19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 3.13.160
DOI: 10.46793/ACUUS2025.3.13.160

BENEATH THE SURFACE: UNLOCKING URBAN GEOTHERMAL POTENTIAL FROM LEGACY SUBSURFACE ASSETS

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Abstract: Urbanisation is accelerating at an unprecedented rate, with an estimated 70% of the global population expected to live in urban areas by 2050. This growth challenges cities to maintain liveability while meeting ambitious sustainability targets. Among the most pressing concerns is the decarbonisation of space heating, which accounts for approximately 18% of the UK's total energy use. This paper explores how legacy underground structures—specifically disused coal mines and shallow aquifers—can be repurposed for sustainable geothermal energy, contributing to low-carbon urban heating systems. Drawing on two case studies in the Leeds region in the UK, the research presents a scalable framework for assessing the geothermal viability of subsurface environments. The first study investigates the feasibility of geothermal heat extraction from aquifers beneath the University of Leeds campus, using legacy hydrogeological data combined with thermal modelling. The second assesses the regional thermal potential of abandoned coal mine workings in the Pennine Coal Measures, leveraging historical mining records and borehole data to evaluate city-scale opportunities for minewater heating networks. The findings demonstrate that legacy data, when systematically integrated, can reveal untapped thermal resources that align with net-zero goals. The proposed methodology is transferable to other urban settings with similar geological and post-industrial contexts, offering a replicable model for sustainable underground energy planning.

Keywords: Subsurface sustainability, Urban sustainable heating, Legacy data reuse and analysis Aquifer thermal potential, Minewater heat recovery

1. INTRODUCTION

Urbanisation is accelerating worldwide, with the United Nations projecting that 70% of the global population will reside in urban areas by 2050 [1]. This trend exerts enormous pressure on urban infrastructure, resource efficiency, and environmental resilience. Among the most urgent priorities is the decarbonisation of urban heating, which accounts for nearly 18% of the UK's total energy use [2]. As cities attempt to grow sustainably while maintaining green and open spaces, innovative energy strategies are essential to transition from fossil fuels to low-carbon alternatives [3, 4].

One such opportunity lies beneath our feet: the urban subsurface. Across the United Kingdom and many post-industrial nations, historical urban development was accompanied by extensive subsurface interventions—most notably, coal mining and urban aquifer tapping [5]. These features, often viewed as legacies of environmental degradation, are now being reconsidered as assets in the transition to net-zero cities. Abandoned coal mines, with their extensive voids, can serve as reservoirs for low-enthalpy geothermal energy, while shallow aquifers in urban catchments also offer potential as natural heat exchangers [3, 5].

Despite growing interest, the geothermal potential of such legacy structures remains underexplored at the city scale. Much of the existing literature [5] focuses on small-scale mine water heat pump systems or isolated aquifer thermal energy storage (ATES) units. What is missing is a methodical approach to scaling these technologies using

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publicly available historical data. This study addresses that gap by integrating two case studies in the Leeds region: a coalfield geothermal assessment across the Pennine Coal Measures, and a shallow aquifer feasibility study beneath the University of Leeds campus.

Through spatial, thermal, and hydro-geological analysis of legacy datasets—including borehole logs, mining records, and aquifer maps—this paper develops a transferable methodology for evaluating subsurface geothermal resources. This work contributes to urban sustainability by outlining pathways for retrofitting existing urban geologies into functioning components of low-carbon energy systems, reinforcing the role of underground spaces in resilient, future-proof cities.

2. BACKGROUND

2.1. Underground Space and Urban Sustainability

The underground environment represents a valuable and underutilized resource in the sustainable development of cities [6]. With surface land becoming increasingly constrained, the **subsurface offers critical opportunities** for energy production, storage, transportation, waste management, and climate adaptation [7, 8]. Integrating underground infrastructure into urban design not only frees up surface space for green areas and social functions but also aligns with broader sustainability objectives—particularly climate action, clean energy, and responsible resource use. In the context of the United Nations Sustainable Development Goals (SDGs), subsurface developments can directly or indirectly support more than ten of the 17 goals [6]. [3] presented a histogram that visualises this relationship, underscoring how geothermal energy, waste heat storage, and aquifer *(e.g., SDG 7, 11, 13)* use contribute to global sustainability targets as shown in Figure 1.

