Geological Resources:
Perception and Impact for Enhancing Sustainability and Resilience in Urban Settings

by

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"*If people knew how hard I had to work to gain my mastery, it would not seem so wonderful at all*."

- Michelangelo

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Declaration

All work presented in this thesis is entirely the authors own. It has not been submitted in any previous application for any degree at any other university. Parts of this thesis have been published as follows:

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Abstract

Unprecedented rates of urbanisation and city growth has created many challenges such as the ability to address the impacts of climate change, manage large-scale population increases and cope with resource insecurity. As a result, cities are becoming increasingly reliant on geo-resources to support their everyday services and development. Geo-resources - naturally occurring assets of the Earth that can be harnessed to create something functional for our consumption - include; geo-materials, sub-surface space, groundwater and geothermal energy. The enhanced utilisation of geo-resources can be seen to contribute to wider policy goals of building sustainable and resilient cities.

Within this context, this study assesses the geo-resource potential of three UK case study sites by developing and implementing a novel geo-resources mapping tool. Alongside this, key stakeholder interviews were conducted, and a detailed examination of urban planning and design documentation undertaken to establish the enablers and barriers to geo-resource use in situ.

The case studies revealed that the geo-resources-potential mapping tool provided an indication of the suitability of a site for utilising a specific geo-resource, which was supplemented by an urban design geo-resource (UDG) matrix to connect the mapping results with geo-resources infrastructure and site-specific urban design guidance and planning policy information. The interview series and document examinations further identified clear factors supporting and preventing the use of geo-resources in specific urban settings. In particular, the study revealed that: costs and finance mechanisms, risks and unknowns, communication, policy, and multiple benefits are the key factors impacting geo-resource uptake.

In operationalising this research, this work provides a starting point to engage urban stakeholders with geological resource expertise and demonstrates how their utilisation can enhance the sustainability and resilience of urban settings as a whole.

List of Abbreviations

AHP	Analytical Hierarchy Process
BGS	British Geological Survey
BEGL	Below Existing Ground Level
BREEAM	Building Research Establishment Environmental Assessment Method
BSTM	Basic Superficial Deposits Thickness Model
CEEQUAL	Civil Engineering Environmental Quality Assessment and Awards Scheme
CI	Consistency Index
CR	Consistency Ratio
CS1	Case Study 1 - NW Cambridge
CS2	Case Study 2 - Chestnut and Aspen Mews
CS3	Case Study 3 - Canary Wharf Crossrail Station
CSH	Code for Sustainable Homes
EA	Environment Agency
ECO	Energy Company Obligation
EU	European Union
GSHP	Ground Source Heat Pump
GSHT	Ground Source Heat Technology
LEED	Leadership in Energy and Environmental Design
NPPF	National Planning Policy Framework
NW	North West
NWCAAP	North West Cambridge Area Action Plan
RHI	Renewable Heat Incentive
RI	Random Consistency Index
SAF	Sustainability Assessment Framework
SDG	Sustainable Development Goal
SPZ	Source Protection Zone
SuDS	Sustainable Drainage Systems
PPG	Planning Policy Guidance
PPS	Planning Policy Statement
UK	United Kingdom
UN	United Nations
UDG	Urban Design Geo-resource
WSUD	Water Sensitive Urban Design

1 - Introduction

Since 1950, there has been a 25% increase in the number of people living in urban areas (United Nations, Department of Economic and Social Affairs, Population Division, 2018). Cities around the world are evolving and expanding to accommodate this global change, however this unprecedented rate of urban growth creates many challenges for cities, such as their ability to address; climate change, population increase, geo-political tensions and resource insecurity (e.g. energy, food, water) (Moir et al.,2014). Cities are inherently complex interconnected systems and represent different concepts depending on an individuals' perspective. For example, to a place maker, cities are built for people, for transport officials cities are places to make connections and improve mobility, and to planners cities are places of mixed land uses and forms. For geologists, urban environments present conditions where natural and built systems interact bringing unique challenges associated with geohazards and difficult ground conditions. However, geologists also acknowledge the opportunities in cities to utilise hidden subsurface resources.

Geological resources (hereinafter geo-resources) are naturally occurring assets of the Earth that can be harnessed for human consumption. The four common geo-resources that are referred to in literature are: geo-materials, subsurface space, groundwater and ground heat/geothermal potential (Parriaux et al., 2006; Li et al., 2016; Admiraal and Cornaro, 2016). It is also true that ground properties (permeability, stability, soil value) are valuable geo-resources (de Mulder and Pereira, 2009) that are sometimes overlooked. Cities are commonly dependent on natural resources and consumption has increased exponentially in line with growth. For example, the United Nations Environment Program (UNEP, 2011, p.10) reported that since the start of the twentieth century, "the strongest increase [in global material extraction] can be observed for construction minerals, which grew by a factor 34, ores and industrial minerals by a factor of 27, and fossil energy carriers by a factor of 12".

In the conceptual and policy 'turn' to sustainability and resilience over the recent decades, re-affirming the relationship between cities and resources has grown important in ensuring the longevity of urban environments. Furthermore, establishing innovative methods (such as through geo-resource use) to improve the sustainability and resilience of cities is particularly relevant for developing countries where the most rapid urbanisation is predicted to occur, and where the level of urban growth that is already established in other parts of the world is yet to be fully realised.

City authorities and practitioners have turned to the concepts of sustainability and resilience to help in tackling the pressures and stresses on cities, cope with and mitigate the impact of geo-hazards, and increasingly exploit and utilise geo-resources. Sustainability is an established concept outlined (although not labelled) at the United Nations Conference on the Human Environment in 1972 (United Nations, 1972). One definition in an urban context is that a sustainable place accommodates its ""inhabitants' development needs without imposing unsustainable demands on local or global natural resources and systems" (Satterthwaite, 1992, p.3). Resilience on the other hand is a more indistinct idea that has been described as "the overarching goal of a system to continue to function to the fullest possible extent in the face of stress to achieve its purpose, where resilience is a function of both the vulnerability of the system and its adaptive capacity" (Dalziell and McManus, 2004, p.7). Some have further argued that "urban resilience is a contested concept and lacks clarity due to inconsistencies and ambiguity" (Meerow et al., 2016, p.40). There is also some debate as to whether resilience is a division of sustainability, or vice versa (Redman, 2014). However, the processes and outputs for creating urban sustainability and resilience are in many cases indistinguishable, and therefore throughout this study these terms are used interchangeably (similarly to many practitioners and policymakers [Elmqvist et al.,2019]). In implementing sustainability and resilience strategies as future-proofing concepts, both should be enhanced irrespective of the ongoing discussion on their inter-relatability, and the value of geo-resources should be considered as part of this.

1.1 The Untapped Potential of Geo-Resources

Even before the concepts of sustainable and resilient cities, communities relied on accessible and sustainable resource supplies if they were to flourish. The influence of topography as well as proximity to natural resources (such as water, forests or areas of exposed stone) are some reasons underpinning the locations of many settlements (Weiberg, 2009), which have over time grown into prosperous cities (Steinhardt, 1990). Cities built in coastal regions or near rivers commonly expanded parallel to the water body before perpendicular growth occurred, such as in New Orleans (U.S.). Other influencing geo-morphologies included hilltops or ridges (Kostof, 1991), which may originally have been chosen for settlement due to their defensive advantage (Steinhardt, 1990).

Humankind has utilised geo-resources throughout its history and has refined its methods of harnessing and consuming them as technologies have developed. For example, the first ground source heat pump (GSHP) was developed in 1912 (Sanner, 2017), and although modern day equivalent GSHPs are much more efficient and compact, this allowed many urban areas to operate independently from larger energy supply systems. With time, improvements have made shallow geothermal heat a much more accessible geo-resource which can contribute towards urban sustainability and resilience by providing additional capacity and an alternative energy supply.

As the dependency on geo-resources has increased, so too has the responsibility to manage them sustainably, although this has been achieved to varying levels of success. There has been misuse and overexploitation of some geo-resources, which has contributed to reduced sustainability and resilience of urban areas. For example, the use of subsurface space for underground infrastructure has been poorly managed over time in built-up regions (such as Birmingham Eastside prior to its redevelopment [Jefferson et al., 2006]) which has led to congestion in the near subsurface and may limit the extents to which new underground structures can span in the future (Bobylev, 2009). Another example is groundwater where, for example, contamination of the groundwater beneath Coventry (England) has been associated with historical industrial activities (Nazari et al., 1993). *With the aid of a geo-resources tool there is potential to prevent further misuse of geo-resources in cities in the future*, and refocus on building urban sustainability in balance with nature.

1.2 The Design and Planning of Sustainable and Resilient Cities

This thesis is set in the context of sustainable and resilient cities and the challenges to be addressed to reach these conditions, with a particular focus on geo-resource use. The methods required to build sustainability and resilience are specific to different countries, regions and cities, however there is a global agenda which recognises the importance of future-proofing urban areas. For example, Sustainable Development Goal (SDG) 11 of the 2030 Agenda for Sustainable Development focuses on making cities "inclusive, safe, resilient and sustainable" (United Nations, 2015a), whilst the UN New Urban Agenda focuses on policies and standards required to achieve sustainable urban development, to transform the way we live in, as well as construct, manage and operate cities (United Nations, 2017).

In the context of this increased push for sustainable development, a recent report by the UN stated that whilst "regional and local governments…are aligning their actions and initiatives toward implementation of the SDGs…the commitment to multilateral cooperation, which is central to implementing major global agreements, is now under pressure." (United Nations, 2019, p.3). For example, the implementation of sustainability and resilience agendas at an international level is shown in documents such as the SDG voluntary national reviews, but these currently evidence that "limited progress had been made at the national level in…important planning stages, including target setting, assessing interlinkages between targets, and policy evaluation. Further, limited progress is evident in terms of applying evidence-and science-based approaches to support implementation" (Allen et al., 2018, p.1457). This highlights the disconnect between global sustainability and resilience aspirations and their implementation within planning policy and practice at national level and below. In the context of this study, the utilisation of geo-resources is also affected where their potential use and value is not clearly defined at the highest levels of governance. Exploring this gap between international/national sustainability and resilience agendas linked to geo-resource utilisation in urban planning in a national context, and their adoption at local and regional levels, will illuminate lessons that can be applied in advancing more sustainable and resilient urban development in the UK.

In practice, the field of urban planning is significant in advancing sustainability and resilience agendas in cities. Urban planning is the process surrounding "land use and [the] development of buildings and infrastructure" (Næss, 2001, p.505) although its role has developed over time (Wildavsky, 1973; Alexander, 1987; Adah, 2018). In contrast, urban design is the various aspects of the built environment that make the essence of a place (Llewelyn Davies Yeang and Alan Baxter Associates, 2000), and the actions which bring urban planning to reality. Urban design plays a significant role on the path towards sustainability and resilience, and therefore its role must be incorporated into useful solutions. In the UK, urban design and construction is managed through the planning system which functions across multiple scales (national through to local) by devolving levels of governance.

Both urban planning and design elements are important towards building sustainable and resilient cities. Good urban design turns aspirational resilience concepts into infrastructure that is both functional and in keeping with the urban setting. For the UK, the Urban Design Compendium describes ones of the key aspects of urban design as the ability of a place to "work with the landscape" (ibid, p.12). This highlights the interconnectedness of natural resources with the built environment, and how the relationship between the two is important for enhancing sustainability and resilience.

Integrating geo-resources into detailed urban design and planning processes at any scale (whether it be at city, neighbourhood, site or building) can be a complex endeavour. However, bridging this divide raises awareness that the subsurface and its resources bring value to urban settings. There are various missions already promoting the profile of the urban subsurface including some government funded departments which are prioritising the issue (such as Project Iceberg, [Future Cities Catapult, 2017]). Over time, a greater sharing of information on the subsurface will enable development stakeholders to make more informed decisions on subsurface resource potential, and give them a clearer picture of subterranean conditions before initiating an intrusive ground investigation. To further improve the understanding of subsurface resources, city stakeholders should work collectively and share information on potential resources alongside potential legislative and policy changes that could enhance sustainability and resilience (Ascott and Kenny, 2019).

1.3 This Study

This project begins to bridge the gap between the development sector and geological resource experts and demonstrates how their unison can enhance the sustainability and resilience of urban areas through new and innovative planning and design. The focus is on three commonly used geo-resources: groundwater, ground heat and subsurface space where the study considers:

1. How can a geo-resource potential tool aid urban design and planning criteria and enhance urban sustainability and resilience agendas?
2. What are the current uses and perceptions of geo-resources by development stakeholders?
3. To what extent are planning policy, sustainability and resilience assessments and urban design guidance documents inclusive of geo-resources?

Each geo-resource is investigated through detailed enquiry of an exemplar case study site, with the overarching research aim of establishing:

How geological resources can enhance the sustainability and resilience of urban environments?

In operationalising this research, a multiple case study approach has been utilised due to its capacity to implement mixed methods across several complementary case study sites. For each site a number of methodologies were applied - stakeholder interviews, a document examination and the development of a geo-resource mapping model with an associated urban design geo-resource (UDG) matrix that connects the geo-resource potential maps with urban design criteria that can aid sustainability and resilience.

These methods were employed to test the influence of geo-resources in building sustainable and resilient urban environments and to garner the views of associated stakeholders as to future geo-resource use in development and construction projects. In executing these methods this study seeks to understand the needs of industry to deliver urban sustainability and resilience goals and introduce geo-resources to these strategies.

The first case study was chosen for its connection with groundwater. The wider site is known as the North West Cambridge development and the residential centre is called Eddington. The site is owned and managed by the University of Cambridge and will include 3000 new houses alongside 100,000 square meters of research space amongst other infrastructure. Part of the design incorporates the UKs largest rainwater harvesting system to support the potable water supply for the site. The non-potable recycled water is used in gardens, toilets and washing machines. Cambridge is a water-stressed region and the innovative inclusion of an urban design utilising water from a decentralised source is seen as a way of enhancing the resilience of the infrastructure and sustainability of the site.

The second case study was chosen for its utilisation of ground heat. It involved retrofitting two blocks of flats in Burton on Trent (called Chestnut and Aspen Mews) with GSHP's. The 60 residential apartments were fitted with a micro district heating network in 2015 and are independent of the mains gas supply to provide heating for the properties. The utilisation of a closed loop GSHP has positively impacted multiple stakeholders of the project, built site-specific resilience, as well as contributed to the wider sustainability agenda of the region.

The third case study was selected for its use of subsurface space. The Canary Wharf Crossrail Station in London has utilised the subsurface for the construction of the train station as well as for retail and leisure facilities. The station is 18 metres below the water level in the docks, making this structure an exceptional piece of design from a construction perspective. London is already a dense city, both in terms of infrastructure and population, and therefore building resilience into infrastructure is challenging particularly for the transport network. The potential of the subsurface for urban expansion is increasingly coming to the attention of city stakeholders, and as a result, the Canary Wharf Crossrail Station confronted a unique set of challenges for subsurface space utilisation.

1.4 Thesis Structure

The study comprises eight chapters written as an analytical narrative around three central case studies. This introduction sets the contextual relevance of the project and the significance of the research area.

Chapter 2 examines existing knowledge and ongoing research of geo-resources within the context of urban development. Following a review of the historical use of geo-resources, the ongoing debate of sustainability vs resilience (the similarities and disparities) within the disciplines of urban planning and design are explored. The concepts of sustainability and resilience are then evaluated from a geological and urban perspective, followed by the ways in which they are measured, assessed and presented. Next, this chapter explores examples of geo-resource use, the lessons learned from international practices and their relevance in a UK setting. The application of the different types of geo-resources within urban centres are investigated to examine the influence and relationship between geo-resources and societal benefits, technological developments and other natural assets.

Chapter 3 presents the overall project design and the analytical procedures undertaken for the research. The overarching approach is justified, followed by a detailed discussion of each method, including the purpose, limitations and output from each technique.

Chapters 4 – 6 contain the main results from the three case study sites relating to: groundwater (North West Cambridge), ground heat (Chestnut and Aspen Mews) and subsurface space (Canary Wharf Crossrail Station). Each case study provides an outline of the geo-resource setting and urban design concepts, the results (and review) of the geo-resources potential mapping tool, an evaluation of the enablers and barriers for effective implementation on site and an examination of the documents impacting the development.

Chapter 7 brings together previous chapters, discussing the cross-cutting themes and findings for all three geo-resources. The implications and interconnecting observations are reviewed as well as the lessons learnt from each analysis and an evaluation of the geo-resource potential tool.

The thesis is concluded in chapter 8 by returning to the research aims and summarising the main outcomes of this study. The value of geo-resources is presented within the framework of sustainable and resilient urban development.

2 - Geo-resources in Sustainable Urban Design and Planning : A Literature Review

2.1 Introduction

Geo-resources have always had a significant impact upon the processes of urbanisation. As urban historian Lewis Mumford (1961) noted in *The City in History*, “the shaping of the Earth was an integral part of the shaping of the city” (p.26). From the siting of settlements in particular topographical locations, to the exploitation of the substrate for building materials, storage, or heat and water (Weiberg, 2009), an understanding of geological conditions has been key to sustaining urban settlements and in mitigating the impact of natural hazards through innovative design solutions, for example, for protection against floods and earthquakes. In time, the morphology of cities has evolved as a more concentrated amalgam of buildings and infrastructure, focused upon trading or industry, the latter often involving the extraction of geo-resources. With the rapid decline of heavy industry in the Western world in the second half of the twentieth century (Rowthorn, 1986) (and industries outgrew the city preferring larger rural locations and cities transitioned to tertiary employment), the utilisation of geo-resources moved from the centre to the periphery of attention as far as city managers were concerned.

In more recent years renewed attention has been paid to how a greater appreciation of underlying geology within the design and planning of urban areas can contribute to disaster resilience from a range of natural hazards. These can be categorised as either geological (such as earthquakes and landslides) or hydro-meteorological hazards (such as flooding and drought), the prevalence and intensity of which has been significantly altered by climate change (Intergovernmental Panel Climate Change, 2014). Equally, and of most importance to this research, a revived interest in urban geo-resources has been stimulated by a concern for resource scarcity (Lehmann, 2015) and the need for careful management and diversification of resources to sustain a dependable supply.

The risks and opportunities associated with these issues are key drivers in the increased policy and academic interest in sustainability and resilience agendas for urban environments. International programs of city resilience building have become popular in recent years with the acknowledgement that “cities can be understood as complex-adaptive systems” (Olazabal, 2017, p.73), and require fundamental changes in design and governance to futureproof themselves from a range of shocks and stresses (Coaffee and Lee, 2016). These international approaches are commonly operationalised at the city scale through action plans (for example, for climate change, infrastructure protection, energy efficiency) and general frameworks of assessment that seek to spot the gaps that need to be plugged in sustainability and resilience efforts as well as catalysing more holistic working practices amongst those stakeholders involved in delivery of city services. Whilst there is emerging evidence that such integrated approaches have been successfully institutionalised at the city scale and embedded into design and planning practices, it is also clear that geological understanding seldom informs decision-making processes in urban planning, (Culshaw and Price, 2011; Chand, 1998) despite the role of geology in sectors such as flood risk, minerals planning, and geological hazards.

The proactive use of geo-resources in urban settings is thus a relatively novel research area with many innovations still in their infancy, yet is becoming increasingly important to broader discourses and practices of urban sustainability and resilience. To understand how to enhance the sustainability and resilience of cities through geo-resource utilisation, this chapter first explores the role of geo-resources from historical times up until modern day where the components of urban infrastructure are influenced by geo-resource use. Second, the concepts and practices of sustainability and resilience are unpacked and examined in international policy as well as in terms of how they are assessed and measured. Third, exemplar sites demonstrating geo-resource utilisation which enhances urban sustainability and resilience are then presented for several key geo-resources before the current status of geo-resource utilisation is explored in the UK. To conclude this chapter, a fourth and final section brings together a set of challenges hindering the optimisation of geo-resource use for advancing urban sustainability and resilience, and which will form the basis of the methodological and analytical frameworks used in the rest of this thesis.

2.2 A Brief History of Geo-resource Use

Communities have been influenced by the availability of natural resources since the Stone Age when humans first decided to settle. The availability of these geo-resources (building materials and water) influences the form and growth pattern that a settlement could take. Bandarin and Oers (2015) describe how historical settlements used geo-materials as building resources for clay based, soft-rock based and hard rock-based construction. These construction methods are examples of temporal isolation where a single urban form exists due to the way that available geo-resources are harnessed.

The Romans were one of the first peoples to develop new ways to exploit geo-materials. Their innovative use of numerous types of building stone led to the mass production of bricks, and following this the rapid growth of settlements. In early and late industrial towns and cities, the ability to exploit geo-resources were far more complex and were driven by technological and infrastructural advances. The development of mass-transport is one such advancement that allowed the movement of geo-resources for use in urban areas. Since the 16th century, canals, rivers and harbours have allowed the movement of materials, the railway network was constructed across Europe by 1875, and seaports were constructed on an industrial scale from the 1960s (Antrop, 2004). Historic England (2008, p.4) have emphasised that "the exploitation of mineral resources and allied technological innovation were fundamental to the early development of Britain's manufacturing industry during the Industrial Revolution". However, these advancements have left a legacy of buildings and infrastructure of varying ages near one another, particularly where newer infrastructure has been constructed to fill the spaces left in-between historical phases of development. This has left a historical overlay of urban design within longstanding urban centres, which makes assessing contemporary geo-resource usage challenging on a granular level where every building is different in size, age, use and makeup.

