 5) Local (web based) information systems and 6) Other aspects (specified by the partner).

Pilot area	Country/Region	Estimated impact of the work performed in MUSE					
		1	2	3	4	5	other
City of Ljubljana	Slovenia	2	5	5	4	4	-
City of Linkoping	Sweden	1	1	3	3	1	-
City of Zaragoza	Spain	5	3	2	3	4	-
City of Zagreb	Croatia	1	1	1	3	1	-
City of Aarhus	Denmark	2	3	2	3	4	-
City of Girona	Spain/Catalonia	2	5	3	3	5	-
City of Prague	Czech Republic	1	2	3	3	2	-
City of Vienna	Austria	3	4	5	4	5	-

Pilot area	Country/Region	Estimated impact of the work performed in MUSE					
		1	2	3	4	5	other
City of Cardiff	UK/Wales	3	2	2	3	2	2 (regulation*)*
City of Glasgow	UK/Scotland	3	3	2	1	1	-
City of Bratislava	Slovakia	1	3	2	2	3	-
City of Cork	Ireland	1	3	3	3	4-5	-
City of Brussels	Belgium	2	4	3	3	2	-
City of Warsaw	Poland	3	3	3	3	3	-

4.2 Lessons learned in the pilot areas

1. Applicability of workflows and the elaboration of output data sets

Numerous workshops (both physical and virtual) were held during the project MUSE for the exchange of experiences with different workflows with colleagues from partner institutions. Hence, provided workflows were successfully applied in pilot areas and enabled partners from different institutions to elaborate output datasets in a standardised way. Although, several partners note that quality and accuracy of the final output dataset very much depends on the input data.

2. Performance of field measurements in comparison to the initial plans

In the most of pilot areas the initial plans of field measurements were achieved despite of the COVID-19 pandemic and a limited possibility of travelling. Some partners report that due to strict lockdowns field work was not possible and due to lack of maintenance equipment installed in the pilot areas got damaged or run out of batteries/power resulting in some data loss (Vienna and Cardiff). Regardless of the pandemic, some periods of data collection was also lost in Ljubljana and Zaragoza due to equipment damage. Keeping the latter factors in mind, all partners agreed that initial MUSE monitoring period should be prolonged into 2021, hence field measurements which were lost earlier in the pandemic (2020) could be completed so that data could be collected representing for all four seasons.

3. Greatest surprises or highlights linked to field work and the preparation of output data sets

Highlights during MUSE project were very site specific and it is difficult to emphasize particular event suitable for all pilot areas. Overall due to COVID-19 pandemic all partners had an opportunity to participate in more online meetings and that was actually an efficient way to share results between partners.

4. Major deviations in the field work and the preparation of the output data sets and your responses to it

In several pilot areas there were no major deviations in field work and preparation of output datasets (Ljubljana, Linkoping, Zagreb, Girona, Bratislava, and Warsaw). In other pilot areas major deviations from the field work and the preparation of the output data sets were related with agreements with stakeholders (Aarhus), COVID-19 pandemic (Vienna, Cardiff, Glasgow, Brussels), extreme weather conditions (Vienna), vandalism (Glasgow), limited time and funding (Cork) and health issues (Zaragoza).

4.3 Recommendations on geoscientific data assessment and mapping in urban areas linked to shallow geothermal mapping and planning

4.3.1 Subsurface temperature measurements

Subsurface temperature measurements were carried out in the pilot areas of Ljubljana, Girona, Bratislava and Cork. These field measurements were used to prepare datasets of average subsurface temperature and measured subsurface temperature profiles.

High resolution temperature profile, preferably measured in the framework of so-called Thermal Response Tests (TRT) for performance tests of Borehole Heat Exchangers (BHE), represent a crucial source of information concerning the actual thermal state of the subsurface. It has to be considered that the ambient subsurface temperature has an equal level of sensitivity on the performance of BHEs than the thermal conductivity of the surrounding rocks. As observed in many locations around the globe, the current thermal regime is influenced by long-term transient temperature signals, which result of climate change and anthropogenic heat injection in urban conglomerates also known as urban heat island effect. As a consequence, the classic concept of an annual seasonal temperature zone with maximum depths of 10 to 30 meters below the surface, followed by a steady state conductive geothermal regime at a constant net flow density is not valid anymore. Instead, long term transient temperature signals can be observed in depths of up to several tens of meters below cities leading to attenuated and even reverted temperature gradient. For that reason, steady state approximation of the average ambient subsurface temperature may lead to prediction errors of up to 5°C in extreme cases.