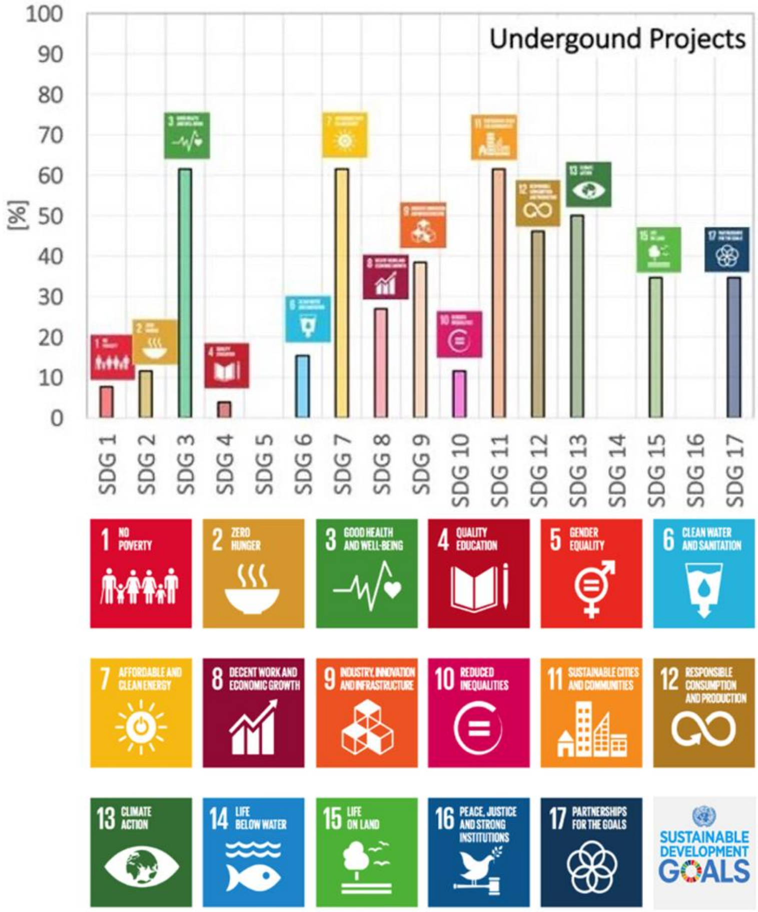

Figure 1. *Top: Histogram illustrating the relevance of subsurface use to the UN Sustainable Development Goals - Longer bars indicate stronger alignment; and, Bottom: Sustainable development goals introduced in the 2030 Agenda for sustainable developmentproposed by the United Nations members in 2015 (adapted from [3 & 8]).*

2.2. Urban Heating and Energy Transitions

Heating remains one of the most carbon-intensive energy demands in cities. In the UK, around **40% of energy consumption in buildings** is attributed to heating, primarily supplied by fossil fuel-based gas boilers [9]. Transitioning to low-carbon heating systems is essential for meeting net-zero targets and improving energy resilience in urban areas [3, 4, 5].

District heating systems powered by **renewable or residual heat sources**—such as wastewater, ambient heat, or geothermal energy—have gained traction across Europe as a pathway for large-scale decarbonization [9]. Among these, shallow geothermal resources stand out for their reliability, longevity, and minimal environmental footprint [4].

2.3. Shallow Geothermal Systems and Subsurface Potential

Shallow geothermal systems encompass a range of technologies designed to harness the thermal capacity of the ground. These include **ground source heat pumps (GSHPs)**, **aquifer thermal energy storage (ATES)**, and **minewater-based systems**, which are well-suited to urban settings due to their scalability and compatibility with building-level or district-scale heating networks [10, 11]. An example is shown in Figure 2 and 3 (right).

[4] assessed the geothermal feasibility of the **University of Leeds campus** using legacy hydro-geological data. Borehole records and groundwater temperature data were modelled to estimate sustainable extraction rates and seasonal recharge potential. This approach showed how previously overlooked data could reduce site investigation costs and de-risk early design stages of geothermal installations.