The evolution and growth of settlements from small dwellings into todays' complex towns and cities has increased the pressure on subsurface resources to meet the demands of expanding urban populations and economies. For example, at the start of the 20th century, many urban designers and urban planners considered the underground to be an obstacle to urbanisation (Doyle et al. 2016) whilst today subsurface space are coming to the attention of researchers for its potential in creating more sustainable and resilient cities (Legget, 1987; Doyle, 2016).

Increasingly, today, cities are relying on geo-resources to support everyday functions. This applies even more so where cities do not have the space to outwardly expand and must densify, putting an even greater stress on often scarce geo-resources. Consequently, there is an emergent requirement to further our understanding of the potential uses of geo-resources in the context of sustainable and resilient urban design and planning. One exemplar initiative of this is Project Iceberg, a collaborative effort between the British Geological Survey, Ordnance Survey and Future Cities Catapult that reviewed the market drivers and technology requirements for an integrated city data framework that allowed for the inclusion of subsurface assets, and is attempting to narrow the knowledge gap through information dissemination (Future Cities Catapult et al, 2017a).

Subsurface geo-resources can be considered in four main groups; underground space, groundwater, geothermal energy and geomaterials (Parriaux et al., 2006; Admiraal and Cornaro, 2016; Hunt et al., 2015). De Mulder and Pereira (2009, p.26) further expanded on these four categories to include "land, soil, water, minerals, energy and underground space,

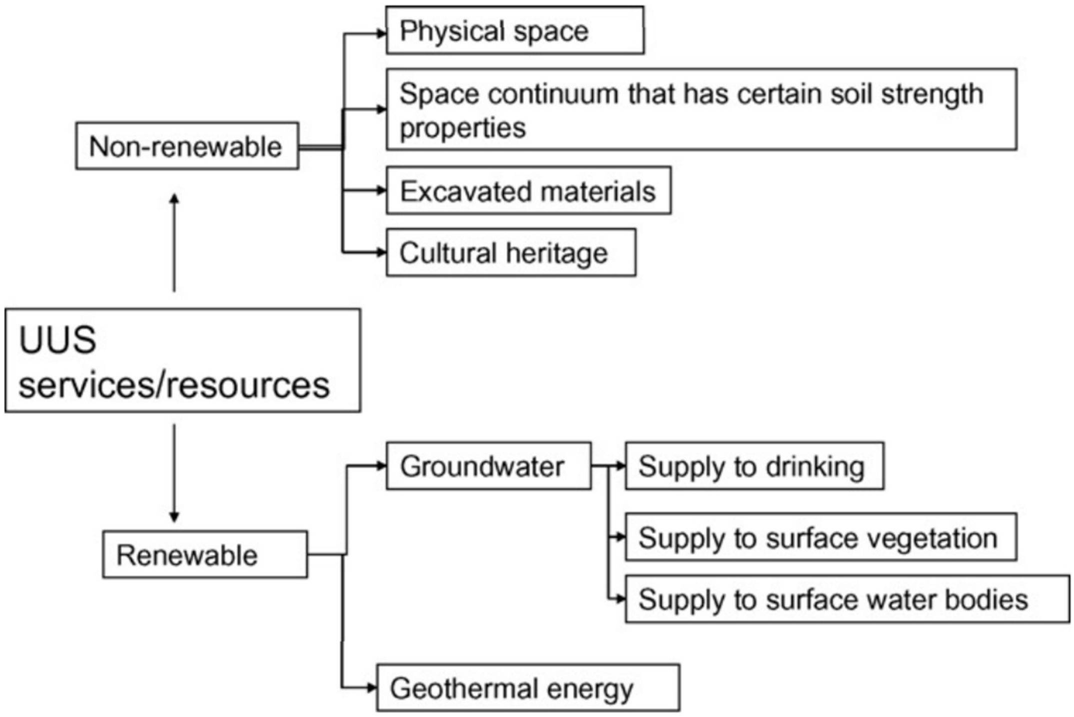


Figure 2.1 – Types of geo-resources (Bobylev, 2009, p.1131).

among others". Bobylev (2009) further delineates geo-resources into renewable and non-renewable assets (Figure 2.1).

Separating the subsurface into these categories allows their importance to be explored individually for their role in urban sustainable development in general, and more specifically, how geo-resources are important determinants of the ability to operate critical urban infrastructure. This study focuses on groundwater, ground heat and subsurface space to examine geo-resources in a UK context. The UK government defines critical infrastructure as "those critical elements of infrastructure (namely assets, facilities, systems, networks or processes and the essential workers that operate and facilitate them), the loss or compromise of which could result in… major detrimental impact on the availability, integrity or delivery of essential services – including those services, whose integrity, if compromised, could result in significant loss of life or casualties – taking into account significant economic or social impacts" (Cabinet Office, 2016, p.3). The energy, food and water sectors particularly can utilise geo-resources to enhance the sustainability and resilience of critical infrastructure.

Geo-resources have the potential to enhance the resilience of the energy sector through the delivery of an independent ground heat source. The ability to draw heat from (and store heat in) the ground via ground source heat technology could provide an alternative to traditional mains gas supplies with options for decentralised systems or linked systems as part of district heat networks. Furthermore, due to physical properties of the ground (soil and rock), in many places it forms a porous (or permeable) media, where the pore spaces act as a store for e.g. water and gases. The Sector Resilience Plan summary report (Cabinet Office, 2016, p.18) describes the need to "build a better understanding of the capabilities within the industry to re-route water supplies from other parts of water networks" and "build a wider knowledge-base of the resilience of water supply assets to flooding". These can be supported by ground properties as well as through urban design initiatives such as water-sensitive urban design and sustainable drainage systems (SuDs). SuDs are an example of an urban intervention which encourages the infiltration of water into permeable ground, increasing water storage and helping to lower flood risk. Ground properties are also relevant for other geo-resources as they determine: how water and heat flow through the ground, what types of vegetation grow, and how easy it is to construct or make use of underground space. Geo-resources can play a vital role in the food industry, by providing local geo-materials to produce fertiliser and delivering land space to reduce the risk of short supply.

The energy, food and water sectors demonstrate only a peripheral role for geo-resources in enhancing the resilience of critical infrastructure. However as discussed above, there are areas where geo-resource utilisation has the capacity to enhance urban sustainability and resilience which have not been mainstreamed. The same general underutilisation of geo-resources is also true in the fields of urban design and planning (Pitidis et al., 2018). Susan Fainstein, a professor of Urban Planning at Harvard University defines planning as the, "design and regulation of the uses of space that focus on the physical form, economic functions, and social impacts of the urban environment and on the location of different activities within it….Urban planning concerns itself with both the development of open land ("greenfields sites") and the revitalization of existing parts of the city, thereby involving goal setting, data collection and analysis, forecasting, design, strategic thinking, and public consultation" (Fainstein, 2020). Often considered aligned to urban planning, it is through innovative urban design, set within a framework of planning that can connect geo-resource utilisation with wider visions of urban sustainability and resilience. For example, the installation of a ground source heat pump can help meet city-wide sustainability and resilience targets by providing and additional and stable supply of energy, further highlighting the unexploited potential of geo-resources in urban development.

Where geologists have been included in urban design and planning decision-making in the construction industry, they have tended to contribute primarily by indicating geo-hazard risk at the foundation design stage. Burton et al. (1993, p.252) suggested that "hazards and resources are uniquely related; people encounter hazard in the search for the useful". However, even though geo-hazards (such as landslides or rock dissolution) are types of shocks which lessen the sustainability and resilience of cities, the management of geo-hazards is much better defined in the fields of urban design and planning than the utilisation of geo-resources. That said, geologists are beginning to contribute towards the wider agenda of city sustainability and resilience but the importance of such a role needs to be re-enforced to maximise the potential impact of geo-resource utilisation on urban goals.

2.3 Sustainability and Resilience

City challenges are often the driving force behind urban sustainability and resilience agendas. The two concepts are heavily discussed in literature, such as definitions, purpose and applications (Holling, 1973; Gordon, 1978; Holling, 1996; Walker et al., 2004; Brand and Jax, 2007; White and O'Hare, 2014; Roggema, 2014; Burton, 2014; Shim and Kim, 2015). They are frequently compared for their connections and disparities, but neither have a universally accepted definition. Sustainability is commonly associated with the Brundtland Report definition which stated that "sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (World Commission on Environment and Development, 1987). One common model of urban sustainability is the three pillars: environmental, economic and social (Wu, 2010), however there are many others conceptual models as summarised in Figure 2.2.

These models are semantically debated however all demonstrate the interdependence across sectors for delivering sustainability and express the need for integrated and coordinated responses both now and in the future (Kaur and Garg, 2019). Establishing best practice principles for these sectors provides a comprehensive approach to apply in different urban settings that could be tailored to suit specific urban challenges where required.

Resilience on the other hand is a versatile concept for growth and stability of natural ecosystems (Holling, 1973; 1996) which has more recently been applied to the study of cities

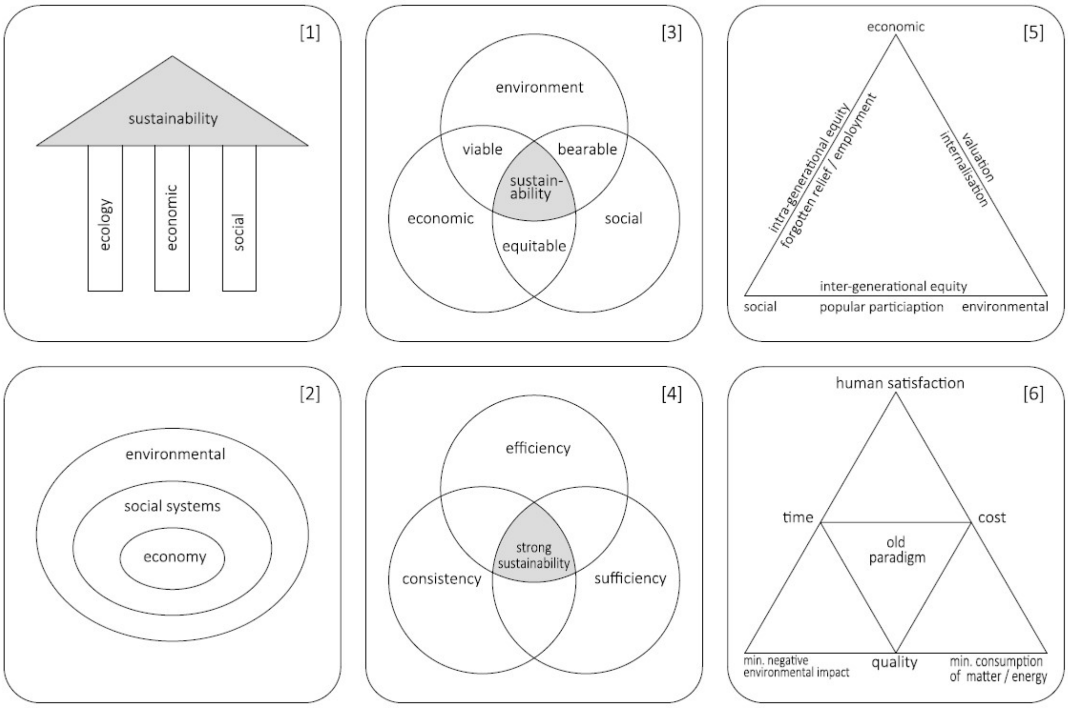


Figure 2.2 – Conceptual models of sustainability (Ali-Toudert and Ji, 2017).

(Coaffee and Lee, 2016; White and O'Hare 2014). The definition of resilience used in this study will be considered analogous with the that of the 100 resilient cities framework, where resilience is viewed as an adaptive and transformative goal and as "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience" (Resilient Cities Network, 2020). This includes seven qualities of resilience and the capacity of a system to be: reflective, robust, flexible, integrated, resourceful, redundant and inclusive (which encompasses the context of city geo-resource management). Whilst many consider resilience little more than a "vacuous buzzword" (Rose, 2007, p.384) or "a hollow concept for planning [and] an empty signifier which can be filled to justify almost any ends" (Porter and Davoudi, 2012, p.329), others uphold that with the "success of the concept [has been] in stimulating research across disciplines"(Brand and Jax, 2007, p1) and incorporating the study of alternative futures and holistic decision-making into urban planning and design (Coaffee and Lee, 2016).

Increasingly, sustainability and resilience are two concepts that have become entwined through their broad definitions and mixed of uses. Walker and Salt (2006, p.9) argued that "the key to sustainability lies in enhancing the resilience of social-ecological systems, not in optimizing isolated components of the system" whilst Leichenko (2011, p.166) claimed that "the idea that resilience is a positive trait that contributes to sustainability is widely accepted". These uses of sustainability and resilience suggest that the understanding of the relationship between the two concepts depends on the context. Some authors consider the two terms in unison and interchangeably as they are perceived to contribute towards a similar result. For instance, Williams (2014, p.10) defines "'successful' urban forms' as 'elements of broad conceptualisations of sustainability and resilience, and are defined as those that: underpin the functioning of an array of urban systems, use resources sustainably, and provide a sound economic base that provides the setting for a good quality of life for their inhabitants. In addition, they can withstand shocks and 'bounce back' or improve their conditions post-shock (whether that shock be environmental, economic, or social)". As previously described, this study considers both sustainability and resilience as concepts for future-proofing urban settings, and therefore are used interchangeably. The two ideals work in harmony to optimise the relationship between natural resources and urban growth, representing aligned aspirations which allow the terms to be used collectively for this research. The blending of these terms is also evident in wider policy discussions with the UN 'Urban' Sustainable Development Goal (SDG) 11 seeing the enhancement of resilience as an integral part of the pursuit of urban sustainability.

In essence, sustainability and resilience are projecting an analogous set of principles, some of which are focused on specific outcomes (such as environmental standards or resource protection) but generally (when used in an urban context) are presenting a similar series of ideas. Semantic arguments to define sustainability and resilience are always possible (whether it is maintaining a state, bouncing back or bouncing forward, etc) and the multiple definitions can misconstrue take-home messages (Meerow et al., 2016; Folke, 2006). This debate is beyond the scope of this study and therefore in the context of urban design and planning, the definitions of sustainability and resilience as described above have been assumed for this research. Bringing these terms together expands the outlook of urban frameworks for advancing sustainable development and opens up a space by which non-traditional knowledge and stakeholders, such as geology and geologists, can be incorporated in design and planning decision-making processes.

2.4 The International Setting of Sustainability and Resilience in Cities - A Geological Perspective

In seeking to incorporate geo-resource thinking into (UK) urban sustainability and resilience assessment methods and governance it is important to understand the scope and scale of existing assessment frameworks and to identify appropriate places where knowledge from geology can be best applied.

One well known strategy is the 2030 Agenda for Sustainable Development. This comprises a series of goals aiming to establish sustainable futures across many areas including health, energy and climate change. SDG 11 is based exclusively on cities and settlements, and amongst several objectives aims to “by 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries” (United Nations, 2015b). Other targets for urban sustainability are based on housing standards, transport, disaster risk and environmental impacts. These target areas often fall under different sectors of urban governance; however, the SDG is well known in urban sustainability forums which facilities collaborative working to achieve the goals.

SDG 11 acknowledges resource efficiency in one of its objectives, however SDG 12 focuses solely on natural resources as it seeks to “ensure sustainable consumption and production patterns”. More specifically, “by 2030, achieve the sustainable management and efficient use of natural resources” (United Nations, 2015c). More specifically, Gill (2016) summarises the inclusion of geology in the SDG’s by grouping aspects of geological science and indicating which are required to achieve the different SDG’s. In a similar fashion, geo-resources can be grouped into aligned topics and considered in contribution to the SDG’s as shown in Figure 2.3 below. Coloured squares indicate that the geo-resource may contribute towards the relative SDG in the matrix.

Gill (2016, p.74) concludes that there is a “need for input from geologists, in a variety of forms, in all of the goals”, which is also true when considered from the perspective of geo-resource use within the context of urban planning and design. It is worth noting that this matrix approach is a subjective form of review, and it can be interpreted differently by others and in other contexts, although the underlying finding is likely to endure.

In addition to this, a global effort was renewed in 2016 when members of the UN General Assembly attended Habitat III to progress efforts towards sustainable urban development. The output was a report detailing the New Urban Agenda which contains a list of principles and commitments. One of these commitments was to “environmental sustainability, by promoting clean energy, sustainable use of land and resources in urban development as well as…promoting sustainable consumption and production patterns [and] building urban resilience” (United Nations, 2016, p.8). The report continues to discuss resilient urban

Goal Number	Sustainable Development Goal - Summary	Sustainable Development Goal - Detail	Geological resources: Groundwater	Geo-materials	Geo-thermal energy	Underground space	Ground properties	landspace/ topography
1	No poverty	End poverty in all its forms everywhere	■	■	■			
2	No hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	■	■		■	■	■
3	Good health	Ensure healthy lives and promote well-being for all at all ages	■					
4	Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all						
5	Gender Equality	Achieve gender equality and empower all women and girls						
6	Clean Water & Sanitation	Ensure availability and sustainable management of water and sanitation for all	■	■		■	■	■
7	Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all		■	■	■		■
8	Good Jobs & Economic Growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all				■		
9	Innovation & Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	■	■	■	■	■	■
10	Reduced Inequalities	Reduce inequality within and among countries						
11	Sustainable Cities & Communities	Make cities and human settlements inclusive, safe, resilient and sustainable	■	■	■	■	■	
12	Responsible Consumption	Ensure sustainable consumption and production patterns	■	■	■	■		
13	Protect the Planet	Take urgent action to combat climate change and its impacts acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change.		■	■			
14	Life Below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	■					
15	Life on Land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	■	■				■
16	Peace & Justice	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels						
17	Partnerships for the Goals	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development						

Figure 2.3 – A visualisation of how geo-resources may contribute towards the Sustainable Development Goals (concept based on Gill, 2016).

development and recognises that the sustainability and resilience performance of an urban area is affected by the ways that cities are "planned, financed, developed, built, governed, and managed" (ibid, p.18). Furthermore, the report identifies that geo-resources can aid urban sustainability and resilience, for example through ecosystem and environmental services, however as this is a very broad framework and the details are not discussed in depth.

Many organisations and governments have worked towards practices that begin to deliver and assess sustainability and resilience in the context of urban design on a national scale. For example, China is experiencing a period of rapid urbanisation and has developed twelve green guidelines that promote the sustainable growth of cities and alleviate many of China's biggest challenges (Huang et al., 2015). These twelve guidelines are categorised into three themes: urban form, transportation and energy and resources as shown in Table 2.1.

Theme	**Green Guideline**
Urban Form	Urban Growth Boundary
Urban Form	Transit-Orientated Development
Urban Form	Mixed Use
Urban Form	Small Blocks
Urban Form	Public Green Space
Transportation	Non-Motorised Transit
Transportation	Public Transit
Transportation	Car Control
Energy and Resources	Green Buildings
Energy and Resources	Renewable and District Energy
Energy and Resources	Waste Management
Energy and Resources	Water Efficiency

Table 2.1 – A summary of China's twelve green guidelines and their categorisation (amended from Huang et al., 2015).

This plan demonstrates the main areas and thoughts that city practitioners consider to achieve sustainability in cities in China, but are also representative of many of the concerns in cities around the world. According to this plan, geo-resources can impact the energy and resources sector most successfully due to the overlap of green guideline categories and geo-resource utilisation potential (for example achieving water efficiency by utilising groundwater within urban design).

The ubiquitous reference to sustainability resilience within international policy is encouraging for the outlook of future cities, however the methods of actioning resilience need to be better defined and assessment methods clarified. One notable exception is the 100 resilient cities framework that said resilience "enables cities to evaluate their exposure to specific shocks and stresses, to develop a proactive and integrated plan to address those challenges, and to respond to them more effectively" (Arup and Rockefeller Foundation, 2015, p.2). The framework was created to provide an understanding of the complexity of city systems. It defines four sectors of urban resilience: health and wellbeing, leadership and strategy infrastructure and environment and economy and society. Each sector has three actions that cities are targeting to enhance their resilience, and the seven qualities of resilience are the characteristics that contribute towards this. Their first report published in October 2016 demonstrated the approaches being implemented in early-adopter cities. For example, New Orleans have started to enhance resilience to address: flooding, post-disaster damage (Hurricane Katrina in 2005) and improvements to housing by implementing projects that introduce resilience growth such as the Gentilly Resilience District project, focused on addressing water management across the city (Arup and Rockefeller Foundation, 2019).

Another approach from a conceptual resilience perspective is suggested by Roggema (2014) which incorporates a flexible approach to city design known as a dismantable city. This idea considers the concept of urban metabolism (Wolman, 1965) as a basis for quantifying city systems. The city is fed by resources and affected by man-made and natural pressures with outputs creating a city network connected by human well-being, environmental quality and waste management. This flow delivers the parameters for measuring the sustainability and resilience of a city, providing they can be modified when subjected to stresses and shocks. Roggema (2014, p.465) further envisages the city with "the potential to spontaneously and unpredictably develop new forms and structures by itself out of chaos" as portrayed by Merry (1995). The idea focuses on being able to disassemble structures and re-develop or re-use them to suit changing city needs.

Furthermore, from a geo-resources perspective, there are geo-resources which may be considered at a city scale (such as subsurface space use), and there are geo-resources to be considered at a wider catchment scale (such as groundwater). Groundwater management may not be suitable at a city scale as it is dependent on processes operating at the river-catchment scale and is legislated at such scales (e.g. Water Framework Directive). However, subsurface space is a stationary geo-resource that can be easily delineated and managed locally. Both can contribute towards urban sustainability and resilience, however the scale of assessment (and its impact) should be considered in the context of urban metabolism.