Based on the experiences gained in GeoERA MUSE, it is recommended to collect recent subsurface temperature profile measurements linked to the performance of TRT measurements in BHEs. In order to achieve reliable data, the following quality criteria are proposed:

- Temperature profile measurements need to be done before the start of a TRT and at least 3 days, preferably more than 1 week, after finalization of the drilling and completion work of the BHE,
- Temperature profile measurements may also be undertaken after TRTs after a shutdown and thermal balancing period of at least 3 weeks, to ensure enough time has passed to establish again a natural temperature regime inside the BHE,
- Temperature profiles linked to TRTs should be assessed by depth logging as this approach is more precise than temperature profiles gained from off-heating circulation tests during a TRT measurement,
- The measurement should not be older than 10 years.

In most European regions, TRT measurements are not obligatory and the data gained from them is not publicly available in archives. It is recommended that Geological Survey Organisations (GSOs) take care of collecting TRT datasets from service providers (planners and drillers) and service contractors. Quality checks need to be performed on temperature profiles done by third parties, as most service providers select the off-heater circulation test for initial temperature measurements, which is the more cost-effective method of temperature profile measurements. If possible, it is recommended that GSOs perform additional temperature measurements in BHEs in case the probe is not yet in use or connected to a heating system. Furthermore, assessment of high-quality temperature profiles in the framework of TRT measurements could also be linked to incentives offered by public bodies. This goes along with the obligation to make such data publicly available, at least in an accumulated way, in web-information systems. The effort in assessing subsurface temperature profiles is not very high. Measurements normally can be performed by standard groundwater well temperature devices at an effort of two staff hours without accounting for the mobilization effort.

4.3.2 Groundwater temperature measurements

Groundwater temperature measurements were carried out in the pilot areas of Zaragoza, Zagreb, Girona and Vienna. These field measurements were used to prepare datasets of maximum, minimum and measured groundwater temperature datasets.

Observed groundwater temperatures provide a crucial input for any thermal management of urban groundwater thermal management concepts. In most European urban areas, we are facing the problem of a low density of observation points as use of groundwater heat exchangers is still at the beginning in many countries and thermal groundwater measurements are affected by a significant effort. For example, groundwater temperature is regularly monitored only in 20% of the groundwater observations wells located in city of Vienna (Austria).

Groundwater temperature measurements can either be performed manually, automatically using loggers or installing geothermal control network. In GeoERA MUSE, multi depth temperature loggers were used in some pilot areas to monitor depth depending temperature profiles in observation wells. Such measurements were complemented by manual profile measurements (requirements: 2 persons around 10 minutes per observation point not accounting for mobilization efforts). Automated multi-depth temperature loggers are affected with production costs of at least EUR 1000 per device and generally need to be tailored for a specific well in dependence of the water table depth. One has to consider that multi depth temperature measurements do not need to be applied in all observation wells. It is recommended to apply it in groundwater bodies having a thickness of more than 10 meters or locations where strong anthropogenic thermal influence is already observed or can be expected (e.g. due to a significant density of operating groundwater heat exchangers).

The investment costs of automated single depth sensors are significantly lower starting at around EUR 100 per device including remote sensing components. It is recommended to define standardized reference depths for single depth sensors, which could either refer to 1) a constant depth below the observed water level (e.g. at least 1 meter below the groundwater table) or 2) at a fixed depth inside the well (e.g. midpoint between groundwater table and bottom of the screen referring to the mean annual groundwater level).