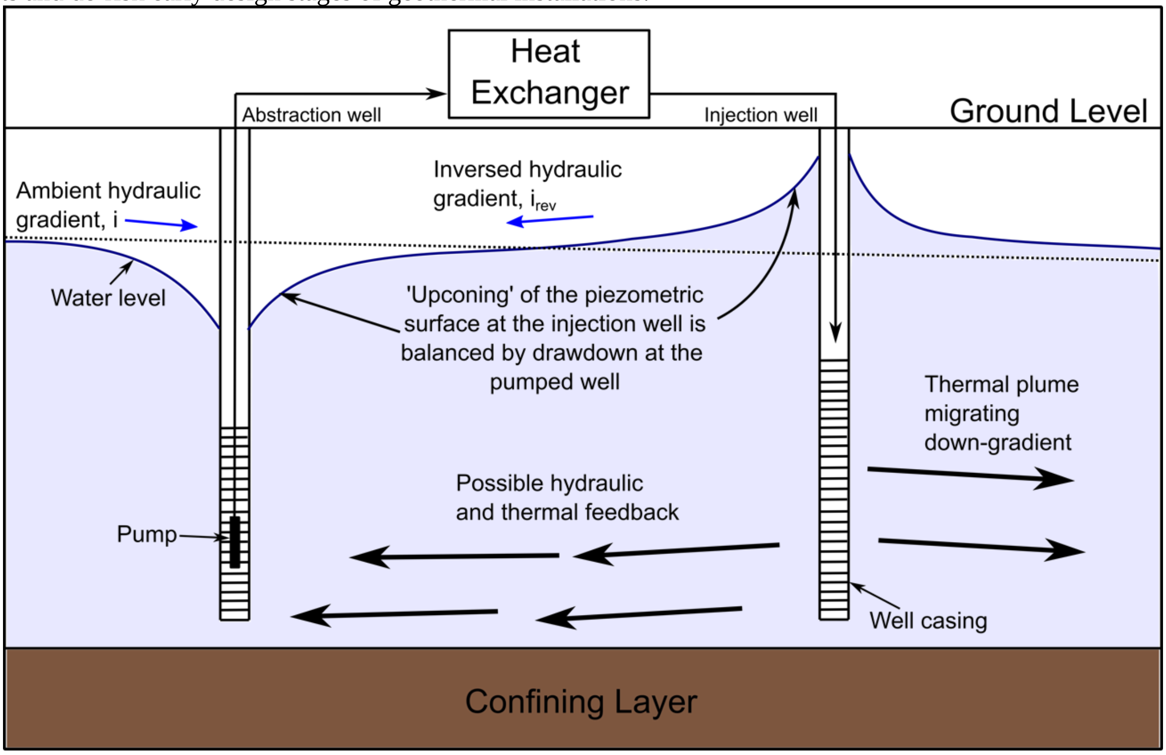

__Figure 2.__ Schematic cross section illustrating the possibility of hydraulic and thermal feedback in a well 'doublet' [4].

2.4. Minewater Geothermal Energy and Industrial Legacies

Similarly, abandoned coal mines are now seen as **geothermal assets [4]**. Filled with groundwater at moderate depths, they can maintain temperatures of 12–20°C, which can be harvested using minewater heat pumps. [3] mapped coal seams within the **Greater Leeds area** to evaluate regional geothermal potential, using GIS-based analysis of seam depth, continuity, and overburden thickness.

The findings indicate that large-scale minewater heating networks could be deployed using existing shaft infrastructure and district-scale heat exchange systems. Such systems shown in Figure 3 not only reduce emissions but also revalorise post-industrial land as energy-positive environments.