Although these ideas are proposed for enhancing urban sustainability and resilience, the actual activities taken to achieve these can vary massively (along with the perceived importance of taking action). In the UK, the ongoing interpretation of sustainability and resilience in the context of city planning has changed the way that urban stakeholders operate. Sustainability and resilience are intrinsic to urban design for climate change and extreme weather preparedness, resource management and future-proofing systems. Some concepts are beginning to translate into practise through policy and design guidance, however applying resilience has many hurdles to contend with, many of which require stakeholder investment for a worthwhile result. For example, sustainable drainage systems (SuDs) have become well-known for sustainable water management, with national, regional and local policy enforcing their implementation across the UK, and stakeholders conforming to this. However, Coaffee and Lee (2016, p.268) highlighted that "there is a need to move beyond siloed governance approaches. Policies should include new innovative approaches that support multi-scale and multi-sector action". Although fragmented governance is a significant issue that is hard to resolve (particularly in the UK which has part-privatised public services), even if collaborative approaches were being encouraged by urban networks.

2.4.1 Measuring Sustainability and Resilience (and Incorporating Geology)

Increasingly, such governance decisions are informed by a plethora of detailed measurement and assessment frameworks for urban sustainability and resilience. The principles of assessment frameworks are "for supporting decision-making and policy in a broad environmental, economic and social context, and transcends a purely technical/scientific evaluation" (Sala et al., 2015, p.314) and is commonly "assessed on quantitative and qualitative indicators at different spatial scales from building to neighbourhood to an entire city/urban level" (Kaur and Garg, 2019, p.148). In practice many such frameworks attempt to bring sustainability and resilience concepts to actions by measuring and focusing on targeted subjects (such as environmental or energy) and often contain indicators to quantify features (Prior and Hagmann, 2013). If done universally, these systems allow sustainability and resilience measures to be benchmarked and compared globally against other schemes. It is the intention of this research to adapt these types of approaches in the utilisation of geo-resources, where factors which impact the geo-resource uptake potential act as key measurable indicators. For example, for the use of subsurface space, the geological conditions, hydrogeology (e.g. groundwater levels) and engineering properties (e.g. ease of excavation) are all indicators for potential subsurface space utilisation.

Whilst in some cases a qualitative interpretation may be adequate in describing the resilience performance of many systems or outcomes, some sustainability and resilience scenarios benefit from numerical results and quantitative approaches to assessment. For example, in 1990 the Building Research Establishment (BRE) created a scoring-based numerical sustainability assessment (BREEAM) for new buildings to measure their performance across several categories of sustainability challenges (Lee and Burnett, 2008). In subsequent versions, two of the assessment categories are geo-resource-related (materials and water) and form part of the assessment in the overall sustainability rating of the build. This tool was the first of its kind to be established for commercial use in the United Kingdom. In one comparative study, Matthews et al. (2014) conducted a search for sustainability assessment framework (SAF) tools which revealed 62 different methods worldwide with BREEAM and LEED (the US equivalent to BREEAM) being the most popular. This study further explored the presence of hazard resilience within an array of SAF tools and concluded that resilience is "not strongly or systematically integrated throughout SAFs" (ibid, p.65), which has "the potential to lead to the design of structures and communities that are vulnerable to the impacts of extreme events" (ibid, p.60). Sharifi and Murayama (2013) similarly analysed seven Neighbourhood Sustainability Assessment tools to find a way to measure their efficiency. It is concluded that there are issues with both the effectiveness and implementation of these mechanisms, namely that "most of the tools are not doing well regarding the coverage of social, economic, and institutional aspects of sustainability; there are ambiguities and shortcomings in the weighting, scoring, and rating; in most cases, there is no mechanism for local adaptability and participation" (Sharifi and Murayama, 2013, p.73).

Urban sustainability and resilience assessments are discussed by Coaffee and Lee (2016, p.130), who found that is it the "combinatorial, dynamic and evolutionary nature of urban resilience that requires measurement – a task perhaps better undertaken through a mixed-methods approach involving quantitative and qualitative measures". This notion is further demonstrated by Cutter et al., (2008) who separated resilience measuring into two steps – first to quantify conditions using indicators, and second to employ the approach in a practical scenario. Implementing a combination of techniques to measure urban sustainability and resilience is advocated as advantageous in these findings. Analytical approaches to assessing sustainability and resilience include: scorecard methods, suitability mapping, geospatial analysis, statistical analysis (such as Spatial Decision Support System (SPSS)) and Analytical Hierarchy Process (AHP)).

The scorecard mechanism is demonstrated by the Disaster Resilience Scorecard for Cities developed by the United Nations Office for Disaster Risk Reduction (UNDDR). Although an international strategy, this method allows local authorities to consider ten aspects of resilience for cities, and assign scores based on specific indicators. For instance, in the context of geo-resources, the preliminary assessment indicators identified to “Safeguard Natural Buffers to Enhance the Protective Functions Offered by Natural Ecosystems” include an awareness and understanding of the role of natural capita, but also the incorporation of blue/green infrastructure in urban design projects (UNDRR, 2017).

Another mechanism for marrying sustainable urban growth with geological characteristics is suitability mapping. Wassing and Van Der Krogt (2006) presented a spatial mechanism for optimising urban development by assigning weights to geological conditions in different urban scenarios. This technique involved identifying relevant geological base maps and applying suitability scores. Maps were then weighted based on the type of urban development and categorised into one of four scenarios defined by an urban planner. These linear scenarios suggest a single ideal outcome (for example to be sustainable or economical or efficient) which may not be appropriate for widespread implementation.

The development of these tools utilises aspects of geospatial and statistical data analysis, which although can be undertaken in a freestanding method are more effective when integrated into applied techniques. These different approaches for measuring and assessing are underpinned by assumptions and commonalities such as; a basic knowledge of sustainability and resilience agendas in cities and the ways in which they can be met, an understanding that communication and coordination will be essential and ultimately that sustainability and resilience are considered to be of equal importance to all urban stakeholders. In practice, assessing urban sustainability and resilience is performed in different contexts dealing with distinct types of resilience. These assessment techniques allow, in theory, different stakeholders that function at different scales to evaluate and join up their thinking and measure how their scheme is performing when compared to other projects or locations. Assessing sustainability and resilience performance in these ways can highlight the weaknesses, strengths and potential that exist in an urban context, and allow knowledge to be transferred from past experience.

Such frameworks are one way of beginning to bridge the gap between urban sectors, connecting resource planners, environmental engineers, architects, and urban designers (amongst others) by encouraging all to think beyond their area of expertise. However, as previously discussed, the relevance of geo-resources to urban sustainability and resilience is often downplayed in many of these methods and their potential utilisation rarely considered and understood in the context of city systems. A tool to assess the potential suitability of an area from a geo-resources perspective integrated with urban policy and guidance agendas would be a first step in helping to address this gap.

2.5 Geo-resource Utilisation

Physical evidence of the successful integration of geo-resources in urban settings to enhance sustainability and resilience can be observed in isolated projects for the different geo-resources. This section first examines geo-resources based on their sub-categorisation, and second explores their trajectory into urban settings and how the perception of geo-resources has impacted their use. Emerging examples of geo-resource exploitation and their incorporation into bespoke settings and planning at a range of scales are presented. The primary focus is on the geo-resources explored through case studies in the main chapters of this research: groundwater, ground heat and subsurface space. Other geo-resources are also briefly discussed.

2.5.1 Groundwater

Groundwater plays an important role in the functionality of cities. According to Döll et al., (2011, p.143), “the source of 35% of the water withdrawn worldwide (4300 km^3/year during 1998–2002) is groundwater. Groundwater contributes 42%, 36% and 27% of water used for irrigation, households and manufacturing, respectively”. The role of groundwater in urban settings is evident in cities where water plays a central role to its function. For example, Caroli and Soriani (2017) discuss the relationships that Venice and Tokyo have with water. Land space in these cities is in short supply and therefore extensions have been constructed within both cities to create additional land space over water. Furthermore, the cities close associations with water have led to the development of comprehensive flood management programs in order to minimise the threats of flooding (ibid). In both cases water is an integral part of city systems and therefore they demonstrate the partnership between urban design and water for sustainable development.

The sustainable management of groundwater is often facilitated by the integration of water-conservation techniques in urban design. Water Sensitive Urban Design (WSUD) is one established process in delivering water sensitive cities (Ashley et al., 2013). WSUD approaches consider the different component of the water cycle and its interaction with urban environments and seek to optimise urban form to suit the context of water conservation. For example, installing green roofs reduces runoff and enrich the ecology, or installing water butts provides water for use in gardens or car washing and creating savings on water bills (Morgan et al., 2013). Vietnam is one such country investing in WSUD infrastructure and reaping the benefits. The Tan Binh Riverside in Ho Chi Minh City is utilising WSUD to create a residential area. The urban regeneration project is increasing the capacity of the canal, better defining the potential floodplains, renovating the water embankments, and applying WSUD concepts across the region for regeneration purposes as shown in Figure 2.4 (Asian Development Bank, 2019). This demonstrates how the management of water as a key geo-resource can be integrated into the urban setting to accommodate city expansion.

A key problem with conventional water management is that "traditional engineering of water and wastewater systems is still often institutionally fragmented, while operationally centralised and constrained by a problem-solving rather than opportunistic approach" (Ashley et al., 2013, p.66). The role of urban governance is thus important in establishing the relationship between urban settings and water. Minnesota is a US state that is reliant on groundwater to provide three quarters of its drinking water (Minnesota Pollution Control

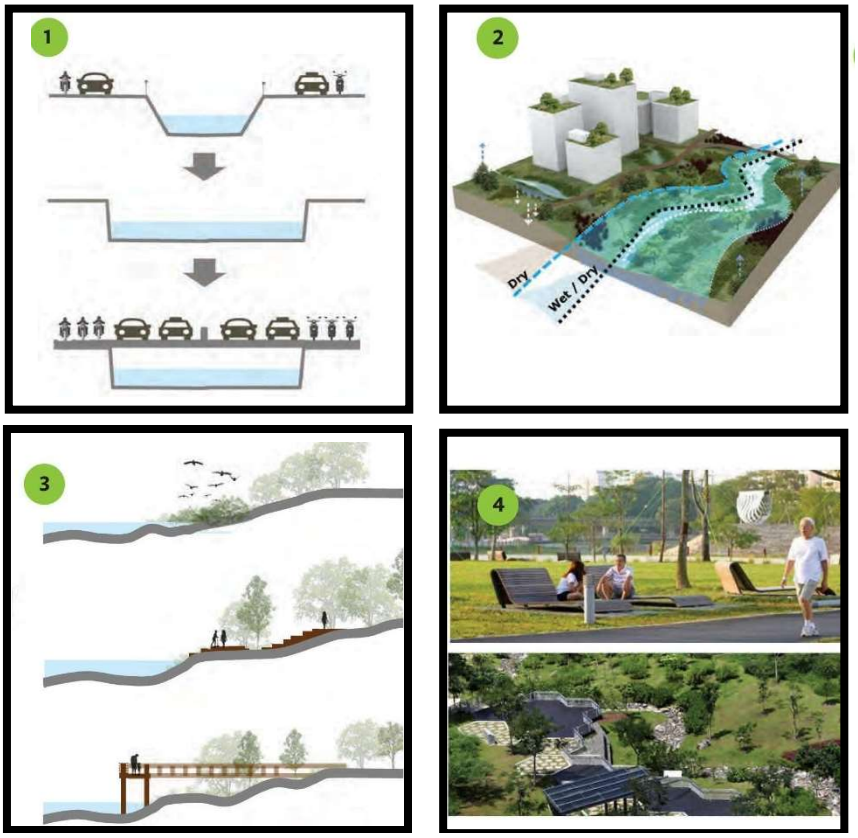


Figure 2.4 – Water Sensitive Urban Design (WSUD) in practice in Ho Chi Minh City. 1 – upgrade of canal, 2 – define floodplains, 3 – renovate waterways, 4 – WSUD tools (amended from Asian Development Bank, 2019).

Agency, 2020). In light of this (and the potential vulnerability this presents) the Department of Natural Resources established a strategic groundwater management plan to increase the sustainability of the groundwater resources (Minnesota Department of Natural Resources, 2013). The plan focuses on the position of governance, prioritising management techniques, data gathering and availability, improving the groundwater permits system, increasing awareness and enforcement of regulations, improving stakeholder communication, co-ordinate with other organisations and endorse water conservation techniques. These targets are being measured by numerous indicators which include water levels (being within sustainability thresholds) and the number of groundwater users implementing conservation techniques and obtaining permits (Minnesota Department of Natural Resources, 2013). This high-level document is adopted by regional and local action plans. Such management plans and actions such as WSUD can be seen to enhance sustainability and resilience by embedding their principles within wider urban systems of strategic planning and design.

In the UK, such approaches are on the increase, but hindered in part as a result of historically fragmented governance in both water management and spatial planning. Water has been managed for hundreds of years in the UK, with piped water first appearing in England during the 15th century (Ofwat, 2020). Technological advancements have allowed mass utilisation from UK subsurface resources (Shepley et al., 2012) and nowadays "approximately one third of public water supplies in England and Wales, 6% in Northern Ireland and 3% in Scotland come from groundwater" (The Geological Society of London, 2014). Currently aspects of groundwater management are shared across three broad authorities in the UK: the government, the Environment Agency (EA) and water companies (Environment Agency, 2016). The water sector was privatised in the UK in 1989 (Department for Environment, Food and Rural Affairs, 2015a) and Ofwat (a UK government department) regulates the water industry by demanding that providers publish a water resources management plan (WRMP) detailing how they will provide water to their customers for the next 25 years without imposing detrimental effects on natural resources. This is achieved by predicting water supply and demand and implementing appropriate measures to govern them. Where demand exceeds supply the relationship between water and cities must be carefully managed through urban design and infrastructure. For example, by locating and repairing leaking pipes, increasing metering and finding new resources (Department for Environment, Food and Rural Affairs, 2017).

Furthermore, for groundwater to be a usable resource it must be of sufficient quality for consumption. The Environment Agency (2006) estimates that "around 81 per cent of groundwater bodies in England and 35 per cent in Wales are at risk of failing Water Framework Directives objectives because of diffuse pollution". For example, the groundwater present beneath Coventry, in the West Midlands, is subjected to pervasive pollution, and although groundwater remediation would be expensive measures could be implemented to improve the groundwater quality for use (Nazari et al., 1993).

Groundwater is a dynamic resource which varies locally in availability, and therefore groundwater modelling has been crucial in working towards and effective governance of groundwater resources. As Shepley et al (2012 p.2) highlighted, “the need for a national framework of groundwater modelling…led the Environment Agency to embark at the end of the 1990s on a large programme to develop conceptual and numerical models of the principal bedrock aquifers of England and Wales and their associated superficial deposits”. From here the Environment Agency developed a licencing strategy for the abstraction and discharge of groundwater resources which dictate what volumes of water are permitted and when. This allows groundwater utilisation to be managed by a single authority on a national scale.

2.5.2 Ground Source Heat

Ground source heat refers to the shallow heat absorbed by the Earth’s surface (<400m depth according to Haehnlein et al. (2010) although this is subjective) and “a heat pump is a device capable of extracting heat from a low temperature source and supplying it to a high temperature sink whilst consuming high-grade energy” (Singh et al., 2010). Traditional ground source heat pump (GSHP) systems encountered in industry and discussed in this study include horizontal closed loop, vertical closed loop (borehole) and vertical open loop (Figure 2.5).

There are some potential risks associated with the widespread implementation of GSHP’s. For instance, Abesser et al., (2010, p.7) suggests that “problems may occur as a result of schemes impacting on the overall groundwater temperature of an area/region, leading to thermal degradation of the aquifer”. In addition to thermal pollution, groundwater contamination may also occur because of GSHP installations (Zhu et al., 2017) as well as subsidence, flooding and the drying up of wells (Fleuchaus and Blum, 2017). These potential issues have not hindered the uptake of ground source heat technology (GSHT) however. Ground source heat is a resource utilised globally to differing degrees. In central and northern Europe there is a high dependency on GSHT (Rybach and Sanner, 2000), with

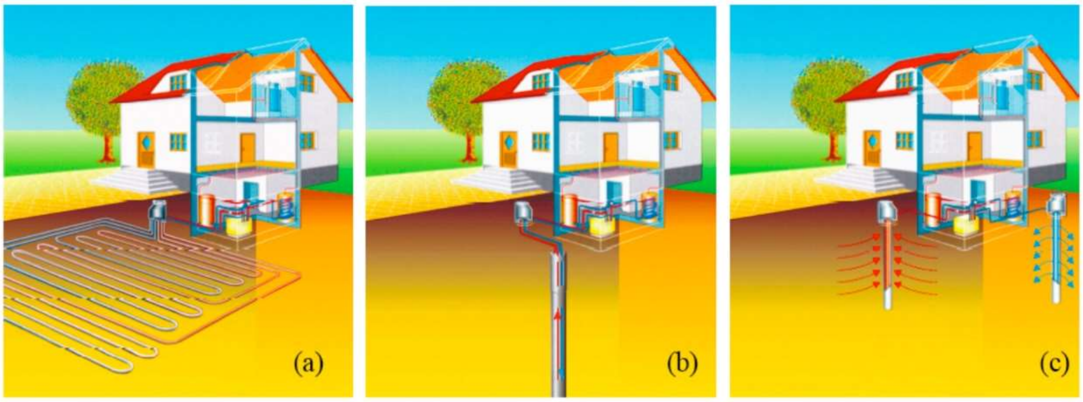


Figure 2.5 – Ground Source Heat Pump (GSHP) system set ups. (a) horizontal closed loop, (b) vertical closed loop, (c) vertical open loop (Bundesverband Wärmepumpe (BWP), 2009, cited in Rodrigo-Harri et al., 2010).

countries such as Sweden, Switzerland and Austria boasting a significant numbers of domestic heat pumps (Fawcett, 2011).

At one time, Sweden massively outpaced the rest of Europe on the uptake of GSHPs (Lund et al., 2004), and today they are still major performers in the field of GSHT. It was identified in the 1970's that the climatic conditions in Sweden were ideal to experiment with ground heat utilisation (Nilsson et al., 2005). Furthermore, many of the shallow GSHP installations are within granite and gneiss which are "normally solid for drilling, and [have]…a generally low groundwater yield" (Gehlin and Andersson, 2019, p.1), and were drilled to an average depth of 190m in 2018 (ibid). GSHT gained momentum in 1974 when the Energy Savings Programme was implemented to decrease national reliance on oil resources, and then from 1978 when heat pumps installations were supported by generous loans and investment grants (Nilsson et al., 2005). Although the focus was primarily on solar heat sources at this time, it advocated all heat pumps as viable choices for heating domestic properties. By the early 1980s, the Swedish Government invested in research and development and a training scheme was established by national authorities (Nilsson et al., 2005). This program created a shared knowledge platform which meant that urban stakeholders and heat pump installers were able to implement systems with an equal awareness of their potential and value.

By the late 1980's financial support for heat pumps was withdrawn in Sweden and this combined with more competitive oil prices saw a decline in the market. Furthermore, the long-term poor performance of early heat pumps lowered the confidence of homeowners. However, this outlook changed again when research shifted from government-driven to industry focused, and GSHPs were developed as cheaper alternatives for small domestic dwellings. The poor durability of the early heat pumps combined with the established issues with GSHT damaged the reputation of GSHPs, however by the mid 1990’s GSHP uptake began to rise. From 1998-2003 a state subsidy for GSHPs was implemented, which led to a steady rise in their use (Nilsson et al., 2005). More recently, Gehlin and Andersson (2019) reported a decreasing number of sales for small GSHPs (less than 10 kWs capacity) from 2009 to 2016 with figures levelling out from 2016 to 2019. The number of large scale GSHPs (more than 10kWs capacity) have been steadily increasing however to the present day.

The key message that the UK energy industry can take away from the history of ground heat utilisation in Sweden is that government-led policy, guidance and investment (both financially and in research and development) endorses urban stakeholder awareness and actions. The GSHP market in the UK is growing year on year (Busby et al., 2009), particularly in response to the rising agenda for sustainable development and the use of alternative energy sources. Curtis et al., (2005, p.7) explains that the uptake of heat pumps has been slow in the UK, and attributes this trend to “a relatively mild climate, poor insulation levels of the housing stock, lack of suitable heat pumps, and competition from an extensive national grid”. Subsequently, GSHPs have improved and the insulation within domestic infrastructure has likely been enhanced, however the convenience of the national grid and the UKs mild climate may still be impacting the uptake of ground source heat technology.

There are currently no central authorities mapping GSHP installations and therefore the market growth can only be estimated. The Environment Agency (2009) reported an increase in the uptake of GSHP installations since 2000, becoming more rapid from 2004 with a 100% growth rate in 2008. Planning policy (the Merton Rule) introduced in 2003 was a key driver for the steady uptake of GSHT (Environment Agency, 2009). This law requires developments of a certain size to harness 10% of its energy from on-site renewable sources. A recent report by the UK Committee on Climate Change (2019) suggest that existing policies are insufficient for the required improvement to carbon reduction and that the current approach encourages a minimum performance for energy efficiency instead of optimising their use for sustainable outcomes. Furthermore, it is suggested that “the low uptake of heat pumps is symptomatic of low awareness, financing constraints, concerns around disruption and difficulty in finding trusted installers with the right skills” (Committee on Climate Change, 2019, p.11).

To tackle some of these problems and increase the general knowledge of GSHPs in the UK, tools which assess the suitability of an area for ground heat utilisation have been proposed. For open loop systems, the British Geological Survey (BGS) and Environment Agency (EA) have produced a GSHP screening tool which indicates whether an area may be 'favourable' or 'less favourable' with regards to suitability for an open loop installation based on subsurface conditions. This is a free tool available on the BGS website, however, is only a preliminary evaluation intended to demonstrate the potentially widespread suitability of the subsurface to host open loop ground source heating systems across England. Improved granularity and inclusion of the wider urban design principles and sustainability agendas would enhance this concept from a sustainability perspective.