As the assessment of groundwater temperatures is affected by significant costs (investments for automated sensors or staff costs for manual measurements), it is recommended to perform sensitivity tests based on available groundwater temperature series and available observation wells suitable for further groundwater temperature measurements. In case of low density of existing thermal observation points, numerical models may support the evaluation of the expected thermal groundwater regime not affected by anthropogenic influences such as existing groundwater heat exchangers, surface sealing or subsurface installations (basements, tunnels or pipelines). In that context, the undisturbed thermal groundwater regime only corresponds to the surface temperature (optionally including climate change), the overburden depth, the thermal properties of the overburden material and aquifer (effective thermal diffusivity) and the hydraulic conditions inside the groundwater (hydraulic conductivity, flow regime and hydraulic connection to surface water bodies). In a next step, observed residuals between measured groundwater temperatures and the theoretical model can be interpreted towards possible sources of anthropogenic influences. For the planning of any future observation points, it is important to consider the spatial scale of any anthropogenic heat source. While groundwater heat exchangers and subsurface tunnels or pipelines normally have a limited range of influence, surface sealing and basements may have larger scales in densely settled centers. For the planning of observation networks, it is crucial not to overestimate the measured signal of local scale heat sources for any management plans derived from such measurements.

After identification of areas of interest for thermal groundwater measurements and monitoring, one has to decide whether to apply single depth or multi-depth temperature sensing. The decision can be made upon the expected thermal heterogeneity inside the groundwater body, which corresponds to the aquifer thickness (see above) or the type of anthropogenic heat source. Please note that groundwater heat exchangers may produce a vertically heterogeneous thermal plume in case warm water at lower density is injected to the groundwater body. Similar applies to observation points close to the interface between groundwater and surface water bodies. For the analyses of multi depth time series, it is recommended to produce time (x) – depth (y) 2D plots which outline the seasonal dynamics of the temperature at different depth of the groundwater bodies (Figure 31).