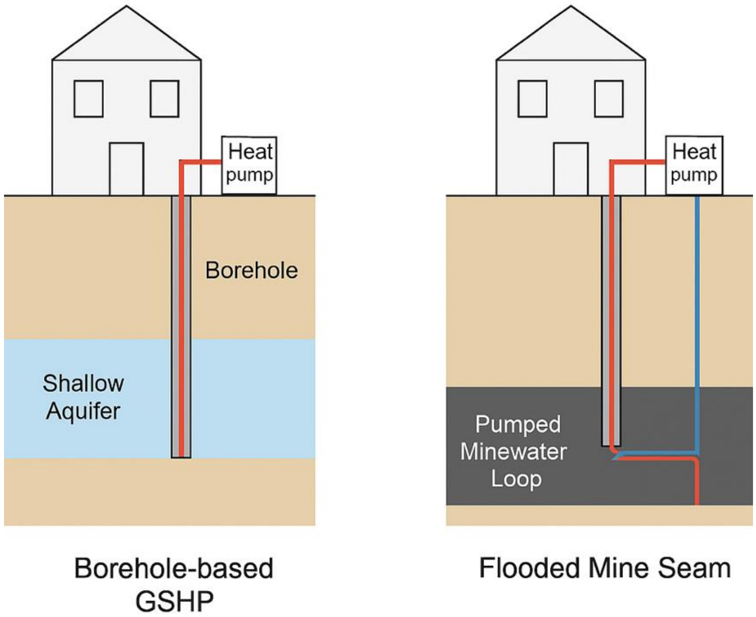

Figure 3. *Conceptual cross-section of minewater and aquifer-based geothermal systems operating in an urban subsurface context. (left side = borehole-based GSHP in shallow aquifer; right side = flooded mine seam with pumped minewater loop. Integrated with heat pump units and surface buildings.)*

2.5. Research Gap and Contribution

Despite isolated pilot projects, city-scale geothermal planning remains limited, particularly in legacy urban landscapes. There is a clear need for a **replicable framework** that integrates public domain geological and hydrological data to pre-screen sites and support local energy planning. Your published case studies collectively respond to this need—demonstrating methods for **data-driven geothermal screening** using available legacy datasets and confirming that both aquifers and coalfields hold viable potential for integration into urban heating transitions.

3. METHODOLOGY

This study draws upon two independent yet thematically linked case studies carried out in the city of Leeds, UK: (1) a shallow aquifer-based geothermal feasibility study at the University of Leeds campus [4], and (2) a regional-scale coalfield geothermal screening across the Greater Leeds area [3]. Both studies rely on publicly available legacy data, demonstrating how historical subsurface information can be used to de-risk early-stage geothermal energy development.

The key datasets used in both studies include (Table 1). These data were pre-processed in GIS environments (ArcGIS Pro, QGIS) and integrated using 3D spatial modelling to estimate geothermal gradients, potential extraction zones, and infrastructure integration potential.

Table 1. *Key datasets in the two case studies..*

Data Type	Source	Application
Borehole logs and lithological data	British Geological Survey (BGS) GeoIndex & OpenGeoscience	Hydrostratigraphy, depth to aquifers
Mining seam maps & shaft data	Coal Authority	Mine depth, seam continuity, void distribution
Groundwater monitoring records	Environment Agency & University archives	Temperature profiling, recharge rates
Building and campus energy use	University estates & planning records	Estimating thermal demand
Surface elevation and geology	Ordnance Survey and BGS 1:50,000 scale maps	Overlay analysis, topographic constraints

The modelling approach used in both cases based on the key datasets obtained is showing in Figure 4.

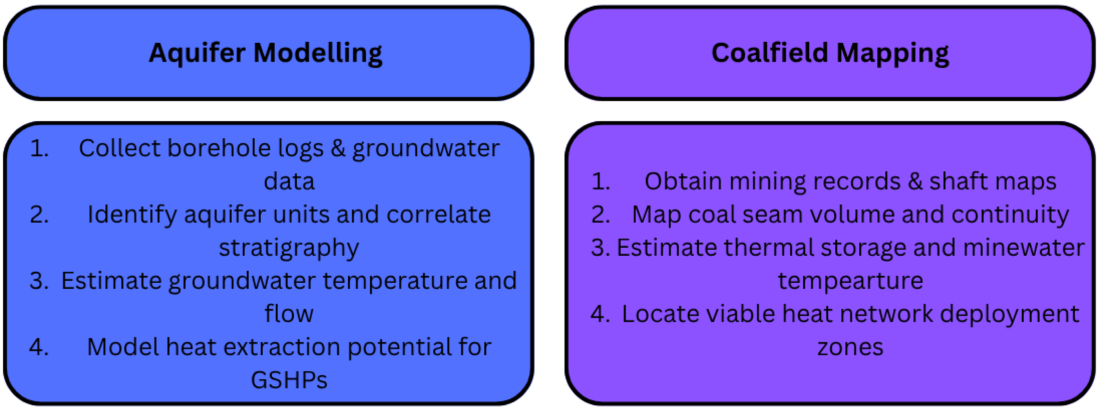

Figure 4. *Workflow diagram summarising the geothermal potential screening methodology applied in both case studies: Left: for shallow aquifer modelling and Right: for coalfield geothermal mapping.*