2.5.3 Subsurface Space

Underground space is utilised in some manner in every urbanised area. The Underworld Exhibition at The Building Centre in London 2018 (Welcome to the Underworld, 2018) highlighted the long-standing relationship that humans have had with the subsurface, and the diverse uses of underground resources as well as the upcoming popularity of its use. Evidence of utilisation of subsurface space dates back to the Palaeolithic period. Cave paintings discovered in the Lascaux cave complex in France demonstrate the dependence humans had on the subsurface to provide shelter long before the urban centres that exist today (Welcome to the Underworld, 2018; Hunt et al., 2016). Occupation of the subsurface both historically and in the present is evident around the world, particularly in extreme climates where the subsurface offers protection from hot and cold weather at the surface. Other subsurface space functions include water reservoirs and cisterns, churches, catacombs, transport tunnels, distilleries, bunkers, waste storage, nuclear reactors, car parking, offices, retail and more (Kaliampakos et al., 2016). These subsurface uses can contribute to urban sustainability and resilience depending on individual city needs.

As with above ground structures, subsurface space has the potential to be converted to meet new functions. For example, in New York a disused trolley terminal will be renovated into an underground park for public use (Yoshimura, 2015), enhancing urban stainability by regenerating a disused space in a city where land space is scarce and there is a high population density. Furthermore, with technological developments the potential uses of subsurface space have diversified in recent times. For instance, the Svalbard Global Seed Vault was strategically located underground to ensure the longevity of its function as the world's largest collection of seed samples (Welcome to the Underworld, 2018).

Hunt et al., (2016) states that subsurface space plays a crucial role in anthropogenic systems and that to ensure sustainability and resilience in urban settings "future urban interventions that progress development…must be considered at the planning and design stages of any infrastructure construction project". This implies that subsurface space (as a component of urban design) should be considered early in the phases of a development proposal, and that by doing so increases the likelihood of developing a holistic subsurface plan. Furthermore, the inclusion of subsurface space within policy in some countries is dictated by "increasing land use pressures, climatic considerations or simply where development opportunities are evidenced" (ibid). Long-term subsurface planning to tackle these issues may maximise the potential value that the subsurface has to offer.

As the use of subsurface space is on the rise, some cities have started to manage this resource by developing bespoke spatial plans. For example, Helsinki, Finland, has established an underground master plan (UMP) for the subsurface area within its administrative city boundary. As Vähäaho (2014, p.390) noted "Helsinki has been the first city to develop a dedicated UMP for its whole municipal area, not only for certain parts of the city. It has been claimed by some non-Finnish experts that the favourable characteristics of the bedrock and the very severe winter climate conditions have been the main drivers for this development". The plan illustrates the location of existing and proposed subsurface structures, and designates underground resources for utilities, construction space and railway tunnels (Figure 2.6). It should however be noted that limited land space was also a key driver for managing subsurface development before urban expansion underground (Ikävalko et al., 2016). These motives for the utilisation of subsurface space contribute towards the long-term existence of Helsinki, and therefore enhance the urban sustainability and resilience. One of Helsinki's most impressive subsurface structures is the Itakeskus Swimming Hall which also functions as an emergency civic shelter (Vähäaho, 2014).

Ikävalko et al. (2016, p.16) explains that the ownership of subsurface space is not clear in Finnish law, stating that "when interpreting the extent of ownership, the lower boundary of a property has been limited to the depth where it can be technically utilized. In practice, this means the depth of 6m from the lowest point of the building lot". Furthermore, any underground construction must first acquire legal rights to develop underground space and pay the City of Helsinki appropriate charges to rent the space. Vähäaho (2018) provides further context to the UMP, stating that discussions with different stakeholder groups were

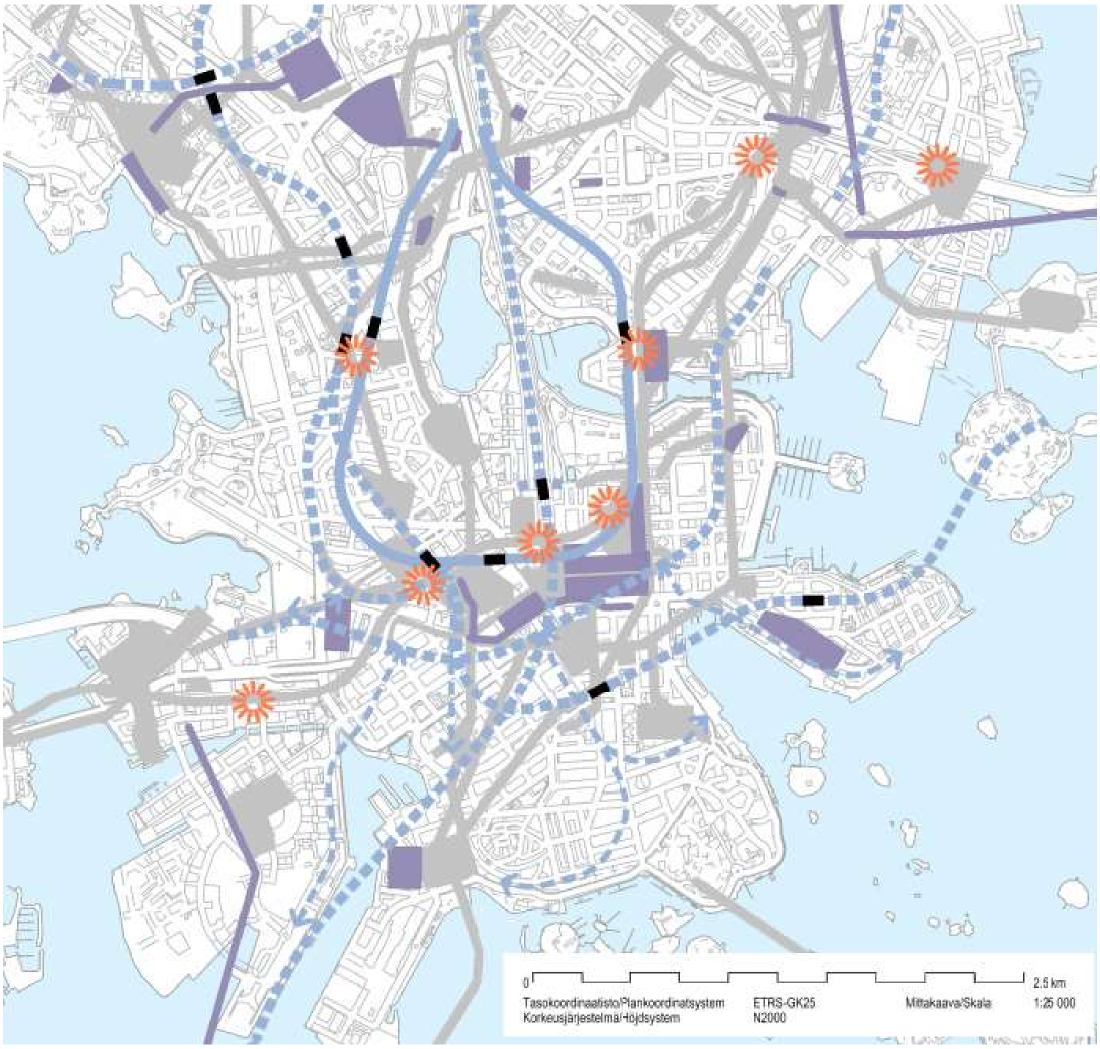


Figure 2.6 – Extract of the Helsinki Master Plan (City of Helsinki, 2020). Grey = existing underground facilities and tunnels, purple = planned underground facilities and maintenance tunnels, blue =planned traffic tunnels, black = underground railway station, orange = target areas for underground public and commercial services.

undertaken in the mid 2000's, and by the late 2000's, water companies and energy providers were involved with drafting the UMP. City planners examined the draft in 2007, and by 2010 an initial version was approved (Vähäaho, 2018). In developing this plan, up to 40 years of geotechnical information from across the city (stored by the Geotechnical Division of the City of Helsinki) was used, and 3D modelling of the subsurface was undertaken. Intrusive ground investigations were also undertaken across the city to correlate with the geological data (Ikävalko et al., 2016).

In the UK, planning policy for subsurface space has predominately focused around private basement development in London for the super-rich. The Basement Information Centre identifies inconsistent decision making across the country with regards to one of the most frequent domestic uses of the subsurface: basement construction (Basement Information

Centre, 2011). Basement construction is becoming increasingly common in London where property extensions above ground are often unachievable. In response to this, several Bills were proposed to help moderate the development of subsurface space (e.g. Planning Subterranean Development Bill (2015-2016) and the Basement Excavation Restriction of Permitted Development Bill (2015-2016)) however both Bills did not progress through parliament. However, in response to the growing number of planning applications for the construction of basements in London, the latest draft of the London Plan includes policy D9 on Basement Development which "considers that smaller-scale basement excavations, where they are appropriately designed and constructed, can contribute to the efficient use of land" (Greater London Authority, 2017, p.131) but also highlights several issues with basement development in built up areas, and the associated hazards; "such basement development can impact on land and structural stability as well as causing localised flooding or drainage issues" (ibid, p.132). Ultimately the policy states that "boroughs, particularly in inner London, should establish policies to address the negative impacts of large-scale basement development beneath existing buildings" (ibid, p.131). This has been demonstrated by some boroughs such as the Royal Borough of Kensington and Chelsea who have produced a basement planning policy (Royal Borough of Kensington and Chelsea Council, 2016). The proposal to include basement development in the latest version of the London Plan demonstrates the recognition of subsurface space as an opportunity to accommodate urban growth.

Within the context of geological resilience in urban environments, subsurface space use is a rapidly advancing topic in the UK and it is possible that we will see more cities implementing subsurface planning in the future. UK cities do not produce underground master plans, and in the majority of situations, exploitation of the subsurface for underground construction and geo-materials has been largely unmonitored. There is no central database for existing or planned subsurface developments in the UK. In addition, mineral ownership is largely held by private individuals and organisations, and in all other cases "land is owned by the Crown unless there is evidence to prove otherwise" (British Geological Survey, 2017(b)).

Hunt et al. (2016, p.9) explored the lack of subsurface planning encountered in UK developments, concluding that the 'first-come, first-served' approach to managing the underground will cause problems over time with the expansion of urban areas. For example, in Birmingham Eastside a chaotic assortment of near-surface services (gas, water, electric, communications, etc) were observed, which in the future will make locating and accessing services for maintenance much more challenging (Jefferson et al., 2006). In some regions, underground mapping surveys are being undertaken where knowledge of the underground is recognised as an asset. In the UK, London's Underground Asset Register was piloted in 2019 to demonstrate the interface for mapping underground infrastructure. Stakeholder communication was identified as an important factor in the success of the pilot project (Geospatial Commission, 2020), however communication can only be optimised once urban stakeholders agree on the value of subsurface space for enhancing urban sustainability and resilience. This knowledge gap should be explored to understand the enablers and barriers to utilising subsurface space in UK developments.

2.5.4 Additional Geo-Resources

As well as groundwater, ground heat and subsurface space which are the focal geo-resources explored through case studies for this research, the role of additional geo-resources which contribute to the functionality of city systems are briefly highlighted below.

2.5.4.1 Geo-materials

Geo-materials has many sub-divisions however this general overview considers geo-materials holistically as an asset to be utilised for urban sustainability. Fookes (1991) defines geomaterials as "processed or unprocessed soils, rocks or minerals used in the construction of buildings or structures, including man-made construction materials manufactured from soils, rocks or minerals". The ability to extract materials from the Earth has been integral to the advancement of humankind and our way of life. This dates back thousands of years when our earliest ancestors would make tools from rocks and building materials from clay. Nowadays geo-materials are largely utilised in the construction industry, and have the highest value where processed into energy resources (Prikryl et al., 2016). Geo-materials can contribute to urban sustainability in multiple ways. On discussing the resource demands for the city of Oxford, Curtis et al. (2016) splits geo-materials into three categories: stones and aggregates, minerals and metals, and hydrocarbons. A heavy dependency is documented on all three, although their origins are considered to be global rather than local. Curtis et al. (2016, p.15) further notes that alongside commercial situations, minerals and metals provide "steel in new buildings, copper in our cables, rare earth metals for our electronics and solar panels, and we need thousands of tonnes of potassium and phosphate to grow the crops that feed us".

In addition, the wider implications of material use is highlighted in maintaining the functionality of modern cities. Fossil fuels are seen to underpin energy supplies, transport systems and manufacturing processes (Curtis et al., 2016), and despite their use are becoming increasingly contested with alternative sources of energy continually being explored.

In many countries, such as the Netherlands, “geomaterials are considered to be owned by the State and, therefore, any exploitation is seen as a case for the national government” (Admiraal and Cornaro, 2016, p.217). The majority of geo-materials in the UK are, however, privately owned, apart from energy supplies (such as oil and gas) and gold and silver (British Geological Survey, 2017c). The National Planning Policy Framework (NPPF) details the law in England for mineral planning, with the most recent revision (February 2019) focusing on sustainability in the context of safeguarding minerals and encouraging their extraction where appropriate (Ministry of Housing, Communities and Local Government, 2019). For example, sand and gravel deposits are frequent in the UK and are commonly extracted, often close to urban centres to lessen haulage costs and contribute towards more sustainable construction. (Marinoni and Hoppe, 2006; Calkins 2008).

2.5.4.2 Ground Properties

Physical properties of the ground are also very important to consider as a resource. Although this is often linked to the hazards associated with poor ground conditions, the characteristics that are advantageous could include: permeability, stability and the ability to excavate the ground.

As previously mentioned, SuDs as well as the development of green infrastructure such as green roofs, green walls and city parks, are example of an urban intervention which encourages the infiltration of water through utilising the grounds permeability (Woods-Ballard et al., 2007). If the subsurface contains unsaturated strata with enough pore space to store water, SuDs can “reduce surface water flooding, improve water quality and enhance the amenity and biodiversity value of the environment. SuDS achieve this by lowering flow rates, increasing water storage capacity and reducing the transport of pollution to the water environment” (British Geological Survey, 2017a). Having permeable surfaces is also important during extreme events such as heavy rainfall to avoid flash flooding.

In addition, Price et al. (2010) recognised ground properties within the concept of ecosystem services. “Ecosystem services refer to the benefits that humans derive from the natural environment” (Wu and Wu, 2013, p.222). Rawlins et al., (2015, p.49) introduced an ecosystem service called carrying which comprises soil properties that support infrastructure “they carry, with associated fill material, a complex range of piped utilities (e.g. water, electric, gas) and structures…[and] urban soils also carry electrical earthing structures”. Price et al. (2016, p.22) promoted this idea “in recognition of the properties of the ground that provide support for development including bearing capacity and electrical earthing potential”.

2.6 Summary: The Geo-resources Challenge

Geo-resources significantly support many city systems; their input is essential to the running of many processes and outputs. Geo-materials (such as sand, gravel and crushed rock) are required for the construction of infrastructure. Groundwater is crucial for domestic and commercial consumption as well as industrial processing. Geothermal potential of the subsurface provides a source of heat for above ground infrastructure. Underground construction space is used for transport networks, as well as services tunnels and providing physical support to above and below ground infrastructure. Underground space as a geo-resource is of immediate interest for proposed developments which have a component of functional underground space (such as car parking or offices).

Cities are complex interdependent systems which are rapidly evolving to incorporate aspects of sustainability and resilience in their development plans, designs and governance. There is much evidence around the world of the different tactics implemented to enhance sustainability and resilience in urban settings, often in isolated or project-specific contexts, but far less evidence that suggests a widespread engagement with geological thinking and geo-resource utilisation towards these goals.

International examples showcase the use of geo-resources to enhance urban sustainability and resilience but also highlight the governance challenges due to the often siloed and fragmented nature of the development industry. To achieve the shared goals of enhanced urban sustainability and resilience, governing authorities, planners, architects, consultants, contractors, developers, and arguably geologists should work more collaboratively (Ascott and Kenny, 2019). The breakdown in collaboration across these fields is hindering the optimisation of geo-resources by restricting data integration, breaking information chains and inhibiting knowledge transfer. The UK construction industry suffers from this as most construction is undertaken by the private sector (Office for National Statistics, 2019), where information is a commodity and rarely shared with ‘competitors’. To date, projects which utilise geo-resources to enhance urban sustainably and resilience in the UK are generally not achieved holistically, with much delivered in a bespoke, ad-hoc or retrofitted manner. Opoku and Ahmed (2014, p.93) investigated the challenges of harmonising the UK construction industry with sustainability, highlighting "the lack of integration between the different project stages and professions in the project team…[,]lack of consideration of sustainability measures by stakeholders, not required by clients, real and perceived costs and inadequate expertise and powers". Even in the exemplar sites discussed in this chapter, geo-resource utilisation will not have been seamless and may have required significant investment in time and money as well as widespread engagement with geologists. The restricted inclusion of geologists in planning and urban design in the UK and internationally, has seen an under exploitation of geo-resources. Understanding the barriers to geo-resource exploitation from the perspective of key urban and built environment stakeholders would begin to address the issues preventing widespread use.

This chapter has explored the past and present role of geo-resources in the turn to urban sustainability and resilience, the different strategies considered in its implementation, and how sustainability and resilience are assessed and incorporated into UK urban design and planning policy. International examples that have successfully incorporate geo-resources in development projects have been explored to illuminate the tactics which may be useful to increase geo-resource utilisation for enhancing urban sustainability and resilience in the UK. The findings from this review have revealed a set of problems inhibiting the use of geo-resources for sustainable and resilience development that will be explored in the forthcoming chapters.

Firstly, there is a lack of geological perspective in urban design and planning. A knowledge gap exists between urban sectors that may be deepening the pre-existing sectorial divide and increasing miscommunication and misunderstanding of geo-resource use. There are contrasting perceptions of geo-resources from the perspective of urban stakeholders and conflicting interpretations of the cost of utilising geo-resources. The provision of generalised site-specific information which gives an indication of the geo-resource potential in all-inclusive terms and connects this information with relevant site-specific planning policy and urban design guidance may begin to increase the understanding of geo-resource utilisation.

Secondly, the role of planning policies, urban design guidance and sustainability and resilience assessment frameworks is unclear across the geo-resource types, with the impact this is having on the uptake and success of geo-resource-utilising infrastructure being ambiguous. The inclusion of information from a geo-resources-perspective across multiple scales is required to assess current governance issues preventing geo-resource utilisation in urban planning and design decision-making.

The next chapter introduces the techniques used in this study to explore the perception and use of geo-resources in urban locations, as well as a new approach to examining geo-resources spatially in the context of case-specific planning policy and urban guidance.

3 - Research Framework and Methodology

3.1 Introduction

In the preceding chapters the current state of knowledge is explored in the fields of sustainable and resilient development, revealing the varied approaches taken to future-proof cities across the globe through the utilisation of geo-resources.

From a geological perspective, developing and testing an approach to measure and map geo-resource potential in site-specific circumstances is the starting point to establish what geo-resource capacity can be determined from geological data for the UK. In this study, this was approached using exemplar sites of geo-resource use and exploring the geological characteristics facilitating them. Following this, to delve into the factors impacting geo-resource use, urban stakeholder interviews were conducted at the case study sites to investigate the enablers, barriers, drivers and failures to geo-resource utilisation in practice, as well as help to establish the ideal user of the geo-resources potential mapping tool. Simultaneously, the way that geo-resource potential can be inserted into current urban development practices was explored to find the best strategy for implementation of the geo-resources potential tool. Therefore, a detailed document examination was conducted alongside the interview series to explore the types of guidance, at a range of scales, that exist for geo-resource use and how best to integrate the geo-resources tool.

Upon completion, the geo-resources potential tools from the case study sites were assessed for their value and practicality with regards to specific geo-resource investigation at a local level. The findings of the interview series and document examination complemented the mapping tool analysis by detailing the factors that are impacting geo-resource use in urban settings in the UK, (and therefore what needs addressing for implementation of the geo-resources mapping tool). These findings are integrated in Chapter 7 where the gaps between planning practice, the geo-resources perspective and the global agendas of resilience and sustainability are discussed. The three case study sites are the NW Cambridge development (CS1), Chestnut and Aspen Mews retrofit project (Burton on Trent) (CS2) and the Canary Wharf Crossrail Station (Central London) (CS3). Each case study utilises water (CS1), ground heat (CS2) and subsurface space (CS3) respectively. The findings of each case study are presented within the framework of sustainable and resilient urban development.

Previous studies have highlighted the limited impact of geo-resources policies from government (von der Tann et al., 2018), that the subsurface is overlooked (Parriaux et al.,

2004) and that there is an ongoing evolution of geo-resources mapping and sustainability assessment tools (Doyle, 2017; Sharifi and Murayama, 2013). To implement a paradigm shift and address these challenges, a mixed-methods approach is necessary. This approach supports the application of this research (through the design and use of a geo-resources potential mapping tool) which also delivers an original contribution to knowledge. Collins et al., (2006) presents the linear route of mixed-methods data collection (Figure 3.1). This shows the overarching approach which has been applied to this research, and is expanded upon in the following sections.