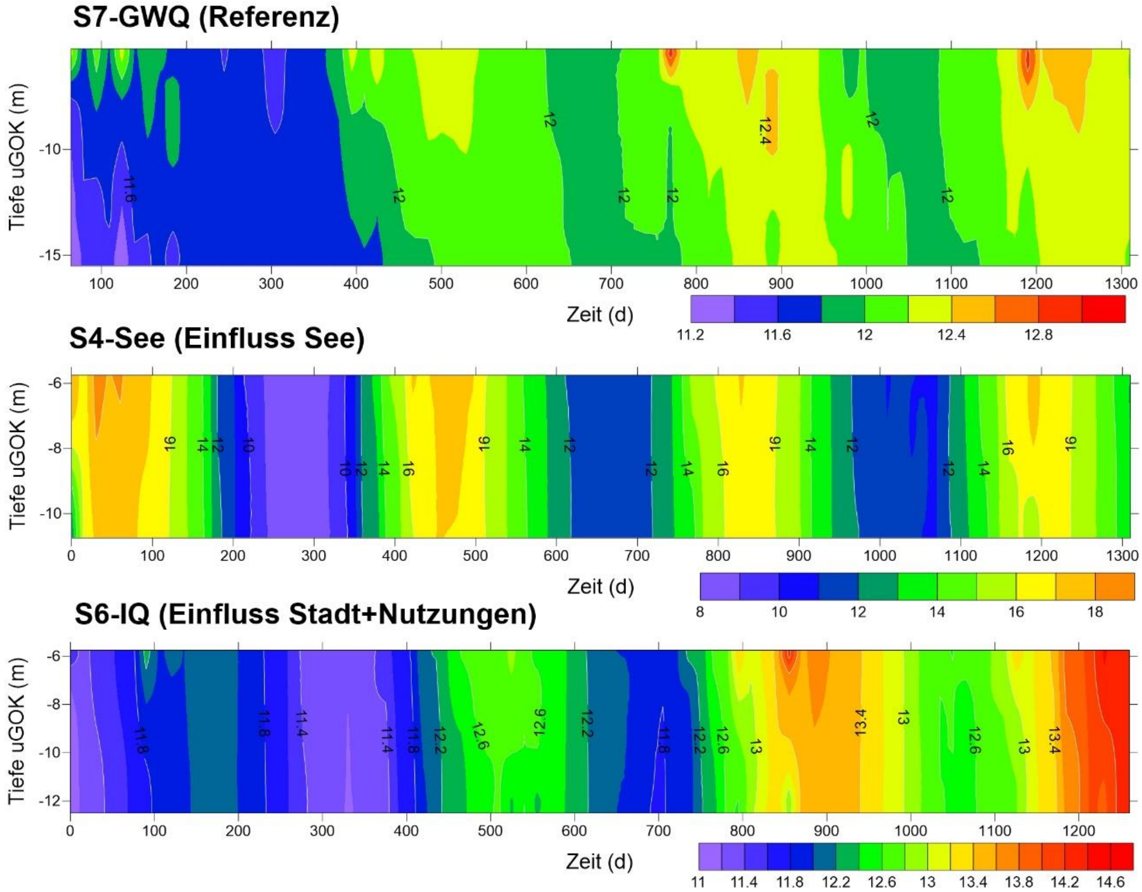

Figure 31: Example of a time versus depth plot of the groundwater temperature at 3 observation wells in Vienna, Austria. The plot also exhibits the continuous warming of the groundwater body over the period of around 4 years at the observation points “S7” and “S6”, which is a consequence of a nearby groundwater heat exchanger.

Moreover, it is recommended to use production wells of operating groundwater heat exchangers as additional and cost-effective observation points. Even if the water is pumped from the screen, which leads to a mixed average groundwater temperature, comparable to a single midpoint temperature measurement, these datasets are very helpful for the creation of maps and management plans. One has to consider that for the operation of groundwater heat exchangers the average mixing temperature of the vertical screen section is of importance. Low cost automated temperature sensors can easily be installed at the connection pipeline or inside the production well connected to remote sensing devices. Furthermore, obligatory monitoring could be linked to permits or offered at low to no costs by municipalities to enlarge the density of groundwater observation networks.

Furthermore, in order to assess groundwater thermal regime under the entire city it is recommended not only monitor groundwater temperature changes in singular monitoring points, but also install a geothermal monitoring network, which facilitates specific groundwater temperature data acquisition and obtain historical records. These data sets allow for the awareness of the spatiotemporal evolution shallow geothermal resources. It is necessary to consider monitoring points in areas where thermal impacts by GWHP systems are produced, at different distances from the thermal discharge point of the GWHP systems. It is necessary monitoring points covering pristine areas, i.e. areas outside anthropogenic activity. The analysis and interpretation of this information should be useful to establish the background temperature of the urban aquifer managed, identify its seasonal behavior and its modulation in depth, aspects that need to be studied in order to know the true magnitude of the existing thermal impacts. Coordination with local water authorities is also crucial to obtain continuous information and data on the regime and operation of all GWHP systems (flow rates and operating temperatures).

To facilitate field work activities, it is recommended establish a control network composed by piezometers expressly built and managed only by geological survey organizations. In any case, monitoring points requiring access permissions from third parties should be avoided. Concerning the observation periods of groundwater measurements it is recommended 1) daily measurement intervals for automated sensors and 2) monthly to quarterly manual measurements, to facilitate maintenance, cleaning the borehole cover and pipe, check the proper functioning of electronic devices, download stored data and avoid accidental loss of data or battery depletion. The required time interval for manual measurements may also be an outcome of the above described sensitivity study for planning groundwater temperature observations. One needs to consider that higher frequencies are recommended in areas influenced by groundwater heat exchangers due to varying or seasonally depending operational modes. It is advisable to observe the thermal data even when reaching a good thermal state of the aquifer. Any irregular change in expected water temperature must be properly described and analyzed to identify its cause and origin. Finally, it is desirable to interpret all the available information gathered from geothermal monitoring network by numerical modelling of groundwater flow and heat transport. This tool is able to reproduce the flow path of groundwater and to simulate the effect of the thermal discharges with acceptable reliability. A valid simulation will help to set the best sustainable management strategies for the GWHP systems.

4.3.3 Groundwater level measurements

Groundwater level measurements were carried out in the pilot areas of Zaragoza, Girona and Cardiff. These field measurements were used to prepare datasets of measured groundwater depth and measured groundwater level.

Most of the time groundwater level measurements are carried out simultaneously with groundwater temperature measurements, hence majority of recommendations listed for the groundwater temperature measurements are applicable for this parameter as well.

4.3.4 Groundwater chemistry and physical parameters

Groundwater chemistry and physical parameters assessment were carried out in the pilot areas of Cardiff, Bratislava and Cork. These field measurements were used to prepare datasets of critical chemical composition and measured electrical conductivity. No specific recommendations linked to the work in GeoERA MUSE were elaborated for these parameters. These field measurements were used to prepare datasets of critical chemical composition and measured electrical conductivity.