3.1. Site 1: Shallow Aquifer Assessment (University of Leeds)

This sub-study used 19 borehole logs from within and around the University campus to assess the hydrogeological characteristics of the shallow sandstone aquifer. The key steps involved:

- **Stratigraphic correlation** of borehole logs to identify aquifer units (Millstone Grit, Sherwood Sandstone Group)
- **Groundwater temperature estimation** using proxy data and nearby Environment Agency wells
- **Sustainable yield estimation** using simplified Darcy flow assumptions
- **Thermal potential modelling** to size a potential ground source heat pump system

Energy demand was estimated based on university building typologies (teaching, laboratory, residential), which was then cross-referenced with available heat extraction potential per m² of borefield footprint.

3.2. Site 2: Coalfield Geothermal Potential (Greater Leeds)

This larger-scale assessment focused on post-industrial coalfields within the Pennine Middle and Lower Coal Measures, encompassing areas such as Middleton, Rothwell, and Garforth. The following workflow was employed:

- Digitisation of historic **coal seam maps** and identification of **seams >1 m thickness**
- 3D spatial modelling to define **accessible depth windows** (100–500 m)
- Identification of **existing mine shafts** and vertical access points
- **Heat capacity estimation** using known volumetrics and temperature gradients (ca. 26–30°C/km)
- GIS-based screening to identify **district heating cluster potential** zones

3.3. Analytical Assumptions

To ensure comparability across both case studies, consistent assumptions were applied:

- **Heat extraction rate** for shallow systems: 20–50 W/m² [3,4]
- **Thermal conductivity** estimates: 2.0–3.0 W/m·K depending on lithology [3,4]
- **Coefficient of performance (COP)** for GSHP systems: 3.5 (standard for UK retrofits)
- Temporal scope assumed: **20-year project lifespan** with potential extension

All estimates were conservatively framed, with emphasis placed on using only existing data—no new drilling or intrusive ground investigation was required at this stage.

4. RESULTS

4.1. Shallow Aquifer Case Study: University of Leeds Campus

The hydrogeological assessment of the University of Leeds site confirmed the presence of a shallow fractured sandstone aquifer (Millstone Grit), with depths ranging between 10 m and 45 m and thicknesses exceeding 15 m in certain areas. Groundwater temperatures at depth were inferred to be between 10–11.5°C, based on regional thermal gradient extrapolation and nearby Environment Agency monitoring wells.

- **Extractable thermal energy** was conservatively estimated at **17–28 W/m²** of borefield area.
- For a 6,000 m² available borefield footprint, this yields a **heat supply of ~120–160 kWth**.
- Over a 20-year period, and accounting for seasonal variations, this equates to a potential **~2.5 GWh/year** of clean thermal energy.
- Demand modelling showed this output could serve up to **6 medium-sized academic buildings**, offsetting approximately **340 tonnes of CO_2 annually**.

An example cross-section of the analysis is shown in Figure 5. Constraints included limited access due to existing buried services and buildings, but adaptive borehole layouts (L-shaped or radial) were found to mitigate surface disruption.