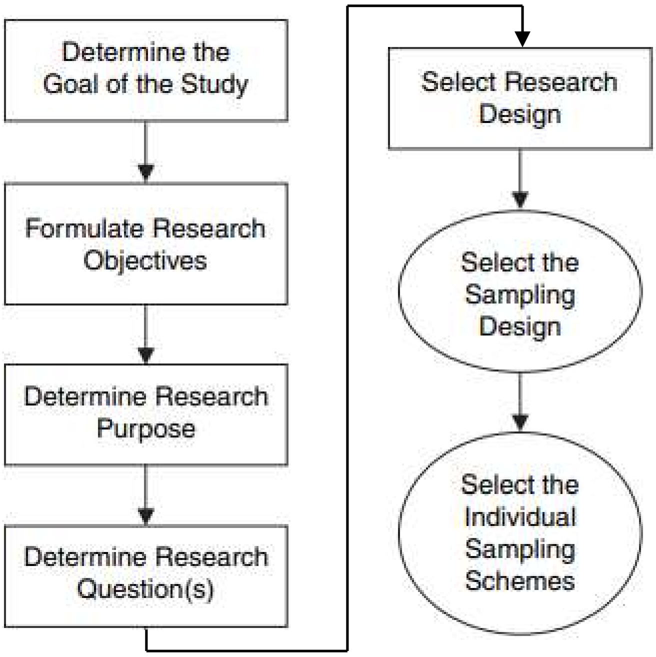


Figure 3.1 – Mixed-methods stepwise strategy (amended from Collins et al., 2006).

Johnson and Onwuegnuzie (2004, p.14) further stated that “the goal of mixed methods research is not to replace either [qualitative or quantitative] approaches but rather to draw from the strengths and minimize the weaknesses of both in single research studies”. It is additionally argued by Yin (2009, p.63) that “mixed methods research can permit investigators to address more complicated research questions and collect a richer and stronger array of evidence than can be accomplished by any single method alone”. Furthermore, the value of this research is increased by its potential impact in industrial practise. Following a mixed methods approach facilitates dissemination by being able to engage with stakeholders through interviews, present the concept of geo-resource use, identify facilitators in planning policy and present a tool which begins to analyse geo-resource potential on a site-by-site basis.

The overarching approach taken in this research followed inductive reasoning. The process started with an observation; that there has been an undervaluation of geo-resources for sustainable and resilient urban growth. This is demonstrated by patterns seen across different urban developments and geo-resources types. At the start, this study hypothesised that a site-specific geo-resource potential mapping tool, as well as an effort to bridge the knowledge gap across urban stakeholder groups, aided by planning policy to expedite change would enhance the sustainability and resilience of urban areas. The definitive theory surrounding this has evolved as this research has been conducted and is discussed in chapter 7.

3.2 The Multiple Case Study Approach

The multiple case study procedure adapted from Yin (2009) (Figure 3.2) is used to explore the relationship between geo-resource use and sustainable and resilient urban development. Sandelowski (1996, p.526) suggested that "the case-oriented approach is especially useful for showing … how different sets of varying factors in different cases can interact to produce common outcomes". To explore the different types of geo-resources through implementing the same techniques across several case studies facilitates a cross-comparison between the findings. Three sites were selected for detailed case study analysis based on the use of geo-resources within an urban design aspect of the site (Table 3.1).

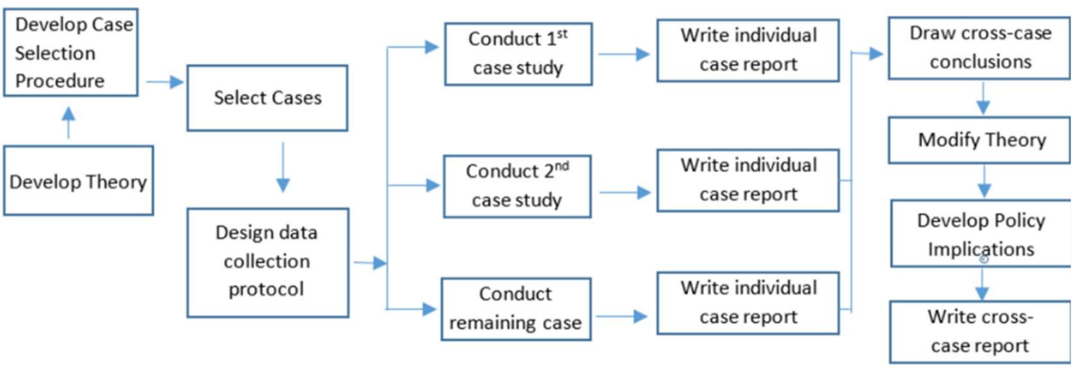


Figure 3.2 – Stepwise multiple case study procedure (amended from Yin, 2009).

Geo-Resource Type	Case Study Name	Case Study Location	Main Urban Design/Geo-resource Interaction
Groundwater	North West Cambridge	Cambridge	Dual water network system (potable and non-potable water supplies) in place to meet the reduced water usage goals of the development.
Ground Heat (Vertical Closed Loop)	Chestnut and Aspen Mews	Burton on Trent	Ground Source Heat Pumps (GSHPs) installed for 60 residential flats which utilise the near subsurface to provide heating for the residents.
Subsurface Space	Canary Wharf Crossrail Station	London	Subsurface space utilised to build a new Crossrail station and subterranean shopping centre.

Table 3.1 – Case study summary information.

The overarching methodology is largely qualitative although one element within this involves quantitative techniques. The benefits and downsides for quantitative vs qualitative research are heavily discussed in literature. However, Rossman and Wilson (1985) highlight three key strengths of combining these approaches. Firstly, is to allow corroboration of results through triangulation (i.e. approaching the same topic from different angles to improve the reliability of results). Secondly, is to promote the use of results from one approach to elaborate on the results from another. Thirdly, is to facilitate a contrast of the findings across multiple approaches and explore future research options.

In implementing research with an overarching qualitative scope, but also utilising quantitative procedures, this thesis presents a narrative benefiting from the strengths of both techniques, but also acknowledging their weaknesses in the relevant sections.

Following the broad scope of a multiple case study procedure, the three sites selected for detailed investigation are analysed via the three procedures. Table 3.2 illustrates how the main approaches link together with the case studies.

Firstly, a geo-resource potential mapping model derived from this study is performed on each case study site, utilising site-specific data relevant to each geo-resource type. Available geospatial geological datasets from Great Britain's national custodians of geological and environmental data was used to create a cumulative geo-resources map and assess whether the data are appropriate to summarise the overall geo-resource potential of a site based on type-specific characteristics.

	Case Study Sites		
Mixed Methods	*Groundwater - NW Cambridge* ↓	*Ground heat - Chestnut and Aspen Mews* ↓	*Subsurface space - Canary Wharf Crossrail Station* ↓
Geo-resource potential mapping tool →	**Quantitative – secondary data analysis** Relevant datasets analysed/integrated to create a site-specific geo-resource potential map. This is then correlated to appropriate site-specific policies and design measures via an Urban Design Geo-resource (UDG) matrix.		
Stakeholder interviews →	**Qualitative – primary data collection** Semi-structured discussions with stakeholder representatives to determine the perception and understanding of geo-resources in urban design.		
Document examination →	**Qualitative – secondary data analysis** A review of the inclusion of geo-resources within planning policy documents, urban design guidance and sustainability assessments relevant to each case study site.		

Table 3.2 – Case studies and corresponding analytical techniques.

This work drew from Li et al. (2016) who demonstrated the types of data available to assess subsurface resources and what environmental aspects are typically considered for an evaluation of the subsurface (Figure 3.3). The indices observed are primarily focused on geo-hazards rather than geo-resources (further exhibiting the over-looked opportunities that may exist from subsurface assets).

Some of the indices present in Figure 3.3 were available for this study from BGS datasets (such as the properties of soil and the aquifer characteristics). There were additional datasets applicable to geo-resources which can be acquired from BGS databases (such as the ease of excavation of material, and suitability of SuDs).

Following the production of a site-specific geo-resources potential map, the outcome was discussed and validated against external reports and information. Ways to apply this information (on a site-specific basis) were then explored using the Urban Design Geo-resource (UDG) Matrix that was produced.

The UDG Matrix is a site-specific construct of policies and urban design guidance documents relevant to each case study site. It demonstrates how a specific use of a geo-resource may contribute to achieving urban design or sustainability targets (from a national to local scale).

Index type		Indices
I – Natural geological condition factors	Regional tectonic stability and seismic geologic condition	Fault activity Seismic intensity Construction site classification
	Topography and geomorphology	Geomorphic unit
	Geotechnical engineering properties	Properties and thickness of soft soil Liquefaction index of sandy soil Thickness of liquefiable soil layer
	Hydrogeology condition	Aquifer characteristics and distribution Yield of single well Corrosiveness of groundwater Watery faults in bed rock
	Geological hazards	Karst area Goaf area Ground fissure

Figure 3.3 – Potential indicators for evaluating geo-resource potential (Li et al., 2016).

The goal is for users to better understand the potential of geo-resources for achieving sustainable urban development goals across a broad spectrum of urban sectors.

Following an evaluation of the geo-resource potential for each case study site, interviews with urban stakeholder representatives for each site were undertaken. The use of interviews as data sources has been perceived by some as an unreliable approach due to the subjectivity of responses from participants (Alshenqeeti, 2014). However, for this research, interviewing is the most appropriate way of attaining information and viewpoints from different urban stakeholder groups to provide an insight into the use of geo-resources in urban design and practise.

The use of semi-structured interviews allows a specific set of questions to be explored, within the freedom of an open discussion. As a more relaxed approach, this encourages experiences and viewpoints to be shared as well as facts and knowledge of a subject. A general topic area is set by an opening question, and the conversation leads on, sometimes provoking a discussion that may otherwise have not occurred. Interviews were supported by prior knowledge gained from the literature review. This aided the free-flow of a discussion particularly where a familiarity with a particular geo-resource approach or sustainability agenda was shared.

The last approach undertaken in order to explore the inclusion of geo-resources is a document examination of site-specific planning policy, urban design and geo-resource specific guidance and sustainability assessment methods for each case study. This is inclusive of national, regional, district, local and site-specific documentation to gain a complete picture of the most influential levels of governance and to identify any significant gaps.

To close the research, the observations from each case study are cross compared for a holistic evaluation of the modelling technique and extent of geo-resource inclusion in the development industry. The connected findings and issues open valuable pathways towards measures for greater consideration of geo-resource use. Each of these methods are detailed further in the following sections.

3.3 Constructing the Geo-Resources Potential Mapping Tool

There is great potential for the subsurface to provide a variety of natural services and resources to urban areas, however in order to ascertain their capacity (and optimise their consumption) information on resource availability, condition and accessibility is needed. Procedures to measure and map geo-resource assets have been established both in research and industry. However, these approaches often lack a connection between geo-resource assets, urban sustainability agendas and relevant urban design policies. A mechanism to connect these facets of information within the context of urban development is needed.

Three-dimensional modelling captures the complexity of the subsurface that two-dimensional modelling cannot, particularly when geological conditions are known to be exceptionally variable. However, for the geo-resources mapping tools it was decided to use two-dimensional data as this was considered adequate to indicate potential geo-resource suitability for connecting with urban design guidance and planning policy. In addition, this tool is intended to be supplementary to the conventional desk studies and intrusive ground works which are required for any development project.

There are many software packages that can provide specialist information on subsurface conditions. De Mulder et al., (2012, p.127) share examples of 3D modelling software and comment on their functionality (such as Cadsmine, EarthModel and Techbase). These are focused on industry requirements (such as tools for technical design parameters and draught planning), however there are projects which have approached the challenge from a research perspective with the intention of the output being used in practise when fully developed. For example, the European Cooperation in Science and Technology (COST) Sub-Urban Action aims to tackle the disparity between those who hold subsurface expertise and those who may want to use it. Through this the Sub-Urban Toolbox was launched which propose the Geo City Information Modelling (GeoCIM) concept. This would be inclusive of anthropogenic and natural surface and subsurface assets and convey the importance of these features to multiple audiences (Venvik et al., 2018). These include governing authorities, the general public, urban planners and subsurface experts.

Ultimately, the Sub-Urban Toolbox is tackling a niche topic that aligns with this research and utilises comparable methods (examining case studies and guidance documents). The Sub-Urban Toolbox operates on an international scale and is linked to broad land use planning at city levels, whereas the novelty of this study lives in its deep dive into site-specific urban development guidance to assess specific geo-resource potential, and contrast holistically across case study scenarios. Furthermore, the target audience for the Sub-Urban Toolbox is primarily city planners whereas this research targets a broader range of urban development stakeholders. In the end analogous research by others demonstrates the challenge of subsurface inclusion in urban development and strengthens the research area for tackling the issue.

One of the primary observations from the COST Sub-Urban Action project was that "it was crucial that planners and builders have access to all the information available on the surface and subsurface" (Venvik et al., 2018, p.37). Having information available on geo-resources lays the foundation to utilising them successfully and provides early-stage awareness to inform planning and urban design aspects. The crucial role of urban stakeholders and governance is also observed in the Deep City Project in a six stage "comprehensive decision platform, linking public and private sectors into new subsurface urbanism plans" (Li et al., 2013, p.563). The approach identifies strategic and operational phases based around data collection, modelling, benchmarking and spatial planning.

Both the Sub-Urban Toolbox and Deep City Project are summarised in Table 3.3, alongside their limitations with regards to geo-resources potential for urban sustainability and resilience.

Name	Summary	Output	Limitations
Sub-Urban Toolbox	Using the mechanics of a bicycle as a metaphor, the project brings together subsurface knowledge and urban planning through an information output, drawing upon their various interactions in different initiatives and applying these to urban needs and governance (COST Sub-Urban, 2017).	An interactive collection of material on; city challenges (in relation to the subsurface), subsurface information (groundwater, geothermal, geotechnical, geochemistry, cultural) and knowledge gaps, urban planning, their integration and implementation through urban governance (COST Sub-Urban, 2017).	Does not highlight site specific urban design guidance or policy or provide options with regards to applications of geo-resource use in site-specific context.
Deep City Project	Six step process focused on defining geo-resource supply capacities (and values), assessing urban needs and marrying subsurface space potential with the feasibility of use of urban underground space. A comprehensive integrated planning tool (Li et al., 2013).	Sourcing and compiling supply and demand criteria into a geographical information system and calculating resource potentials that can be represented spatially – linking subsurface aspects with decision making criteria, planning policy and critical success factors (Li et al., 2013).	Aimed at city or districts scale rather than local level. Furthermore, the project focuses on planning policy in the context of urban agendas, rather than sustainability goals or design guidance.

Table 3.3 – A comparison of the Sub-Urban Toolbox and Deep City Project initiatives with limitations in relation to this research.

In addressing these limitations, a mapping method has been developed to show geo-resource potential, and is demonstrated on the three case study sites.

The geo-resources tool will offer early-stage site-specific information on geo-resources in locations where urban stakeholders have a pre-existing interest. Furthermore, the tool is a mechanism for delivering information on geo-resources to planners, developers and engineers, breaking down the barriers between sectorial siloes. Six steps were undertaken to create the mapping tool and are summarised in Figure 3.4. The example demonstrated within Figure 3.4 is the creation of the groundwater mapping tool, however this process was applied to the other geo-resource types too (ground heat and subsurface space).

3.3.1 Step 1

For each respective geo-resource (groundwater, ground heat and subsurface space) there are criteria that influence their characteristics and availability for use. The main factors considered for each geo-resource within the mapping tool have been shown below (Table 3.4).

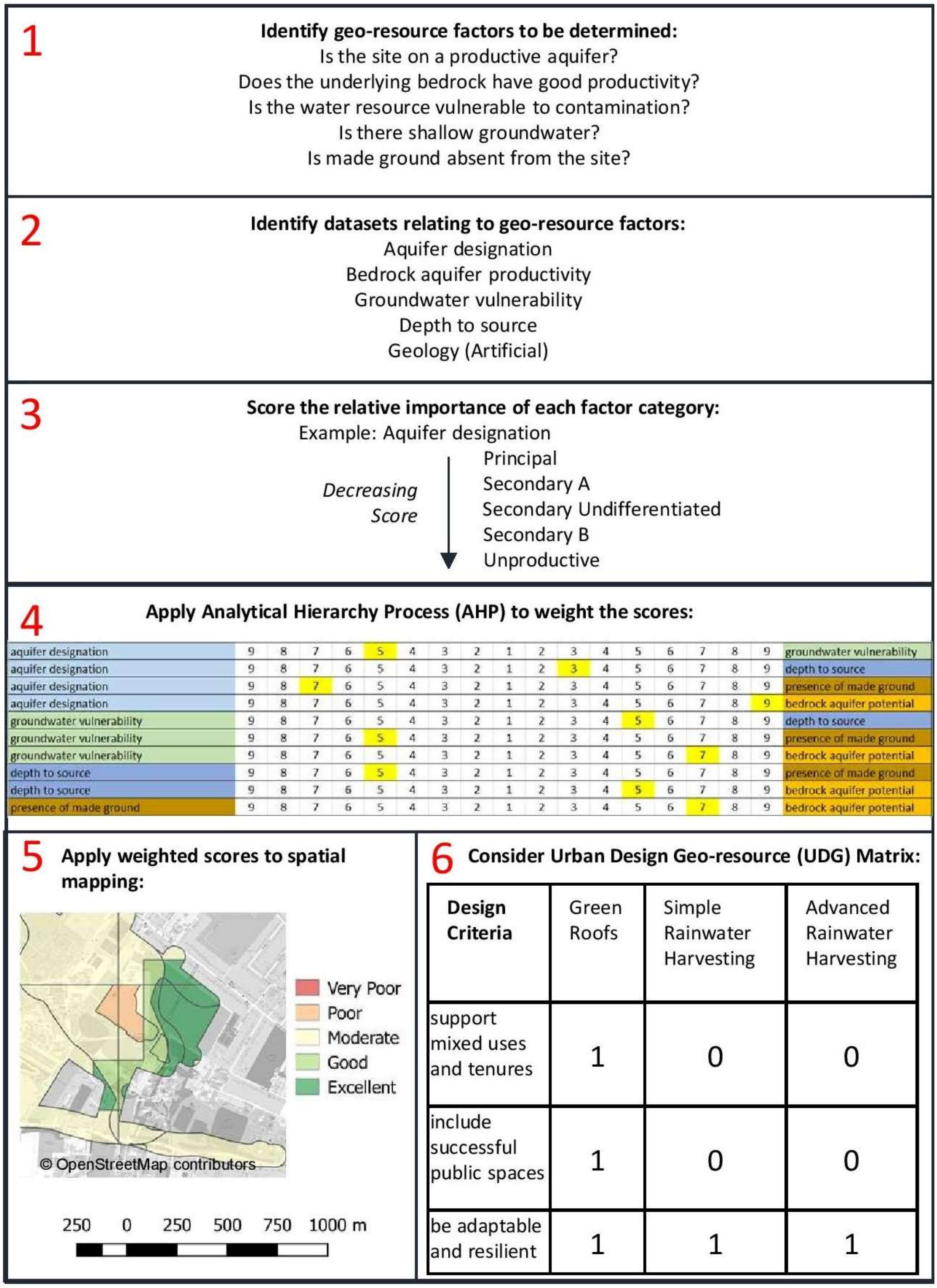


Figure 3.4 Summarised stages of geo-resources potential mapping tool creation process shown for groundwater potential mapping tool.

Groundwater	Significance
Is there a productive aquifer at surface that can sustain a groundwater supply?	The ability of water to pass into and be stored in materials (rock or deposits) impacts the suitability of a layer to supply groundwater. Aquifer designations indicate the likelihood of a rock or deposit to contain and transfer groundwater.
Does the underlying bedrock have good groundwater productivity?	The water yield that can be expected from bedrock aquifers indicates the potential volume of groundwater that could be extracted from underlying aquifers to support supplies.
Is the groundwater resource vulnerable to contamination?	The level of vulnerability indicates how at risk an aquifer may be to contamination. High risk aquifers are most vulnerable and should be studied before a potential contamination pathway into an aquifer is created.
How deep is the groundwater?	The depth to groundwater indicates the likely depth that will need to be drilled and is therefore important as a proxy for the potential cost of drilling and borehole/pump infrastructure.
Is made ground the site?	The presence of made ground may be a source of contamination for groundwater or require specialist construction methods in order to penetrate or build over. Therefore, the presence of made ground (and its type) is an important consideration for groundwater utilisation.
Ground Heat (Vertical closed loop)	**Significance**
Is there a productive aquifer at surface that would impact ground heat?	Thermal energy can be transported by groundwater, and therefore knowing the ability of a rock to store and transfer groundwater may increase or decrease the efficiency of a GSHP system.
Is the groundwater vulnerable to contamination?	Where groundwater is particularly vulnerable, drilling into an aquifer to install a GSHP borehole may create a potential contamination pathway. These high risk areas are less suitable for ground heat utilisation.
How deep is the groundwater?	The presence of shallow groundwater also impacts the thermal properties of the subsurface. Alike aquifer designations, the presence of groundwater may increase or decrease the efficiency of a GSHP system.
Is the subsurface easy to excavate?	The ease of excavation indicates what techniques may be required to drill a borehole and is therefore important as a proxy for the potential cost of drilling and borehole/pump infrastructure.
Is made ground absent from the site?	The presence of made ground may be a source of contamination for groundwater or require specialist construction methods in order to penetrate or build over. Therefore, the presence of made ground (and its type) is an important consideration for ground heat utilisation.
Subsurface Space	**Significance**
Is the site suitable for foundations?	The suitability of the site for foundations may be a proxy for the suitability for subsurface construction due to the alignment of characteristics (i.e. good foundation

	conditions may indicate good subsurface conditions for construction).
Is the subsurface easy to excavate?	The ease of excavation indicates what techniques may be required to achieve necessary depth for utilising subsurface space. This is also a proxy for the potential cost of excavation and the required infrastructure to support subsurface development.
Is there shallow groundwater that may impact construction?	Shallow groundwater may impact the construction method, dewatering requirements, and design parameters for subsurface structures.
Can excavation materials on site be re-used?	Excavated materials may offset some costs of subsurface space development by re-using elsewhere on site, or could be sold as a commodity and exported to other sites. Higher quality and more desirable materials offer greater potential for re-use.
Is made ground absent from the site?	Made ground may be a source of contamination which requires specialist disposal upon excavation. Furthermore, should there be a sufficient thickness of made ground, specialist designs (such as ground gas protection membranes) may be required to enable subsurface space occupancy.