4.3.5 Hydraulic tests and specific yields

Field measurements were used to prepare datasets of hydraulic conductivity. Hence there are no specific recommendation regarding hydraulic tests and specific yields.

4.3.6 Petrophysical measurements

Petrophysical measurements were carried out in the pilot areas of Ljubljana, Cardiff and Cork. These field measurements were used to prepare datasets of thermal conductivity (in unconsolidated sediments) and thermal conductivity of hardrock samples.

4.3.6.1 Thermal conductivity of unconsolidated sediments

In general, the information value of thermal conductivity (TC) measurements in outcrops of unconsolidated sediments is rather low as the measured effective TC is strongly influenced by the moisture of the sediments. Therefore, it is recommended to measure the moisture content in addition to the effective TC at outcrops as well. In order to make any upscaling to greater depths or at larger spatial scales repeated measurements of the effective TC and the moisture at different annual seasons (wet and dry seasons) it is strongly recommended to evaluate the dependency of the effective TC of the moisture of the sediment.

Apart of outcrops, associated to construction sites or quarries, fresh drilling cores resulting from actual subsurface exploration campaigns (e.g. tunneling or building foundations) might offer vital samples for TC measurements of unconsolidated sediments as they represent the effective moisture conditions in the subsurface. For that reason, it is recommended to GSOs to stay in contact with municipality building departments and local geological surveys for ensuring access to fresh drilling cores. Please note that for quality reasons, it is recommended to either perform such measurements immediately after the extraction of cores at the drilling site or soon afterwards in case the core is insulated towards evaporation (e.g. by plastic sealing).

For performing needle probe-based measurements in unconsolidated sediments it is recommended to minimize the thermal resistivity between the needle probe by avoiding air filled gaps between the needle sensor and the whole in the sediment investigated. This can be applied by using thermal conductive gels water or fresh bentonite or similar suspensions.

4.3.7 Geophysical exploration

Geophysical exploration was carried out in Linköping and Brussels pilot areas. These field measurements were used to prepare datasets of geomagnetic characterisation and passive seismic measurements.

4.3.7.1 Geomagnetic characterization

The use of ground magnetic characterization was chosen as a field mapping method that could give valuable data related to the bedrock conditions and indirectly to the thermal properties of the subsurface. The application of the method and is usefulness is given by the geological setting, size and openness of the survey area and not the least the scope and size of the SGE project. The task for the Linköping pilot was to find the most suitable place for a large High Temperature Borehole Energy storage (HT-BTES) in the crystalline bedrock. This would involve 1000-1400 wells to 300 m depth with an individual spacing c. 5 m, thus have an area imprint of c 0.2 km^2. Even though, the placing of the HT-BTES had some restrictions related to land permits and distance to the heat source (in this case surplus heat from a large incineration plant) there still was a large land area (c. 2-3 km^2) that could facilitate the HT-BTES, and hence be surveyed. Another aspect was that the survey area was mainly agricultural with few manmade installations that could affect the magnetic measurements. The geological setting with mainly two dominating crystalline rock types, i.e. felsic gneiss and mafic metabasite, also facilitated the use of magnetic survey as to map their occurrences in the survey area. The usefulness of the data was also greatly enhanced by the existence of outcrops which gave valuable data on the magnetic susceptibility that could be used as base-line values for the interpretation. In our case there was also a clear correlation between rock type and the thermal conductivity which, hence, enabled the construction of a thermal conductivity map bas on the magnetic survey data.

The method is cost efficient, however, mainly motivated in projects with higher capex and with a high degree of freedom regarding placing of e.g. a multiwell SGE system. The method is also mainly applicable in areas with crystalline bedrock. It is also most applicable in open terrain as manmade installation affects the results.

4.3.7.2 Very Low Frequency (VLF)

The Very Low-Frequency method is an electromagnetic geophysical method that utilizes radio frequencies within the range of 3–30 kHz. If an electrically conductive subsurface structure exists, with an appropriate size and orientation to the incoming radio waves, an electrical field will be induced within the subsurface conductor. This electrical field, in turn, gives rise to a secondary magnetic field, which can, in turn, be measured. Hence, VLF measurements can be utilized to infer the presence of conductive subsurface structures, such as water-bearing fracture zones.