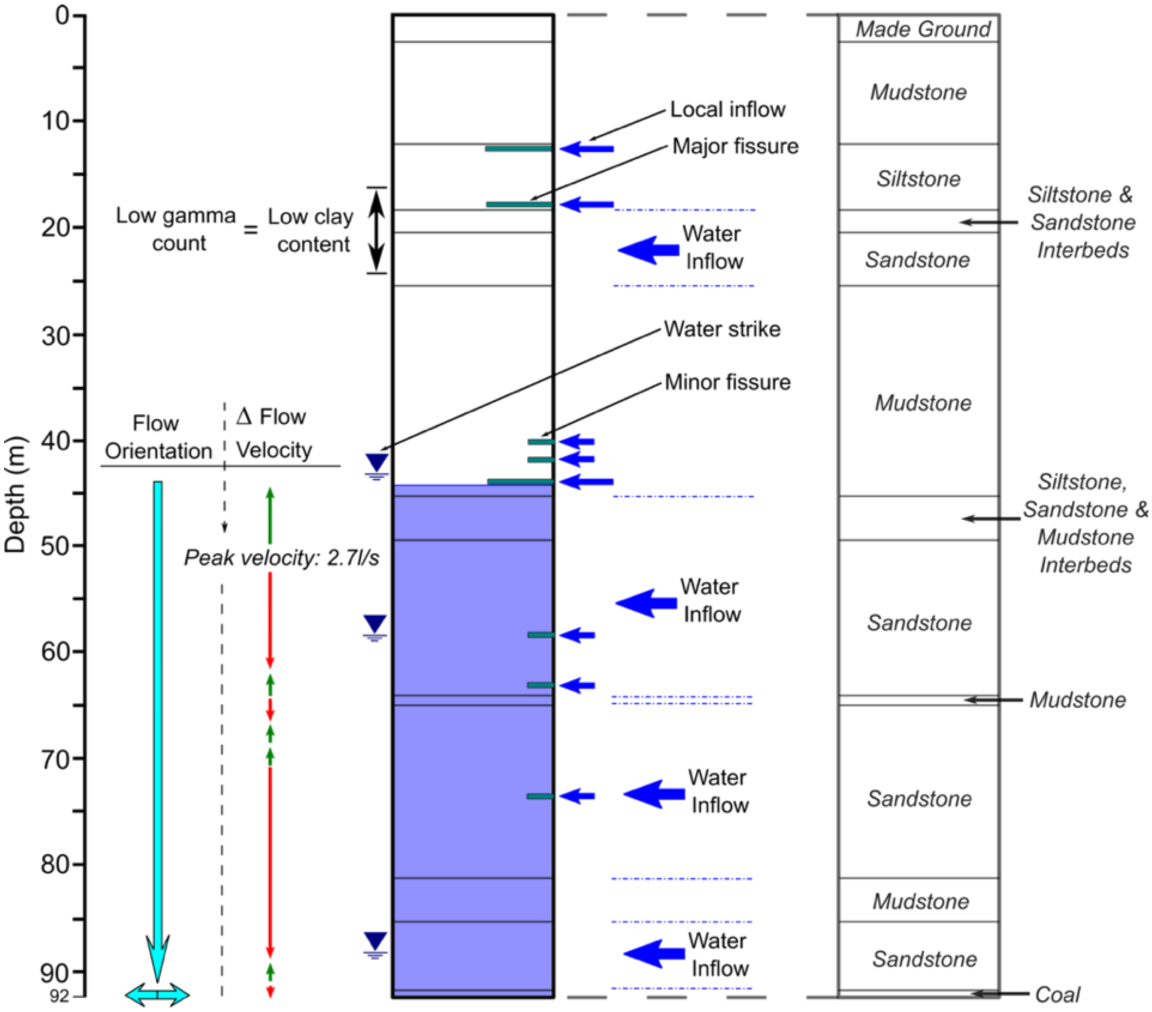

Figure 5. *One-dimensional schematic cross section through borehole X, summarising the hydrological conditions inferred from geophysical logs [4].*

4.2. Coalfield Geothermal Screening: Greater Leeds Area

Analysis of legacy mining datasets identified over 350 km² of accessible coal seams, with over 75 seams exceeding 1 m in thickness and occurring at depths of 150–400 m. Seam temperature estimates ranged from 13–20°C, suitable for low-enthalpy heating systems when combined with high-efficiency heat pumps.

- Estimated minewater volumetric capacity suggests extractable thermal power of 3–8 MWth across five high-potential clusters (e.g., Middleton, Rothwell, Garforth).
- A conservative model indicates potential for >40 GWh/year thermal output across the region.
- These areas show strong alignment with residential heat demand zones and existing district energy infrastructure.

Example of a heat map is shown in Figure 6. The mapping tool developed by [3] enables spatial screening of subsurface potential and cross-referencing with socio-technical variables such as fuel poverty indices, network connection density, and land availability.