Table 3.4 – Factors considered for each case study geo-resource potential utilisation tool (groundwater, ground heat and subsurface space).

3.3.2 Step 2

For each question relevant datasets have been identified that provide the information to assess the factors influencing geo-resource availability. The datasets used have been listed and justified in Table 3.5. In some cases, multiple datasets have been utilised to transform the data into the relevant information. Any re-working of the datasets has also been described in Table 3.5.

Groundwater	Dataset	Background	Reworking	Summary of Justification	Scale/Resolution
Am I on a productive aquifer?	Basic Superficial Deposits Thickness Model (BSTM)	Mathematical model of thicknesses of superficial deposits derived from borehole data	Less than 10m thickness is unlikely to provide adequate water as the saturated thickness of the aquifer is insufficient. Therefore any superficial deposits less than 10m of recorded thickness have been removed from the BSTM data. This was then used to clip the superficial aquifer designation, and combined with the bedrock aquifer designation to create the files.	Indicates the calculated thickness of superficial deposits from archived borehole logs. This can therefore indicate where deposits are less than 10m thick and therefore not considered suitable for a groundwater supply.	1:50,000 scale
	Superficial aquifer designation/ Bedrock aquifer designation	"Joint Environment Agency and British Geological Survey dataset identifying the different aquifers of England and Wales" *	The reduced BSTM data was used to isolate the superficial aquifer designation data where deposits were greater than 10m thick. The bedrock aquifer designation data was not edited.	Indicates the water-bearing properties of geological units (superficial/bedrock as appropriate).	1:50,000 scale

Does the underlying bedrock have good productivity?	Aquifer Potential map	"A map that shows the distribution of bedrock aquifers (at outcrop and concealed) that can provide sustainable yields"**	The aquifer potential data was not edited.	Indicates the sustainable yields of groundwater in litres per second. Also indicates the presence of a concealed aquifer at depth.	
Is the water resource vulnerable to contamination?	Groundwater Vulnerability map	Joint Environment Agency and British Geological Survey dataset providing information on groundwater vulnerability. Some three-dimensional data are used within this map (e.g. superficial thickness).	Combined groundwater vulnerability map used. Worst case vulnerability classification used from the bedrock and superficial aquifer vulnerability designations.	Indicates the perceived risk to groundwater that development is likely to have.	1 kilometre square resolution
Is there shallow groundwater?	Depth to Groundwater Source	Mathematical model showing the depth from the ground surface to the top of an aquifer.	Used instead of the groundwater levels dataset as Depth to Source measures depth to aquifer whereas the groundwater levels	Indicates the depth to the shallowest aquifer and therefore gives an indication	Constituent datasets variable but predominantly - 1:50,000 scale

			dataset could record phreatic/perched water table or aquifers that have limited productivity.	of the accessibility of the groundwater supply.	
Is made ground absent from the site?	Artificial Geology	An extract of the BGS Geology map, providing a visualisation of mapped artificial deposits	Areas within the site boundaries were created where no artificial ground was recorded.	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.	1:50,000 scale
Ground Heat (Vertical closed loop)	**Dataset**	**Background**	**Reworking**	**Justification**	**Scale/Resolution**
Am I on a productive aquifer?	Basic Superficial Deposits Thickness Model (BSTM)	Mathematical model of known thicknesses of superficial deposits	Superficial deposits less than 10m of recorded thickness have been removed from the BSTM data. This was then used to clip the superficial aquifer designation, and then combined	Indicates the calculated thickness of superficial deposits from archived borehole logs. This can therefore indicate where deposits are less than 10m	1:50,000 scale

			with the bedrock aquifer designation to create the files.	thick. Deposits less than 10m thick are removed as: 1 – “unsaturated zone is likely to be effectively less than 10 m thick” (Busby et al., 2009, p.302) meaning the impacts of groundwater will be more comparable. 2 - Vertical closed loop heat exchangers are typically installed between 15m and 120m deep (Energy Saving Trust, 2007). 3 – Below 10m depth, ground temperatures are constant (Energy Saving Trust, 2007) which are more desirable conditions for ground heat exchangers	

	Superficial aquifer designation/ Bedrock aquifer designation	"Joint Environment Agency and British Geological Survey dataset identifying the different aquifers of England and Wales" *	The reduced BSTM data was used to isolate the superficial aquifer designation data where deposits were greater than 10m thick. The bedrock aquifer designation data was not reworked.	Indicates the water-bearing properties of geological units. The ability of the subsurface to store and transfer groundwater may increase or decrease the efficiency of a GSHP system. (superficial/bedrock as appropriate).	1:50,000 scale
Is the groundwater vulnerable to contamination?	Groundwater Vulnerability	Joint Environment Agency and British Geological Survey dataset providing information on groundwater vulnerability.	Combined groundwater vulnerability map used. Worst case vulnerability classification used from the bedrock and superficial aquifer vulnerability designations.	Indicates the perceived risk to groundwater that development is likely to have. Drilling into an aquifer to install a GSHP borehole may create a potential contamination pathway.	1 kilometre square resolution
Is there deep groundwater?	Depth to Source	Mathematical model showing the depth from the ground surface to the top of an aquifer.	Used instead of the 'depth to groundwater' dataset as Depth to Source measures depth to aquifer whereas the	Indicates the depth to the shallowest aquifer (which many coincide with the water table). Saturated ground	Constituent datasets variable but predominantly - 1:50,000 scale

			groundwater levels dataset could record phreatic/perched water table at shallower elevations.	tends to increase thermal conductivity influencing the efficiency of a GSHP system	
Is the subsurface easy to excavate?	(Civils) Excavatability	British Geological Survey dataset based on geotechnical property information.	A new column was created due to cases when data was 'na' for typical strength or typical density excavation type. The new column 'typ_ex' presents data from the filled column to maximise map coverage.	Indicates the anticipated equipment required to excavate the ground. Important as a proxy for the potential cost of drilling and borehole/pump infrastructure.	1:50,000 scale
Is made ground absent from the site?	Artificial Geology	An extract of the BGS Geology map, providing a visualisation of known artificial deposits	Areas within the site boundaries were created where no artificial ground was recorded.	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.	1:50,000 scale
Subsurface Space	**Dataset**	**Background**	**Reworking**	**Justification**	**Scale/Resolution**

Is my site suitable for foundations?	(Civils) Foundations	Aims to “provide general guidance on the foundation conditions of rocks and soils present within geological units” (Entwisle et al., 2016).	The foundations data was not reworked.	Indicates the expected suitability of the ground for constructing foundations, and therefore a proxy for the suitability for subsurface construction.	1:50,000 scale
Is the ground easy to excavate?	(Civils) Excavatability	British Geological Survey dataset based on geotechnical property information.	A new column was created due to cases when data was ‘na’ for typical strength or typical density excavation type. The new column ‘typ_ex’ presents data from the filled column to maximise map coverage.	Indicates the anticipated equipment required to excavate the ground and therefore what techniques may be required to achieve necessary depth for utilising subsurface space.	1:50,000 scale
Is there shallow groundwater that may impact construction?	Groundwater Levels	“A raster grid, with 50 x 50 metre pixels holding values that represent the probable maximum depth, in metres, to the water table” (McKenzie, 2014).	Converted into vector data and grouped into ranged classifications (e.g. 0 – 2m, 2 – 5m, etc).	Indicates the anticipated maximum depth to the water table. May impact the construction method, dewatering requirements, and design parameters for subsurface structures.	50m pixel resolution (1:50,000 scale)

Can excavation materials on site be re-used?	(Civils) Fill	Aims to “provide general guidance on the use of geological units, as defined … by their lithostratigraphic description” (Entwisle et al., 2012).	The fill data was not reworked.	Indicates the potential reuse of subsurface materials to offset some costs of subsurface space development (by re-using elsewhere on site or selling on).	1:50,000 scale
Is made ground absent from the site?	Artificial Geology	An extract of the BGS Geology map, providing a visualisation of known artificial deposits	Areas within the site boundaries were created where no artificial ground was recorded.	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.	1:50,000 scale

Table 3.5 - Datasets utilised for each geo-resource potential tool. Each dataset has been justified for use relative to each specific geo-resource tool. Background information for each dataset is provided along with information on reworking and scale/resolution of use.

3.3.3 Step 3

Following the identification and collation of the relevant datasets, the category of interest within each dataset (and for each geo-resource) was scored high to low relative to the other categories within that dataset (but not across datasets) (Table 3.6). Higher scores represent more positive conditions for potential geo-resource utilisation.

Groundwater	
Am I on a productive aquifer?	
Categories	Score
principal	3
secondary a	2
secondary undifferentiated	2
secondary b	0
unproductive	0
unknown	0
Does the underlying bedrock have good productivity?	
Categories	Score
Good aquifer (>6 l/s) at outcrop, concealed aquifer at depth	3
Good aquifer (>6 l/s) at outcrop	2
Moderate aquifer (1-6 l/s) at outcrop, concealed aquifer at depth	2
Moderate aquifer (1-6 l/s) at outcrop	2
Concealed aquifer at depth	1
No suitable aquifer	0
Is the water resource vulnerable to contamination?	
Categories	Score
High	1
Medium	2
Low	3
Unproductive	3
Is there shallow groundwater?	
Categories	Score
<=50m	3
50-100m	2
>100-150m	1
>150-200m	1
>200-250m	1
>250-300m	1
>300-350m	0
>350-400m	0
No Source	0
Is made ground absent from the site?	
Categories	Score
Made Ground (Undivided)	0

Infilled Ground	0
Landscaped Ground (Undivided)	1
Worked Ground (Undivided)	1
No artificial cover recorded	2

Ground Heat (Vertical closed loop)

Am I on a productive aquifer?

Categories	Score
principal	0
secondary a	0
secondary undifferentiated	1
secondary b	2
unproductive	2
unknown	0

Is the groundwater vulnerable to contamination?

Categories	Score
High	1
Medium	2
Low	3
Unproductive	3

Is there deep groundwater?

Categories	Score
<=50m	0
50-100m	0
>100-150m	0
>150-200m	1
>200-250m	1
>250-300m	1
>300-350m	1
>350-400m	1
No Source	2

Is the subsurface easy to excavate?

Categories	Score
Hand Tools	2
Ripping	1
Power Tools	3
Drill and Blast	0

Is made ground absent from the site?

Categories	Score
Made Ground (Undivided)	0
Infilled Ground	0
Landscaped Ground (Undivided)	1
Worked Ground (Undivided)	1
No artificial cover recorded	2

Subsurface Space	
Is my site suitable for foundations?	
Categories	Score
Generally unsuitable for most foundation types (water)	0
Generally unsuitable for most foundation types	0
Generally very poor foundation conditions OR poor to moderate conditions (where ground is no longer tidal)	0
Variable foundation conditions from poor (in dynamic environment) to good (in stable environment)	1
Generally unsuitable foundation conditions (unless assessed as stable or stabilised by engineering works	1
Difficult foundation conditions (due to the presence of boulders)	1
Generally good foundation conditions	3
Good to poor foundation conditions	2
Foundation conditions unknown because lithologies are unknown	0
Good to very poor foundation conditions	2
Generally good foundation conditions BUT might be locally moderate or poor	2
Generally good foundation conditions BUT might be locally moderate or poor where dissolution occurs	2
Generally good foundation conditions BUT may be locally variable or poor	2
Generally good foundation conditions BUT might be locally poor	2
Is the ground easy to excavate?	
Categories	Score
Hand Tools	3
Ripping	1
Power Tools	2
Drill and Blast	0
Is there shallow groundwater that may impact construction?	
Categories	Score
0-2m	0
2-5m	0
5-10m	1
10-20m	1
20-50m	2
50-100m	2
100m+	2
Can excavation materials on site be re-used?	
Categories	Score
Mixed ‘soil’ fill	2
Mixed ‘soil’ fill (partly suitable)	1
Coarse ‘granular’ soil fill	2
Coarse ‘granular’ soil fill (partly unsuitable)	1
Fine ‘cohesive’ fill	2
Fine ‘cohesive’, dry fill	2
Gravel clay	2
Fine soil (silty)	2
Fine soil (sulphide/sulphate)	1

Fine soil (specialist clay)	2
Fine soil ('wet')	1
Chalk fill	2
Rock fill	2
Rock fill (sulphide/sulphate)	1
Mixed rock and soil	2
Mixed rock and soil (sulphide/sulphate)	1
Unsuitable for fill	0
Unknown	0

Is made ground absent from the site?

Categories	Score
Made Ground (Undivided)	0
Infilled Ground	0
Landscaped Ground (Undivided)	1
Worked Ground (Undivided)	1
No artificial cover recorded	2

Table 3.6 – Scores applied to the categories utilised in each dataset, for each geo-resource utilisation potential tool.

However, there are several problems with scoring geo-resource characteristics in this way. Firstly, there are a different number of categories within each dataset that need to be considered within the geo-resource mapping tool. Where there is a stepwise logic to these categories, the scoring may purely be reflective of the number of categories within the dataset instead of their significance, although this is resolved by only using scoring of 0-3 across all categories. In addition to this, the assigned scores are arbitrary unless a weighting mechanism can be imposed within the method to give the numbers comparable values and impart a value on their influence compared to the other factors. In order to address both of these matters, the Analytic Hierarchy Process (AHP) was employed.

3.3.4 Step 4

AHP is a decision-making technique which generates a set of weights based on relative importance (Saaty, 1977)[1].

3.3.4.1 Step 4.1

The first phase was to conduct paired comparisons between the different factors used in the geo-resource mapping. For example, as shown by the yellow boxes in Table 3.7 for ground heat (vertical closed), aquifer designation was judged of equal importance to groundwater vulnerability, but deemed strongly more important than the presence of made ground. The

[1] Factors are prioritised by multi-criteria decision making in a hierarchical structure, and the results are validated through cross-analysis.

pairwise comparison was undertaken by a domain expert for every possible pairing for each geo-resource type, and was recorded on a response form (Appendix A).

Ground Heat – Vertical Closed	Extremely More Important		Very Strongly Important		Strongly Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly Important		Very Strongly Important		Extremely More Important	
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater vulnerability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavat-ability
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavat-ability
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavat-ability
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavat-ability

Table 3.7 - Demonstrates the pairwise comparison results for ground heat where the shaded numbers represent the perceived relationship between the two factors. Yellow = original response. Red = adjustments following step 4.4.

A comparison matrix summarised the results of the pairwise comparisons as shown in Table 3.8. The comparison matrices for all geo-resources are presented in Appendix B.

Ground Heat – Vertical Closed	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavat-ability
aquifer designation	1	1	1/5	5	1/3
groundwater vulnerability	1	1	1/5	3	5
depth to source	5	5	1	3	3
presence of made ground	1/5	1/3	1/3	1	1/5
excavatability	3	1/5	1/3	5	1
TOTAL	10.20	7.53	2.07	17.00	9.53

Table 3.8 – Comparison matrix summarising the pairwise comparison results for the ground heat potential mapping tool.

The second phase was to calculate the relative weights from the comparison matrix. Each column was totalled and normalised (by dividing each element within the matrix by the sum of its column). For example, from the first row in Table 3.8 for aquifer designation vs groundwater vulnerability:

1÷7.53 = 0.13

The results for all comparisons for ground heat (vertical closed) are presented in Table 3.9 below. The results for all geo-resources are presented in Appendix C.

Ground Heat – Vertical Closed	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	Excavat-ability	TOTAL
aquifer designation	0.10	0.13	0.10	0.29	0.03	0.66
groundwater vulnerability	0.10	0.13	0.10	0.18	0.52	1.03
depth to source	0.49	0.66	0.48	0.18	0.31	2.13
presence of made ground	0.02	0.04	0.16	0.06	0.02	0.30
excavatability	0.29	0.03	0.16	0.29	0.10	0.88
TOTAL	1.00	1.00	1.00	1.00	1.00	

Table 3.9 – Relative weights calculated for the ground heat potential mapping tool.

Following this, the normalised results for each row were summed, and the row totals were divided by the number of factors being compared. For example, for ground heat (vertical closed) the number of factors being compared was five (aquifer designation, groundwater vulnerability, depth to source, presence of made ground and excavatability). Therefore, for the first row (aquifer designation):

0.66 ÷ 5 = 0.13

When multiplied by one hundred, the result was the percentage weight that each score should be weighted by. For ground heat, aquifer designation, this meant that the percentage weight was 13%. This is repeated for all ground heat attributes (as shown in Table 3.10) and for all geo-resources as presented in Appendix D.

Ground Heat	aquifer designation	ground-water vulnerability	depth to source	presence of made ground	Excavat-ability	TOTAL	Relative weight	Relative weight (%)
aquifer designation	0.10	0.13	0.10	0.29	0.03	0.66	0.132	13
groundwater vulnerability	0.10	0.13	0.10	0.18	0.52	1.03	0.206	21
depth to source	0.49	0.66	0.48	0.18	0.31	2.13	0.426	43
presence of made ground	0.02	0.04	0.16	0.06	0.02	0.30	0.060	6
excavatability	0.29	0.03	0.16	0.29	0.10	0.88	0.176	18

Table 3.10 – Ratio for relative weights calculated for the ground heat potential mapping tool.

3.3.4.2 Step 4.2

However, in order to verify the reliability of the weightings, a consistency index (CI) was calculated.[2] "In general, a higher consistency of judgements implies better judgements and therefore will result in more reliable estimates of the relative weights", however, "a tolerance consistency index of 10% is set for comparisons involving no more than 9 elements" (Mendoza and Macoun, 1999, p.56).

Calculating the CI has three stages:

1. For each column in the comparison matrix (Appendix B), the column sum was multiplied by the relative weight for each factor, and the results added together:

   (column 1 sum x relative weight) + (column 2 sum x relative weight) + (column 3 sum x relative weight)…etc.

   For example, for ground heat (vertical closed):

   (10.2 x 0.1313) + (7.53 x 0.2057) + (2.07 x 0.4258) + (17.00 x 0.0610) + (9.53 x 0.1762) =6.486

2. The number of elements was subtracted from the answer to stage 1.

   For example, for ground heat (vertical closed):

[2] The CI "is a measure of how logically consistent the judgements of the expert/participant are" (Mendoza and Macoun, 1999, p.56). For example, if a response form was measuring the importance of A,B and C, the answers may say B>A and A>C, which means therefore that B>C. However, if the response is B<C then this is inconsistent.

6.49 – 5 = 1.486

3. The answer from stage 2 was divided by the number of indicators minus 1.

   For example, for ground heat (vertical closed):

   1.49 ÷ (5 – 1) = 0.371

   The result is a decimal which when multiplied by 100 is the CI percentage.

   For example, for ground heat (vertical closed):

   0.371 x 100 = 37.1

Therefore, for the ground heat (vertical closed) weighting, the consistency index (CI) is 37.1%.

For the calculated CI to be valid, it must be compared against a separate measure (Saaty, 1977). In simple terms, "the numerical judgements have to be approximations, but how good these approximations are is the question" (Saaty, 1977, p.247). In answer to this, Saaty developed the Consistency Ratio (CR), which is a calculation to indicate how similar the judgements are to randomness.

For this value to be calculated, the CI for each geo-resource was divided by an appropriate value in the Random Consistency Index (RI) generated by Saaty (1977, p.249) [3]. Therefore, the equation is:

Consistency Index ÷ Appropriate Random Consistency Index (RI) value = Consistency Ratio (CR)

For example, for ground heat (vertical closed), the CR is:

37.1 ÷ 1.115 = 33.3

The results for all geo-resources are presented in Table 3.11.

[3] For a scale of 1 – 9 on the response feedback sheet (i.e. the number of categories available as a response), a RI of 1.115 is used when 5 factors are being compared (i.e. for ground heat horizontal and vertical closed, groundwater and subsurface space), and an RI of 1.150 is used when 6 factors are being compared (i.e. for ground heat vertical open).

	Consistency Index (CI) (%)	Consistency Ratio (CR) (%)
Ground Heat (Horizontal closed)	15.3	13.7
Ground Heat (Vertical closed)	37.1	33.3
Ground Heat (Vertical open)	35.9	31.2
Groundwater	37.4	33.5
Subsurface Space	16.3	14.6

Table 3.11 – Consistency Index (CI) and Consistency Ratio (CR) for all geo-resource potential mapping tools.

The results of the CI and CR calculations showed that the calculated weightings for every geo-resource are above the 10% tolerance threshold, and therefore the judgements on the response forms need to be revised in all instances.

3.3.4.3 Step 4.3

To improve the consistency rating, a new matrix that presents the inconsistency of each judgement was calculated. The value assigned to the comparison between the two factors was multiplied by the ratio of the two weights of the factors being compared. As an equation:

Results of the pairwise comparisons x (relative weight of factor 1 ÷ relative weight of factor 2) = Inconsistency Value

For example, for ground heat (vertical closed), a comparison was made between the two factors aquifer designation and groundwater vulnerability. The original judgement was that they are of equal importance (and therefore the value assigned to the pairwise comparison was 1). The relative weights calculated for each factor were 0.1313 for aquifer designation and 0.2057 for groundwater vulnerability. Therefore, the calculation was:

1 x (0. 1313 ÷ 0. 2057) = 0.64

This calculation was performed for every combination of factors (as shown in Table 3.12 for ground heat (vertical closed) and shown in Appendix E for all geo-resources).