The method is as the magnetic survey sensitive to manmade installations such as cables, metal fences etc. This gives restrictions that the method is mainly applicable in open terrain where it, however, can give valuable indications and directions of water-bearing fracture zones that may affect the location and thermal impact of a SGE well. VLF is as the magnetic survey time efficient and relatively large land areas can be covered during a few days of field work.

4.3.7.3 Wire-line logging

This includes a range of different methods that are used for a wide range of purposes for characterizing the geology in boreholes. Logs that measure the natural radiation provide information that can be used directly to describe the subsurface layering and occurrence of different types of soil and/or rock. Especially the use of spectral gamma ray logs gives, together with information on rock density and thermal conductivity, data that can be used for calculating the heat flow and heat productivity of a SGE well. On the other hand, resistivity tools give data on water conductive zones and also occurrences of brine ground water. Information that give important input to the hydraulic conditions in the SGE well.

The benefit of wire-line logging is that these methods are simple and relatively fast to perform in shallow wells. In the early stages of pre-investigations for larger BTES one appealing scenario is that geophysical logging is performed in one centrally placed cored borehole and in additional marginal percussion drilled boreholes. The logged cored borehole is used as a key well for the interpretation of the logged percussion drilled wells. The core can also be used for thermal conductivity measurements. The data could then be complemented with TRT measurements, which further strengthens the possibilities to get the best design and performance from the given settings. However, in the best of worlds, this scenario may not be possible for all projects.

Wire-line logging, with at least natural gamma ray and resistivity, is recommended as it provides important data that can be used both in design of the SGE and for the geological characterization of the subsurface. It could to some extent be regarded as a minimum regulatory requirement that logging is performed. This would successively as the number of logged wells increase give a data base that provide decision support regarding management of the subsurface, including SGEs, especially in urban areas.

4.3.7.4 Thermal conductivity measurements on rocks (TCS-analysis)

The method involves laboratory analysis of rock samples and cores and provide data on the specific thermal conductivity related to rock type. The method is primarily applied for making regional prognosis maps of the thermal conductivity of the rock types composing the bedrock surface.

Thus, there is a limited use of TCS-data for a single SGE well since TRT or DTRT measurements are the most efficient way to get the composite thermal conductivity of the well. However, in connection to larger multi-well SGEs for heat storage TCS analyses of cores and outcrops provide empirical information on the occurring rock types that could be correlated to a specific log signal in investigation wells and also the responses from a ground magnetic survey. Together these data sets give a high degree of confidence regarding knowledge of the subsurface thermal properties, especially information on any thermal heterogeneity in the rock mass, that must be considered in assessing the thermal impact of the surroundings.

4.3.7.5 Thermal Response Tests (TRT)

Although the performance of TRT measurements and the collection of related data was not in the focus of the activities in the GeoERA MUSE pilot areas, we briefly want to outline some recommendations given by the project team. TRT measurements represent one of the most important data sources for the evaluation of resources linked to closed loop systems (BHEs) as the provide the following information on subsurface conditions:

- Lithological profiles, derived from drilling reports,
- Standard TRT measurement: Effective thermal conductivity (TC) also accounting for the influence of advection by groundwater flow,
- Enhanced TRT measurement: Depth related effective TC profiles,
- Subsurface temperature profiles.

As the performance of TRT measurements is associated with significant investment costs (in the order of EUR 2000 to 5000 per measurement) the density of measurements is still rather low in European urban areas. Moreover, the accessibility to TRT data is still rather limited as most of the tests have been performed so far by private entities. We recommend initiating strategic cooperation between GSOs and local authorities to collect TRT results and make such datasets better accessible in the future.

It is also recommended to perform reliability and quality checks on TRT datasets assessed by third parties. Uniform quality standards and binding technical guidelines are still at the beginning at a European level. Only a few countries, like Germany already issued sound technical guidelines and standards to perform TRTs. In previous projects, like CE177 GeoPLASMA-CE, we identified 3 major sources of error linked to the performance of TRT measurements:

1) Insufficient calibration and pairing of temperature sensors linked to the device or noise introduced by the device itself (mostly linked to the control of the heating device inside the TRT instrument),
2) Insufficient quality or disturbing influences while performing the test itself (e.g. insufficient TRT duration, insufficient thermal insulation towards atmospheric signals),
3) Insufficient quality of the data processing and interpretation of TRT measurements.