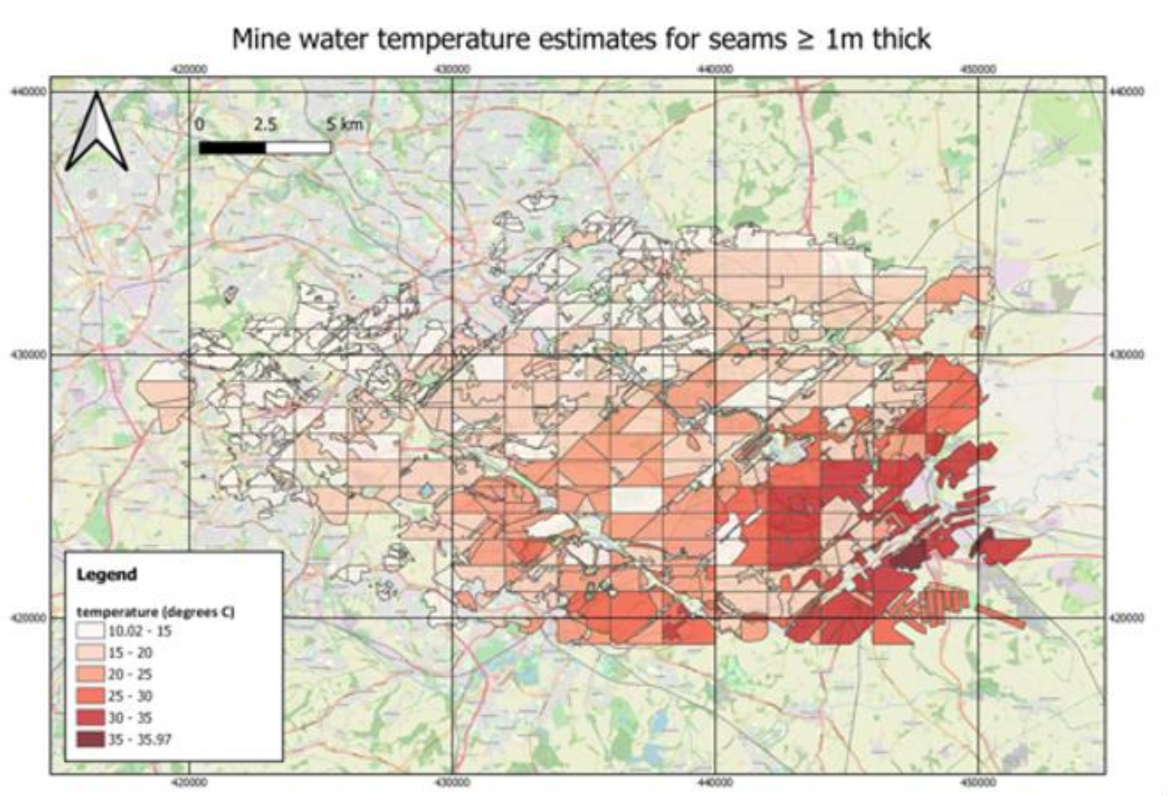

Figure 6. *GIS heat map overlaying coal seam depth of 1 m, shaft locations, and local building density to identify candidate heat network zones [3].*

4.3. Comparative Potential and Integration Pathways

While the university site supports decentralised, small-scale systems, the coalfield zones present opportunities for regional decarbonisation strategies, especially when integrated with municipal housing or industrial heat users. A summary comparison is shown in Table 2.

Table 2. *Comparative Potential and Integration Pathways.*

Parameter	**University Campus (Aquifer)**	**Greater Leeds (Coalfields)**
Depth	10–45 m	150–400 m
Temperature range	10–11.5°C	13–20°C
Estimated output	~2.5 GWh/year	~40 GWh/year (multi-site)
Technology	Vertical GSHPs	Minewater heat pumps
Network scale	Building cluster	District-level
Carbon reduction potential	~340 tonnes CO_2/yr	>6,000 tonnes CO_2/yr

5. DISCUSSION

5.1. Leveraging the Urban Subsurface for Sustainability

The re-utilization of subsurface space, including aquifers and abandoned coalfields, represents a strategic opportunity to decarbonize urban heating while advancing sustainability goals. As demonstrated in both Leeds-based case studies, the integration of legacy data with modern spatial modelling can offer a low-cost, non-invasive starting point for planning geothermal infrastructure — aligning directly with SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) [6, 8].