The combination with the lowest values are the most inconsistent comparisons made on the response form. Several responses were changed to improve the consistency for ground heat (vertical closed). This was achieved by moving the value closer to the ratio of the relative weights in the original response form, and repeating the process above until the CI and CR were less than the 10% tolerance level.

Ground Heat (Vertical Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	Excavat -ability
aquifer designation	1.00	0.64	0.06	10.77	0.25
groundwater vulnerability		1.00	0.10	10.12	5.84
depth to source			1.00	20.94	7.25
presence of made ground				1.00	0.07
excavatability					1.00

Table 3.12 – Inconsistency value calculated for each category for the ground heat potential mapping tool.

This process was repeated for all geo-resources until acceptable tolerances were reached. The final comparison matrices for all geo-resources are presented in Appendix F.

3.3.4.4 Step 4.4

Through this process, adjustments were made to the initial response form to give a CI and CR of less than 10% (i.e. within the tolerance of the calculation). The adjusted (more consistent) responses were used to re-calculate the weights (Table 3.13) by following the process in step 4.1.

Ground Heat (horizontal closed)	**Relative Weight**	**% Weight**
aquifer designation	0.0518	5.18
groundwater vulnerability	0.0692	6.92
groundwater levels	0.3838	38.38
presence of made ground	0.3216	32.16
excavatability	0.1736	17.36
Ground Heat (vertical closed)	**Relative Weight**	**% Weight**
aquifer designation	0.1316	13.16
groundwater vulnerability	0.2507	25.07
depth to source	0.4150	41.50
presence of made ground	0.0518	5.18
excavatability	0.1509	15.09
Ground Heat (vertical open)	**Relative Weight**	**% Weight**
aquifer designation	0.2339	23.39
groundwater vulnerability	0.0784	7.84
depth to source	0.2516	25.16
presence of made ground	0.0269	2.69
excavatability	0.0385	3.85
bedrock aquifer potential	0.3707	37.07
Groundwater	**Relative Weight**	**% Weight**
aquifer designation	0.1729	17.29
groundwater vulnerability	0.0891	8.91
depth to source	0.1979	19.79

presence of made ground	0.0386	3.86
bedrock aquifer potential	0.5015	50.15
Subsurface	**Relative Weight**	**% Weight**
suitability of foundations	0.1789	17.89
re-usability of fill	0.0551	5.51
groundwater levels	0.2996	29.96
presence of made ground	0.0596	5.96
excavatability	0.4068	40.68

Table 3.13 – Adjusted weights for all geo-resource potential mapping tools providing a tolerant Consistency Index (CI) and Consistency Ratio (CR).

3.3.5 Step 5

Following the allocation of scoring (Step 3) and calculation of relative weights (Step 4), the scored categories from each dataset (Table 3.6) were multiplied against the relevant weights (Table 3.13) to give the weighted scores for each geo-resource category. Following this, the weighted scores were applied to each case study site to provide both a non-spatial and spatial analysis of site-specific geo-resource potential.

Applying weighted scores in a spatial context was a stepwise process which required access to pre-existing spatial data for each geo-resource category. The required spatial geological data was supplied by the British Geological Survey under an academic licence.

3.3.5.1 Step 5.1

Firstly, the weighted scores were qualified by a value. This was achieved by creating score range classifications for each geo-resource. Five geo-resource potential ratings (from very poor to excellent) were generated using equal interval range classifications[4].

This approach used common difference values calculated by the following equation:

(maximum weighted score - minimum weighted score) ÷ number of divisions = common difference

For example, for groundwater:

(2.961 - 0.089) ÷ 5 = 0.5744

[4] The score rating is based on the national range of scores that can be achieved from each dataset. A site-based scale may offer more granular information on the suitability across the site however a national scale is sufficient to provide an indication of geo-resource potential on site. Furthermore, if the scale were based only on on-site data, the potential use of the geo-resource could not be compared to any other site.

The calculations for the range classifications for groundwater are shown in Table 3.14. The range classification values for all geo-resources are presented in Table 3.15.

Rating	Interval Range	Calculation	Value
Very poor	First lower boundary	minimum score	0.089
Very poor	First upper boundary	minimum score + common difference	0.664
Poor	Second lower boundary	first upper boundary + 0.001	0.665
Poor	Second upper boundary	second lower boundary + common difference	1.239
Moderate	Third lower boundary	Second upper boundary + 0.001	1.240
Moderate	Third upper boundary	Third lower boundary + common difference	1.814
Good	Fourth lower boundary	Third upper boundary + 0.001	1.815
Good	Fourth upper boundary	Fourth lower boundary + common difference	2.390
Excellent	Fifth lower boundary	Fourth upper boundary + 0.001	2.391
Excellent	Fifth upper boundary	Fifth lower boundary + common difference	2.965

Table 3.14 – Calculations for the range classification intervals for groundwater potential mapping tool.

Following this process for all geo-resource types, five independent score range classifications were devised. Score ranges are not transferable between geo-resource types as the weighted scores for each category have been designed solely for use by that geo-resource. The score ranges calculated for each geo-resource potential tool are shown in Table 3.15.

	Ground Heat (Horizontal Closed)		**Ground Heat (Vertical Closed)**		**Ground Heat (Vertical Open)**		**Groundwater**		**Subsurface Space**	
Excellent	1.812	2.247	1.975	2.406	2.398	2.977	2.391	2.965	2.073	2.590
Good	1.376	1.811	1.544	1.974	1.818	2.397	1.815	2.390	1.554	2.072
Moderate	0.941	1.375	1.113	1.543	1.238	1.817	1.240	1.814	1.036	1.553
Poor	0.505	0.940	0.682	1.112	0.658	1.237	0.665	1.239	0.518	1.035
Very Poor	0.069	0.504	0.251	0.681	0.078	0.657	0.089	0.664	0.000	0.517

Table 3.15 – Calculated range classification intervals for all geo-resource potential mapping tools.

Where the information for each category is known for a site, the appropriate weighted scores can be added up to give a general geo-resource potential rating for that site. This provides a non-spatial evaluation of a particular area, however the weighted scores were attributed to mapping data to provide a spatial analysis.

3.3.5.2 Step 5.2

The following stages were undertaken sequentially to derive a spatial geo-resource potential analysis:

a) In a new excel spreadsheet, three columns were created (as shown in Figure 3.5) – the first was named 'objectid', and starting from 1, should increase by 1 for each occupied row. The second column was named the same as the column from the original dataset that is used for scoring, and contain all of the categories listed (for example for the aquifer designation dataset, the column was 'typology' and contained 'Principal', 'Secondary A', 'Secondary B', etc). The third column was named 'score' and contained the relevant weighted scores for each category within the dataset.

objectid	typology	score
1	Principal	0
2	Secondary A	0
3	Secondary (undifferentiated)	0.348
4	Secondary B	0.696
5	Unproductive	0.696
6	Unknown	0

Figure 3.5 – An example Excel table which assigns weighted scores to dataset attributes.

A separate file was created for each dataset utilised for each geo-resource and was saved in a CSV file format.

b) In ArcMap, new layers were created delineating the site boundary for each case study.

c) Using the Buffer tool, a 50m buffer was added to each case study site and the case study shape files were saved as 'Cambridge_50', 'Burton_50' and 'London_50' respectively. (The buffer accounts for the worst-case minimum accuracy/resolution for the utilised datasets (1:50,000 scale)).

d) The raw shape files were loaded for every dataset into ArcMap.

e) In ArcMap, ArcToolbox → Analysis Tools → Clip was opened. Each relevant dataset was entered into Input Features. The relevant case study shape file ('Cambridge_50', 'Burton_50' or 'London_50') was entered into the Clip Features. The new file was saved in the format 'case study_dataset' as the Output Feature Class (For example

‘Burton_50_aqu_des_bed’). This was repeated for every dataset map used and for each case study.

f) In ArcMap, the join function was used to add the table from stage a) to the dataset maps. The table was joined based on the second column (which matches the name of the column from the original dataset). Within the join options, the ‘keep all records’ option was selected and ‘Validate Join’ query was run prior to actioning the join. The resulting shape files contain additional columns in their attribute tables including the ‘score’ column.

g) The new shape files were saved as the ‘case study name_dataset name_JOIN’ (for example ‘Burton_area_gw_vul_JOIN’.

h) In pgAdmin, a new database was set up for each geo resource by right clicking on Databases → Create → Database… .The database was named after the geo-resource type and case study (for example ‘GT_Ver_Closed-BURTON_50’).

i) Once created, each database was right clicked and Create → Extension… was selected. In the Name drop down option, ‘postgis’ was selected and saved. pgAdmin was then closed.

j) Several datasets were edited before being incorporated into a geo-resource potential mapping tool. The changes are summarised in Table 3.5 (reworking column).

k) The PostGIS Shapefile Import/Export Manager software was opened and View connection was selected. Using the username and password to set up pgAdmin, the Database name which corresponds to the shape files that are being imported was selected and OK was clicked.

l) Using Add File, the relevant dataset shape files which contain the joined data to be imported were selected. The SRID column was changed to 27700 for every shape file added, and then imported. (This sets the shapefile coordinate system to British National Grid).

Once all of the relevant shape files were imported for one database, a new connection was made to import the other shape files into the other geo-resource databases. To do this, stage i) was repeated however the Database name was changed to correspond with the next geo-resources set of datasets to be imported.

m) In pgAdmin, the path Servers → PostgreSQL 10 → Databases was followed to locate the five databases created in stage h) for each geo-resource type. Starting with GT_Ver_Closed-BURTON_50, the Database was selected and Tools → Query Tool was selected. The code from Appendix G was pasted into the Input box and Run. The process was repeated for the remaining Databases and run the respective code from Appendix H.

n) In QGIS, the Add PostGIS Table(s) extension and New options were selected. In the pop up, the Connection Information was entered to link to the GT_Ver_Closed-BURTON_50 Database.

o) Connections were made to the other databases by repeating stage n) and entering the relevant Connection Information.

p) Once complete, the GT_Ver_Closed-BURTON_50 Database was connected to through the Schema tree, and the overlap4 shape file was opened.

q) The shape file was saved as 'Burton_area_ground_heat_vertical_open', following the format 'location_georesource'.

r) Stages p) and q) were repeated to connect to each database, visualise the maps for each geo-resource, and save the shape files with the applicable names.

s) For each shape file, shape file were right-clicked in the Layers Panel and Properties was selected. In the Style tab, the Symbols drop down box was changed to Graduated. For Column, Total was selected from the drop down options. For Colour ramp, RdYlGn was selected. Classify was clicked and entries were manually changed for the Values and Legend to those shown in Table 3.15.

3.3.5.3 Step 5.3

Implementing stages a) to s) resulted in the output of a site-specific geo-resource potential map. For quantitative output of this information, the following steps were used to create site-specific score coverage data.

i. A new Excel Spreadsheet was created named 'export_score' and saved in CSV format.
ii. In pgAdmin, the GT_Ver_Closed-BURTON_50 Database was selected.
iii. Tools → Query Tool was selected and the following code was run in the input box:
CREATE TABLE export_score AS

SELECT total, SUM(st_area(geom)) FROM overlap4 GROUP BY total

iv. Once complete, the browser tree was opened down to Tables (Database → Schemas → public →Tables → export_score). The export_score table were right-clicked followed by Import/Export.

v. The first box was switched to Export. For Filename, the export_score csv file was navigated to (created in step i). and when prompted yes was selected to replace the file. Under Miscellaneous, the Header option was switched to Yes.

vi. In the CSV file, the two columns labelled total and sum will be populated in A and B respectively. The values in Total are all of the possible score totals for the site map. The values in Sum are the areas covered. The file format was saved as XLSX using the Save As function. This allowed formulas to be saved for the following steps.

vii. = SUM(cells) was used to add up the values in the sum column. This is the total site area.

viii. Two new columns were then created. One which contained a list of the totals and the other which contained the added up area for that total (i.e. the total score area).

ix. One of the total score areas was divided by the total site area and then multiplied by 100 to get the percentage of the site containing that total score. This was repeated for all of the total scores and their respective areas.

x. The total scores and their presence across the site were translated into the geo-resource potential ratings (created in Step 5.1) to quantify the results by percentage area. The relevant geo-resource potential score ranges were copied into the spreadsheet and a new column for calculating the percentage area of site was created next to the upper and lower score limits.

xi. =SUMIFS(area_of_site,total, ">=" lower score bracket,total, "<=" upper score bracket) was used in the new column. This calculation added up the total area of the site (%) for each score total and queried whether the score total is between the lower and upper score brackets for the selected rating (for example, if the score total was 1.275 for 30% of the site area, was this number between 2.07256 and 2.58970 which is the score bracket for ‘excellent’ geo-resource potential for subsurface space use). It returns the % area of the site which is within the lower and upper score boundary for ‘excellent’.

This formula was used to query the score totals for all five potential geo-resource ratings.

3.3.6 Step 6

Using a combination of the geo-resource potential map and the score coverage calculations, the results were then considered within the Urban Design Geo-resource (UDG) Matrix for each individual geo-resource type.

The UDG matrix was designed specifically for each case study site and geo-resource type. It utilises the sustainable development ambitions and urban design criteria of national, regional, district and local agendas, and assesses how the use of geo-resources can contribute towards their conditions.

To create the UDG matrix required a blank Excel spreadsheet. The first column identified the level of the criteria (international, national, local, etc), and the second column provided the name of the document from which the criteria (policy or guidance information) was sourced. The third column summarises the criteria from the urban planning, design or assessment documentation.

The matrix contains potential methods of geo-resource use across the horizontal axis, and the sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). The intersecting boxes are marked with a 1 where the criteria is supported by the geo-resource use (or the geo-resource use can fulfil the criteria), and a 0 where there is no link (Appendix I).

Figure 3.6 demonstrates the are two approaches which could be taken from the geo-resources potential map outputs. Firstly, if the user has prioritised certain criteria, the user can see which geo-resource use may fulfil the criteria (i.e. has the greatest number of 1's in the UDG matrix). For example, for the groundwater UDG matrix, pursuing the national criteria to be adaptable and resilience (under the UK Government Design Guidance) encourages the employment of advanced rainwater harvesting, whereas the criteria to support mixed uses and tenures does not. Alternatively, if the user is pursuing a specific method of geo-resource use, the user can see how implementing it may fulfil or complement certain criteria. For example, for the groundwater UDG matrix, permeable paving and soakaways could significantly contribute towards successful public spaces (under the UK Government Design Guidance), whereas advanced rainwater harvesting does not (Figure 3.6).

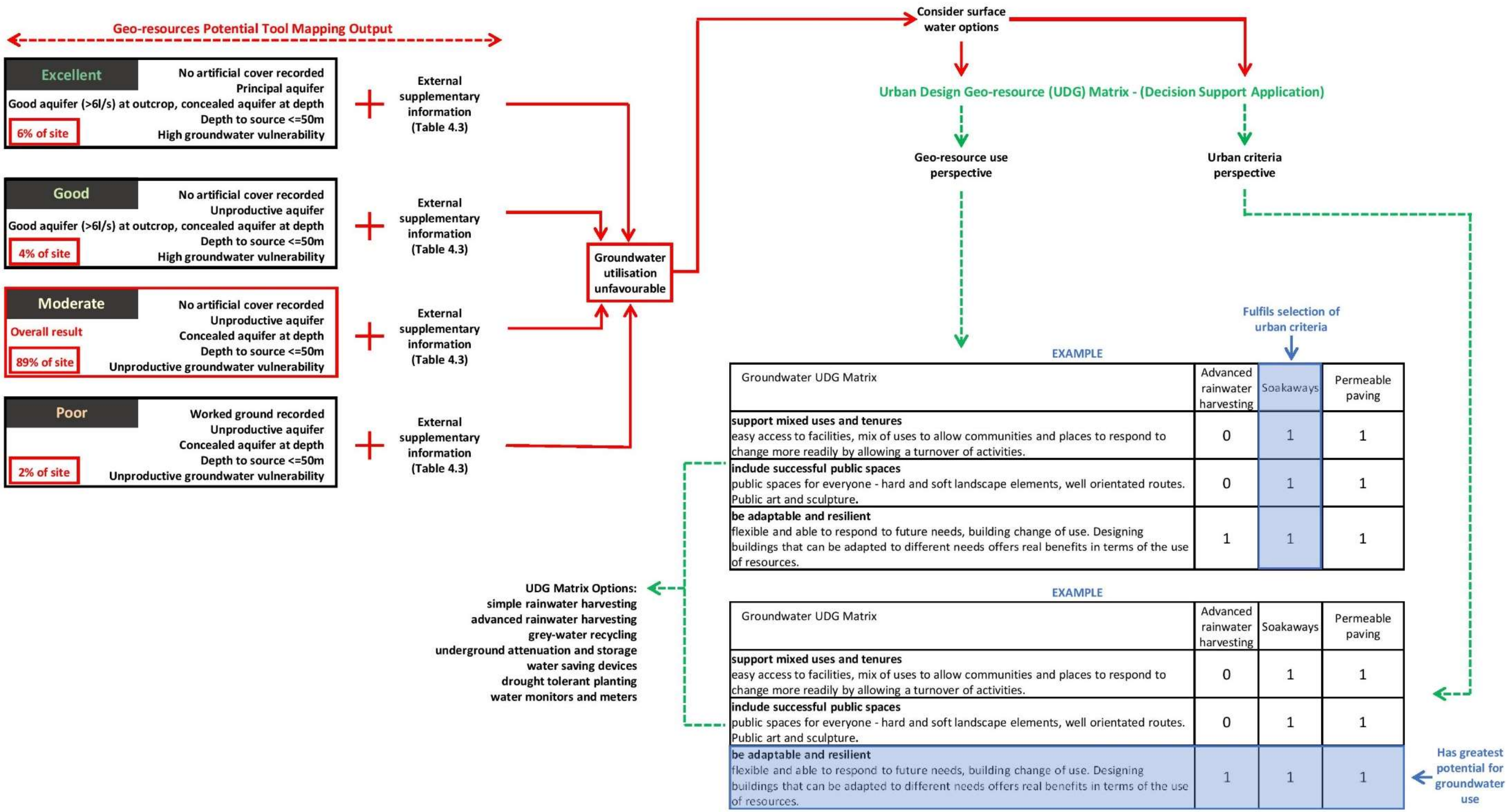


Figure 3.6 – Flow diagram summarising the method of applying the geo-resource map output to the Urban Design Geo-resource (UDG) matrix using groundwater as an example.

As the UDG matrix is site-specific, a UDG matrix for each case study has been created to address regional and local scale urban sustainability and resilience objectives.

Following its creation, collaboration between urban stakeholders with specialist expertise (such as geologists) would result in the optimal use of the UDG matrix. For the case studies, the in-depth investigation undertaken for this research provided adequate knowledge for the researcher to discuss the content of the UDG matrix within the relevant chapters.

3.3.7 Data Collection, Access Statement and Model Limitations

As a CASE partnership project with the British Geological Survey (BGS), this research benefited from access to their spatial geological datasets to develop the geo-resource mapping model. Furthermore, certain datasets (such as the groundwater vulnerability maps) are owned by the Environment Agency (EA) and have been authorized for use within this research project. The datasets utilised for this study have accompanying user guides which have been crucial for evaluating the individual datasets for use in generating the maps.

The geo-resource potential maps are available in ESRI shape format and are viewable in Geographical Information Systems (GIS) such as ArcMap or QGIS. The method used to create the geo-resources model requires software packages including: Microsoft Excel, QGIS, ArcGIS and pgAdmin (PostgreSQL).

3.3.7.1 Geo-resources Mapping Tools and Data Limitations

As with the generation of any new modelling approach, the geo-resources potential maps have a variety of limitations which are discussed below. This outlines the limitations of the geo-resources mapping tools rather than the limitations of each dataset used in this project. Dataset limitations are discussed in the dataset user guides and can be accessed separately. User guides are available for all of the datasets used in this study except for the depth to source map and aquifer potential map as these are already amalgamations of datasets.

- In preparing the geo-resource potential maps, a worst-case scenario was assumed whilst utilising each dataset. Encountered ground conditions may be better than expected which may allow different construction methods to be implemented following professional review. This means that the maps can be used to create construction scenarios with the most difficult (but possible) ground conditions, and allows stakeholders to prepare a budget and programme which can only be improved upon. This is partly fulfilled by the UDG matrix, which highlights how utilising the geo-resource on site can fulfil site-specific planning policy and urban design guidance.

- The digital datasets used were those available at the time of creating the geo-resources models and interpretations were made based on these datasets. However, datasets are constantly being modified and updated as new information becomes accessible, meaning later versions may contain more accurate or modified information.

- All geo-resource potential maps are limited by the resolution of the data. For most datasets, coverage is at 1:50 000 scale which means that the data should not be used to characterise ground conditions at less than a 50m interval. The geo-resource maps were developed from these datasets and therefore should also only be used at 1:50 000 scale. The case study sites are approximately 150 (CS1), 0.5 (CS2) and 0.92 (CS3) hectares in size which is adequate for the mapping tools, however application of the maps to very small sites is not recommended as the map-data does not have a high-enough resolution. Furthermore, it should be acknowledged that the map outputs will present more variable information for larger sites due to the granularity of the data.

- The datasets only provide information two-dimensionally (i.e. across a plane) which in many cases is data at ground level. Complete evaluation of subsurface geo-resources requires three-dimensional interpretation. The superficial thickness model (BSTM data), and depth to source map provide pseudo three-dimensional information, however the vertical profile is not fully represented in the geo-resources mapping tool. This is particularly relevant in areas; without superficial deposits at surface, where the bedrock varies significantly at shallow depths (such as the chalk outlier observed on the NW Cambridge map) and in areas where there is a significant thickness of superficial deposits that are highly variable with depth.