Therefore, it is recommended to install a network of TRT benchmark and quality check sites across Europe to guarantee a high level of quality and reliability of TRTs. TRT benchmark sites could be realized by synthetic heat sinks (first pilot instruments are already existing at ZAE Bayern in Munich, see also https://www.gewsplus.de/index.html - information only available in German language) or by BHE probes at well-known geological conditions not influenced by groundwater flow. The Geological Survey of Austria recently installed a benchmark BHE site at its premises in Vienna.

For more information on quality criteria and concepts for TRT benchmark tests please refer to the deliverables of the EU Interreg project CE177 GeoPLASMA-CE (www.geoplasma-ce.eu).

5 OUTLOOK

The GeoERA MUSE project provided a great opportunity for all EuroGeoSurveys organisations to collaborate and advance research agendas in their pilot areas, collect new data, develop unique workflows and create dialogue between project partners and local stakeholders. Even though the project finished all involved EuroGeoSurveys in the project acknowledge the advantages which project MUSE gave and foresee continuation of works in their pilot areas, such as field work, long-term environmental monitoring, 3D geological modelling, communication with stakeholders, future collaboration with EuroGeoSurveys and dataset usage for future or on-going local projects.

Due to COVID-19 pandemic all meetings and workshops between EuroGeoSurveys had to be hold online (although meeting were held pre-covid in Essen, Cardiff, Utrecht and Zagreb), therefore more people were able to participate in these online meetings and that was an efficient way to share results between partners, even if the opportunity for side/evening discussions was less. During monthly AWC meetings, technical questions could be shared and solved and partners were able to discuss how to obtain certain results or receive advice on which method is more suitable for their study area and geology. This allowed partners working in different pilot areas to use and co-develop harmonised methods to obtain their end results.

6 REFERENCES

Acuña, J., Lazzarotto ,A., Garcia, J., Mazzotti-Pallard, W., Topel, M., Hesselbrandt, M., Malmberg, M. & Abuasbeh, M., 2021: Tools for design of high temperature borehole thermal energy storage in district heating production. Final Report, working package 3.1. Termiska Energilager, Energiforsk. Stockholm

Acuña, J., Stokuca, M., Mazzotti, W. & Munter, E., 2018: Förundersökningar för högtemperaturlager. Provborrning och responsmätning vid NetonNet, Dikestriangeln, Distorp Åken och Distorp Hagen (in Swedish). Bengt Dahlgren, Report, Stockholm, 63 pp.

Boon, D, P., Butcher, A., Townsend, B., Woods M. 2020a. Geological and hydrogeological investigations in the Colchester Northern Gateway Boreholes: February 2020 survey. British Geological Survey Open Research Report, OR/20/011. 26pp.

Boon, D., Farr, G., Hough, E. 2021. Thermal properties of Triassic Sherwood (Bunter) Sandstone Group and Mercia Mudstone Group (Keuper Marl) lithologies. *GET2021 – 2nd Geoscience and Engineering in Energy Transition conference*. November 2021, Strasburg France. [extended abstract - Submitted]

Boon, D., Farr, G., Williams, L., Thorpe, S., Patton, A., Kendall, R., Holden, A., Scheidegger, J., Self, S., Abesser, C., and Harcombe, G.: 2020b. Concept for shallow geothermal opportunity mapping, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-19146, https://doi.org/10.5194/egusphere-egu2020-19146

Boon, D.P., Farr, G., Abesser, C., Patton, A.M., James, D.R., Schofield, D.I. & Tucker, D.G. 2019. Groundwater heat pump feasibility in shallow urban aquifers: experience from Cardiff, UK, *Science of the Total Environment.* https://doi.org/10.1016/j.scitotenv.2019.133847

Casasso, A., Pestotnik, S., Rajver, D., Jež, J., Prestor, J., & Sethi, R. (2017). Assessment and mapping of the closed-loop shallow geothermal potential in Cerkno (Slovenia). Energy Procedia, 125, 335-344. https://doi.org/10.1016/j.egypro.2017.08.210

Chambers, R., Gilfillan, S., Johnson, G., & Boyce, A. (2019, December). Investigations into Geochemical Fingerprints of UK Carboniferous Coal Measures at the Glasgow UKGEOS Site, Scotland. In AGU Fall Meeting Abstracts (Vol. 2019, pp. H51J-1618). https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/501386

Ditlefsen, C. 2021: Vurdering af potentialet for geologisk varmelagring (UTES) - Aarhus Kommune. 35 pp. MUSE report in Danish. GEUS 2021. Report 2021/26.