Shallow geothermal systems, while spatially constrained, are ideal for campus-scale or institutional users with predictable demand and land control. Conversely, minewater geothermal presents a city-scale solution, with heat recovery potential capable of serving thousands of households. The complementary nature of these systems reinforces the need for tiered urban geothermal strategies.

5.2. Economic Feasibility

Initial capital expenditures for shallow ground source heat pump (GSHP) systems are typically higher than conventional gas boilers (ca. £1,000–£1,800 per kWth installed), but operational cost savings and government incentives (such as the UK's Boiler Upgrade Scheme or potential carbon credits) can deliver payback within 8–12 years.

For minewater systems, infrastructure costs are higher due to the need for heat exchange equipment, network piping, and water treatment. However, the scale of thermal delivery — particularly in high-density areas — offers greater returns over time. A 3 MWth minewater system, for instance, could deliver £150,000–£200,000 in annual energy savings depending on fossil fuel displacement rates.

5.3. Policy and Planning Implications

Urban planning systems must evolve to treat subsurface as a finite, strategic resource, rather than an unregulated void. Integrating geothermal feasibility studies into local development frameworks and city masterplans could significantly streamline adoption.

Furthermore, the availability of digitised borehole, shaft, and geological data presents an opportunity for governments to build open-access geothermal mapping platforms — supporting both public and private sector actors in early decision-making.

Example: The Coal Authority's minewater heat project database, and the BGS's OpenGeoscience portal, already offer strong precedents for replicable national-scale geothermal resource screening.

5.4. Data Gaps and Limitations

Despite promising results, several limitations persist:

- Legacy data coverage is uneven, with gaps in key hydrogeological parameters like transmissivity and water chemistry.
- Temperature profiles are often absent or outdated, requiring inference from regional gradients.
- Subsurface infrastructure conflicts (e.g., sewer lines, tunnelling) can reduce available installation zones, especially in dense urban cores.

Thus, while legacy datasets are powerful, targeted ground validation (e.g., temperature logging or pumping tests) remains essential before full-scale implementation.

5.5. Transferability

The methodology developed through these studies is highly transferable to other post-industrial cities in the UK (e.g., Glasgow, Newcastle, Sheffield) and internationally — particularly where mining legacies or campus-scale aquifers exist. By standardising workflows that integrate GIS, legacy data, and thermal modelling, cities can make evidence-based decisions with minimal upfront investment.

6. CONCLUSIONS

This study has demonstrated the substantial potential of repurposing urban subsurface environments — particularly shallow aquifers and legacy coal mine workings — for sustainable geothermal heating solutions. By leveraging freely available historical and geological data, both case studies in Leeds illustrate that low-carbon, decentralized or district-scale heating infrastructure can be feasibly assessed without intrusive investigation, reducing project risk at early stages.

The University of Leeds aquifer study showed that even constrained urban campuses can benefit from targeted ground source heat systems, offering significant carbon savings and a pathway to institutional energy autonomy. Meanwhile, the Greater Leeds coalfield screening identified large-scale thermal potential in disused mineworkings, underlining the viability of minewater systems as part of city-scale heating transitions — especially in post-industrial urban contexts.

The findings support four key recommendations:

- Integrate geothermal screening into early-stage masterplanning for new developments and urban retrofits, particularly in areas with known subsurface data.
- Develop national or municipal-level geothermal mapping platforms that combine geological, demand, and infrastructure layers, enabling transparent feasibility assessments.
- Adopt a dual-scale strategy that pairs shallow aquifer heat pumps for localized users (campuses, schools, hospitals) with deeper minewater networks for dense residential zones.
- Incentivise low-carbon heating infrastructure through consistent policy frameworks, building regulations, and financial support — especially for heat network deployment and retrofitting.

By shifting how we understand and value the subsurface, cities can align thermal energy use with broader climate resilience, circular economy principles, and sustainable development objectives.

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