Farr, G., Patton, A.M., Boon, D., James, D., Coppell, L & James., L. 2019a. Cardiff Urban Geo-Observatory, Groundwater Temperature Data 2014-2018. British Geological Survey https://ukgeos.ac.uk/data-downloads/cardiff/sensor-data

Farr, G., Patton, A.M., Boon, D., James, D., Coppell, L., James, L. 2019b. *Cardiff Urban Geo-Observatory: groundwater temperature data 2014-2018, metadata report.* Cardiff, UK, British Geological Survey, 14pp. (OR/19/053) (Unpublished) http://nora.nerc.ac.uk/id/eprint/525332/

Hesselbrandt, M., Acuña, J. & Funehag, J., 2020: Impermeable Boreholes for High Temperature Thermal Energy Storage. Energiforsk Report 2020:666 Stockholm, 62 pp.

Hesselbrandt, M., Erlström, M., Sopher, D. & Acuña, J., (n.d.). Multidisciplinary approaches for assessing a High Temperature Energy Storage (HTES) facility in Linköping, Sweden. Energies. https://doi.org/10.3390/en14144379

HM Government, 2020. The ten point plan for a green industrial revolution https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 pp + appendices.

Kendall, R.S.; Williams, L.R.; Patton, A.M.; Thorpe, S. 2020 *Metadata report for the Cardiff superficial deposits 3D geological model.* Nottingham, UK, British Geological Survey, 19pp. (OR/16/031) (Unpublished) http://nora.nerc.ac.uk/id/eprint/529171/

Kovač Z., Nakić Z. & Pavlić K. (2017). Influence of groundwater quality indicators on nitrate concentrations in the Zagreb aquifer system. *Geologia Croatica*, 70(2), 93-103. https://doi.org/10.4154/gc.2017.08

Kreitmair, M.J, Makasis, N., Bidarmaghz, A., Terrington, R.L,. Farr, G., Scheidegger, J.M & Choudhary, R. 2020. Effect of anthropogenic heat sources in the shallow subsurface at city-scale. ICEGT 2020

Monaghan, A. A., Starcher, V., Barron, H. F., Shorter, K., Walker-Verkuil, K., Elsome, J., ... & Callaghan, E. (2021). Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources. Quarterly Journal of Engineering Geology and Hydrogeology. https://doi.org/10.1144/qjegh2021-033

Parkes, D., Busby, J.; Kemp, S. J.; Petitclerc, E.; Mounteney, I. 2021. The thermal properties of the Mercia Mudstone Group. Quarterly Journal of Engineering Geology and Hydrogeology, 54 (2). https://doi.org/10.1144/qjegh2020-098

Patton, A.M., Farr, G., Boon, D.P. James, D.R., Williams, B., James, L., Kendall, R., Thorpe, S., Harcombe, G., Schofield, D.I & Holden, A.; White, D. 2020. Establishing an urban geo-observatory to support sustainable development of shallow subsurface heat recovery and storage. *Quarterly Journal of Engineering Geology and Hydrogeology*, 53 (1). 49-61. https://doi.org/10.1144/qjegh2019-020

Scheidegger, J., Farr, G., Christelis, V., Mansour, M., Jackson, C., Patton, A., James, L., Boon, D & Holden, A. 2019. Groundwater modelling to support sustainable heat recovery from a shallow urban coastal aquifer. IAH hydrogeological modelling conference.

Walls D.B., Burnside N. M. & Boyce A.J. 2. 2021. Old versus New: Comparing Mine Water Geothermal Systems in Glasgow. *Proceedings World Geothermal Congress 2020+1.* https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2020/14148.pdf

Watson, S. M., Westaway, R., & Burnside, N. M. (2019). Digging deeper: The influence of historical mining on Glasgow's subsurface thermal state to inform geothermal research. *Scottish Journal of Geology*, 55(2), 107-123. http://mr.crossref.org/iPage?doi=10.1144%2Fsjg2019-012