  For the geo-resources mapping models, borehole data (depth information) was utilised to verify the map for each case study site. However, three-dimensional data should be integrated into the mapping process to account for vertical variations. To include more information on vertical variations, triangulating borehole data across an area to create simple geological surfaces at depth would build a picture of subsurface conditions, and should be considered for later iterations of the mapping tool.

- Although relevant basic data has been acquired for the geo-resource maps, they are limited by a lack of other pivotal data. CS1 (NW Cambridge) would have benefited from incorporating regional groundwater flow and groundwater availability data , CS2 (Chestnut and Aspen Mews) from incorporating subsurface temperature data and CS3 (Canary Wharf Crossrail Station) from existing subsurface structures. These data are either unavailable or not accessible at a granular enough scale to be valuable within the mapping tool. Later iterations of the mapping tool should check for these data in case appropriate datasets do become available.

- The geo-resource maps involve scoring and weighting dataset attributes to determine the potential utilisation of geo-resources on a site. The case study sites range from having excellent to poor potential for geo-resource use, however, given the success of utilising geo-resources at these sites, it would be logical to assume that all three should be achieving a high rating. Amending the scoring procedure to portray high ratings should be considered for future iterations of the mapping tool.

- As previously mentioned, the current rating system is based on the national score-range. If the scale was limited to the scores attainable only at a site level, it would demonstrate more varied ratings across the site for the use of geo-resources but would not be comparable to any other site.

- The geo-resources potential mapping model does not account for any economic or engineering design aspects but may work alongside external reports on these subjects.

- The geo-resource maps should be used as an indicative guide to the geo-resource potential of a site and should not be considered as a replacement for site investigations or specialist reports.

- With regards to the UDG matrices, the output only provides an indication of which geo-resources connect with planning policy/urban design criteria, and could be improved upon by identifying the optimum solution to attaining the connection.

  Information included within the UDG matrices are only relevant for the time that the geo-resource utilisation is being considered. Planning policy and urban design guidance is constantly updated and therefore the criteria will need updating if its use is delayed.

In addition to these issues, limitations specific to each geo-resource mapping tool are discussed within the relevant case study chapter.

3.4 Qualitative Interview Approach

Being able to evaluate the geo-resource potential of a site (as described above) plays a role in creating sustainable urban areas. However, to deliver the value of the geo-resource mapping tool requires implementation of the technique by the right people and at the right time. Kajornboon, (2005, p.2) for example, noted that "the researcher has to know and select the appropriate method for addressing the needs of the research question", thus semi-structured interviews were undertaken to explore the utilisation of geo-resources at the case study sites. To connect the interview process with the overarching scope of the research project (and the geo-resources potential mapping tool), the following objectives were focused on throughout the interview analysis:

- To explore the general understanding and awareness of sustainability and resilience agendas;
- To survey the perspective of geo-resources in different stakeholder groups for building the sustainability and resilience of urban areas;
- To investigate geo-resource use in urban design within the context of the case studies.

As previously mentioned, there has been some debate over the suitability of interviewing as a scientific research tool. For instance, Brewerton and Millward (2001, p. 74) stated that "due to their openness to so many types of bias, interviews can be notoriously unreliable, particularly when the researcher wishes to draw comparisons between data sets". However, for a factual based study such as this, the effects of subjectivity are significantly diminished with interviewing allowing "comparability by ensuring that all questions are answered by each respondent" (Barriball, 1994, p. 329). In additional, Bell (2005, p. 157) reflecting on the adaptability of conducting interviews, stated that "a skilful interviewer can follow up ideas, probe responses and investigate motives". In short, there are opportunities from conducting interviews which significantly outweigh the difficulties associated with the method.

Qualitative interviews are typically categorised into one of three forms: unstructured, semi-structured and structured (DiCicco-Bloom and Crabtree, 2006; Gill et al., 2008; Knox and Burkard, 2009). This research implemented semi-structured interviews where a set of pre-determined open-ended questions were asked to stakeholder representatives for the three case study sites. Corbetta (2003, p.270) further clarified that within the remit of semi-structured interviews "the interviewer is free to conduct the conversation as he thinks fit, to ask the questions (s)he deems appropriate in the words (s)he considers best, to give explanations and ask for clarification if the answer is not clear, to prompt the respondent to elucidate further if necessary, and to establish his (or her) own style of conversation".

3.4.1 Interview Design

The dialogue is led by the discussion and guided only by the themes set out in the interview design. The interview component of this research broadly followed the four pan-paradigmatic stages set out by Robinson (2014) and reproduced in Figure 3.7.

The four-point approach to qualitative sampling

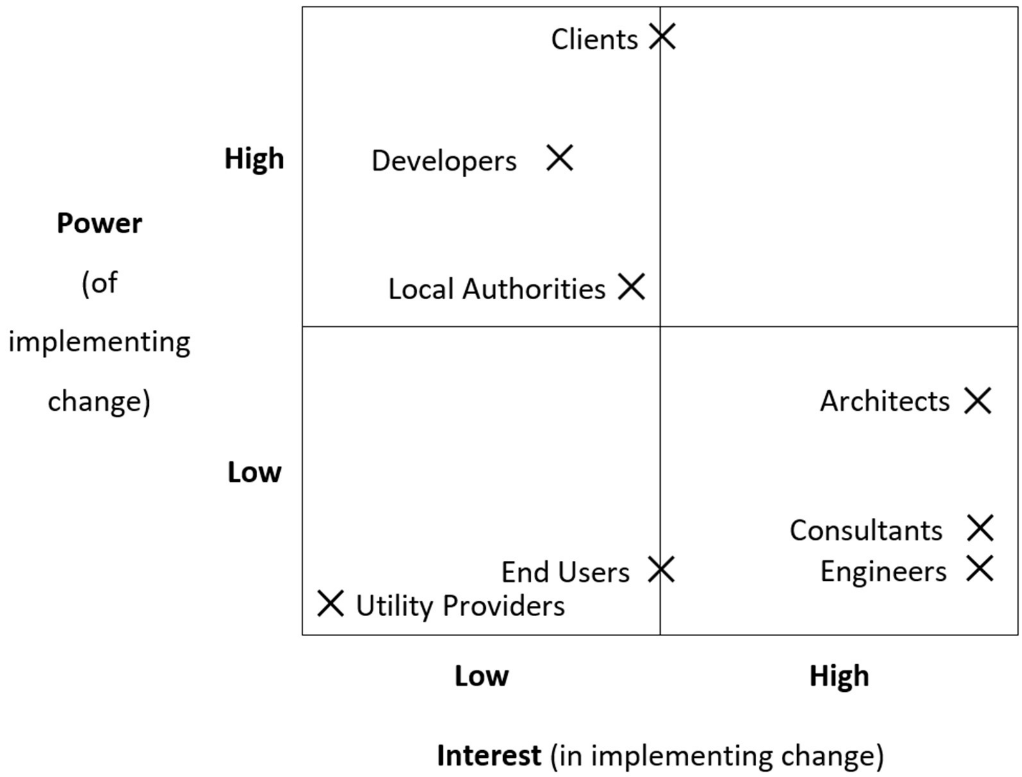
	Name	Definition	Key decisional issues
Point 1	Define a sample universe	Establish a sample universe, specifically by way of a set of inclusion and/or exclusion criteria.	Homogeneity vs. heterogeneity, inclusion and exclusion criteria
Point 2	Decide on a sample size	Choose a sample size or sample size range, by taking into account what is ideal *and* what is practical.	Idiographic (small) vs. nomothetic (large)
Point 3	Devise a sample strategy	Select a purposive sampling strategy to specify categories of person to be included in the sample.	Stratified, cell, quota, theoretical strategies
Point 4	Source the sample	Recruit participants from the target population.	Incentives vs. no incentives, snowball sampling varieties, advertising

Figure 3.7 – The four stages to qualitative research (Robinson, 2014).

3.4.1.1 Point 1 - Define a Sample Universe

Interviewees were selected based on their breadth of experience and expertise relevant to the geo-resource use or sustainable design aspect of each individual case study. The types of stakeholder that participated in an interview are shown in Figure 3.8. Stakeholder matrix A

Stakeholder Matrix A



Stakeholder Matrix B

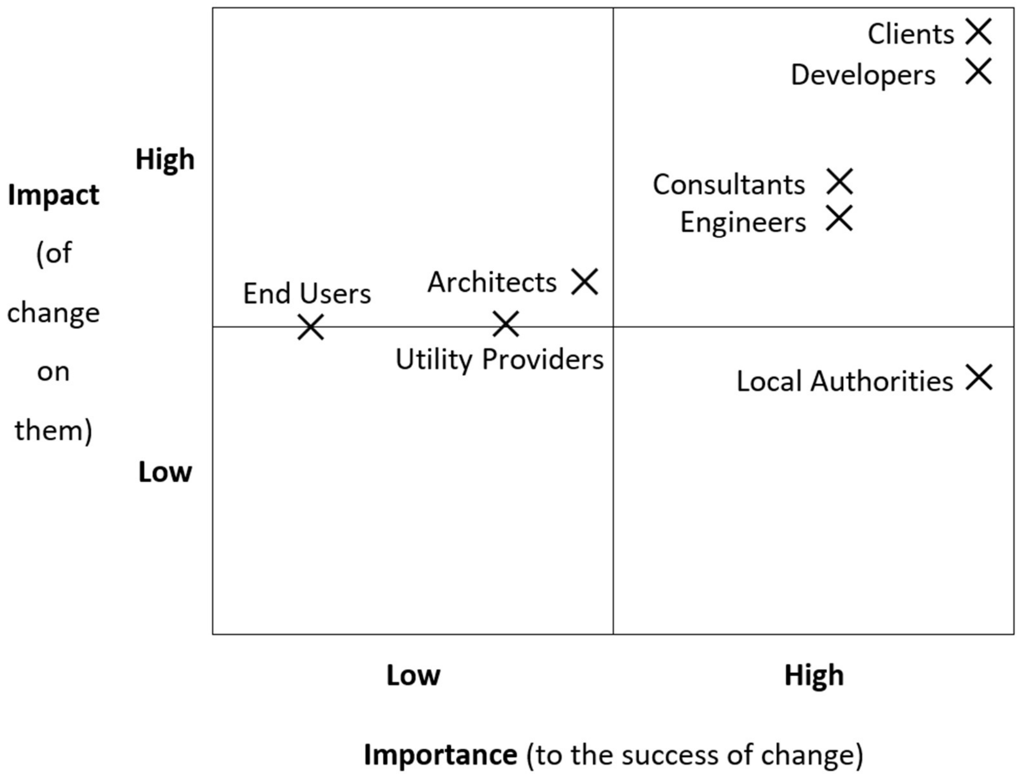


Figure 3.8 – Stakeholder matrices detailing the type of stakeholders participating in interviews as well as their perceived level of power and interest in implementing change, and their impact and importance.

is an interpretation of the level of interest that stakeholder groups have in implementing change, and the power these stakeholders have to execute change. Stakeholder matrix B is an interpretation of the importance of the stakeholders to the success of the change, and the impact of the change on them.

3.4.1.2 Point 2 – Decide on a Sample Size

Overall, 30 interviews were undertaken with stakeholder groups illustrated in Figure 3.8. At this point data saturation was reached as indicated by the stabilisation of the code definitions when transcribing the interviews (Saunders et al., 2017).

3.4.1.3 Point 3 – Devise a Sample Strategy

For each of the three case studies, possible representatives from each stakeholder group were identified (Figure 3.8). However, this was not always possible, and the views of some stakeholders were obtained from other sources (such as review platforms and feedback reports). Table 3.16 identifies the stakeholder types for each case study that contributed to a discussion and was achieved through purposive sampling strategy that relies on the researcher to utilise their knowledge and choose appropriate candidates to participate in the study (Dolores and Tongco, 2007). This technique was employed in the belief "that certain categories of individuals may have a unique, different or important perspective on the phenomenon in question and their presence in the sample should be ensured" (Robinson, 2014).

Cambridge (GW)	Local council Engineer Consultant Client Utility Provider End User
Burton on Trent (GT)	Local council Consultant Developer Client
Canary Wharf (SS)	Engineer Consultant Architect Designer Client

Table 3.16 – Stakeholders participating in interviews for the relative case studies.

3.4.1.4 Point 4 – Source the Sample

Participants were recruited from by approaching companies and individuals associated with case study sites, and making enquiries with the relevant governing authorities and organisations. In addition, snowball sampling was incorporated into the interview questions to extend participation to other potential interviewees.

3.4.2 Interview Process

Prior to the start of each interview participants were provided with a participant information leaflet (PIL) and consent form. The PIL explained the purpose and methodology of the project as well as the use of participant data. The consent form was signed by each participant in accordance with conditions set by the ethics approval process at the University of Warwick (Approval Reference: REGO-2018-2191).

Interview questions were aligned across individual interviews by a flexible interview outline that was supplied to each interviewee in advance. Questions were tailored to each interviewee and were organised thematically. The questions encouraged interviewees to consider themes in their answers, for instance, when asking participants 'what factors were most important in enabling geo-resource use for the project?', the interviewees could explain their views within the context of the case study.

The following headings characterise each interview section:

- Interviewee profile

  Confidentiality of the participants is maintained by only referring to their company or field of expertise. This section builds a profile of the individual for accurate character reference.

- Company

  To consider the company's familiarity with sustainable development and geo-resources.

- Main Discussion/Project (drivers, enablers, barriers and failures to geo-resource utilisation)

  To discuss what factors are drivers, enablers, barriers and failures to geo-resource utilisation at the relevant case study site or general urban development projects.

- Sustainability/Resilience Assessments

To gage the understanding, perception and use of sustainability and resilience assessments.

- Project Governance

  To assess the perception that stakeholders have of other stakeholder groups for geo-resources and sustainability.

- Interview Close

  Asking for recommendations for other potential interviewee candidates and offering an opportunity for return questions.

Interviews lasted between 15 and 135 minutes but were on average 60 minutes in duration. Interviews were recorded where possible and were fully transcribed following completion of the interview and subsequently coded.

3.4.3 Coding Interview Data

The interview data collected was processed through qualitative content analysis performed on the verbatim transcripts. The coding approach enabled progressively deeper levels of extraction from literal interview transcripts to capture the broad spectrum of answers from interview participants. Coding was achieved manually and using spreadsheets as there was an insufficient number of interviews to warrant the use of NViVo.

The first step in the coding process was to become familiar with the transcribed interviews whilst considering the overall aim of the research. Following this, each interview was dissected to identify meaning units and then condensed meaning units (Erlingsson and Brysiewicz, 2017). The condensed meaning units contain the original value of a statement but represent it in a concentrated form. Once complete, the next stage was to create codes for the meaning units to cross-examine the information through different interview transcripts. Four categories of codes were devised to classify the condensed meaning units: enablers, barriers, drivers and potential failures. Coding can be achieved in several ways but is ultimately a way to simplify and reduce data into a more useable form (DeCuir-Gunby et al., 2011). Codes act as markers which highlight emergent themes across vast amounts of information that otherwise may have been overlooked.

By performing this examination, it was possible to identify persistent themes across the interviews. The total number of times each theme was repeated was summed as the final part of the approach. A selection of the most common themes observed across the interview series are presented in Figure 3.9.

North West Cambridge (Groundwater)		**Chestnut and Aspen Mews (Ground Heat)**		**Canary Wharf Crossrail Station (Subsurface Space)**	
Enablers	**Drivers**	**Enablers**	**Drivers**	**Enablers**	**Drivers**
- Effective partnerships - Supported by policy - Feasible/viable design - Solution to multiple issues	- More efficient for water distribution - Sustainability high on the agenda - Driven client	- government subsidy - economic feasibility - good communication - motivated stakeholders	- planning requirements/policy - effective systems - reducing building problems/ maintenance	- economic returns over project life cycle/ cost effective solution - safeguarded space	- government targets - carbon reduction - futureproofing - avoiding existing infrastructure
Barriers	**Potential Failures**	**Barriers**	**Potential Failures**	**Barriers**	**Potential Failures**
- Expensive - Safety concerns/ risk/liability	- Breakdown in communication	- high risk perception - expensive design/high capital costs - poor planning policy	- financial problems - land ownership issues	- high capital costs - prioritising costs - subsurface obstacles	- land cost - unsettled legal dispute

Figure 3.9 – Themes observed across each interview series for each case study site.

3.4.4 Data Collection, Access Statement and Limitations

As previously stated, this study passed the ethics approval process for research studies at the University of Warwick in June 2018 (Approval Reference: REGO-2018-2191). Interview data was collected in line with the research protocol associated with the authorisation and consent forms were signed by all participants whose data was utilised for this study. There were however limitations to this approach.

One limitation to consider was the level of subjectivity of the interview approach. For example, due to the nature of semi-structured interviews, the way that questions were asked and the directions that the discussions followed would have influenced the result of each interview. Furthermore, the identification of codes and themes within the interview transcripts was limited to the interpretation of the researcher.

In addition, the process of gathering interviewees was occasionally hindered following the introduction of the General Data Protection Regulation (GDPR) in 2018, however it did not discourage individuals from participating in an interview. Occasionally permission from the clients or associates of the interviewees was required to conduct an interview, which only caused a delay and not a complete stop to the work.

Another limitation is the amount of time each interviewee had available to partake in an interview. This would have influenced the depth of the answer that an individual could provide and therefore may have impacted the results.

3.5 Qualitative Document Examination

The themes that surfaced from the interview technique frequently touched upon the role of urban planning and urban design guidance because it is these sectors that influence and control the policies of urban sustainability across the development industry.

This research has developed a new geo-resources mapping tool and explored the perception of geo-resources and their utilisation through case study sites. However, geo-resource utilisation in the UK is heavily influenced by the governance of urban areas and in particular their multi-level systems of planning and associated design guidance. The English planning system is complex, as demonstrated by the need for a 'Plain English Guide' to communicate a high-level overview of how the system works (Department for Communities and Local Government, 2015). A closer inspection of planning policy and guidance relevant to the case study sites revealed whether any particular articles or levels of planning served to facilitate geo-resource utilisation, and what challenges are impacting knowledge and implementation. Besides this, there are also non-statutory guidance documents and sustainability assessments relevant to geo-resource utilisation which impact the rate of uptake and affect stakeholder perceptions.

To meet this end, an examination of relevant documents was undertaken for each case study site which has enabled triangulation of the results from the other elements of the mixed-methods approach (Figure 3.10). As Gross (2018) noted, "when used in triangulation, documents can corroborate or refute, elucidate, or expand on findings across other data sources, which helps to guard against bias".

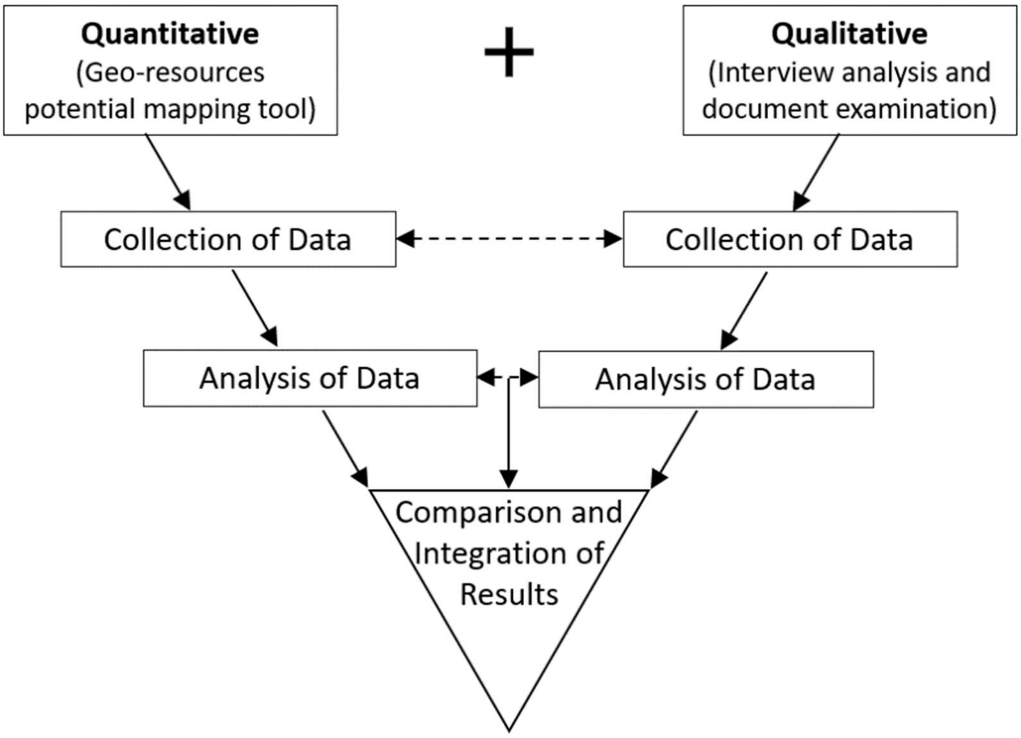


Figure 3.10 – schematic of the triangulation from elements of the mixed-methods approach (amended from Creswell, 2003, cited in Bentahar and Cameron, 2015).

3.5.1 Document Examination Design

The first stage of this analytical technique was to find the documents relevant to each case study site. A pre-requisite for this was to establish what documents existed at the different planning levels from an international to site-scale. Through the detailed inspection of case study reports and documents for the case study sites, multi-scale planning policy trees were established for each location (Figure 3.11).

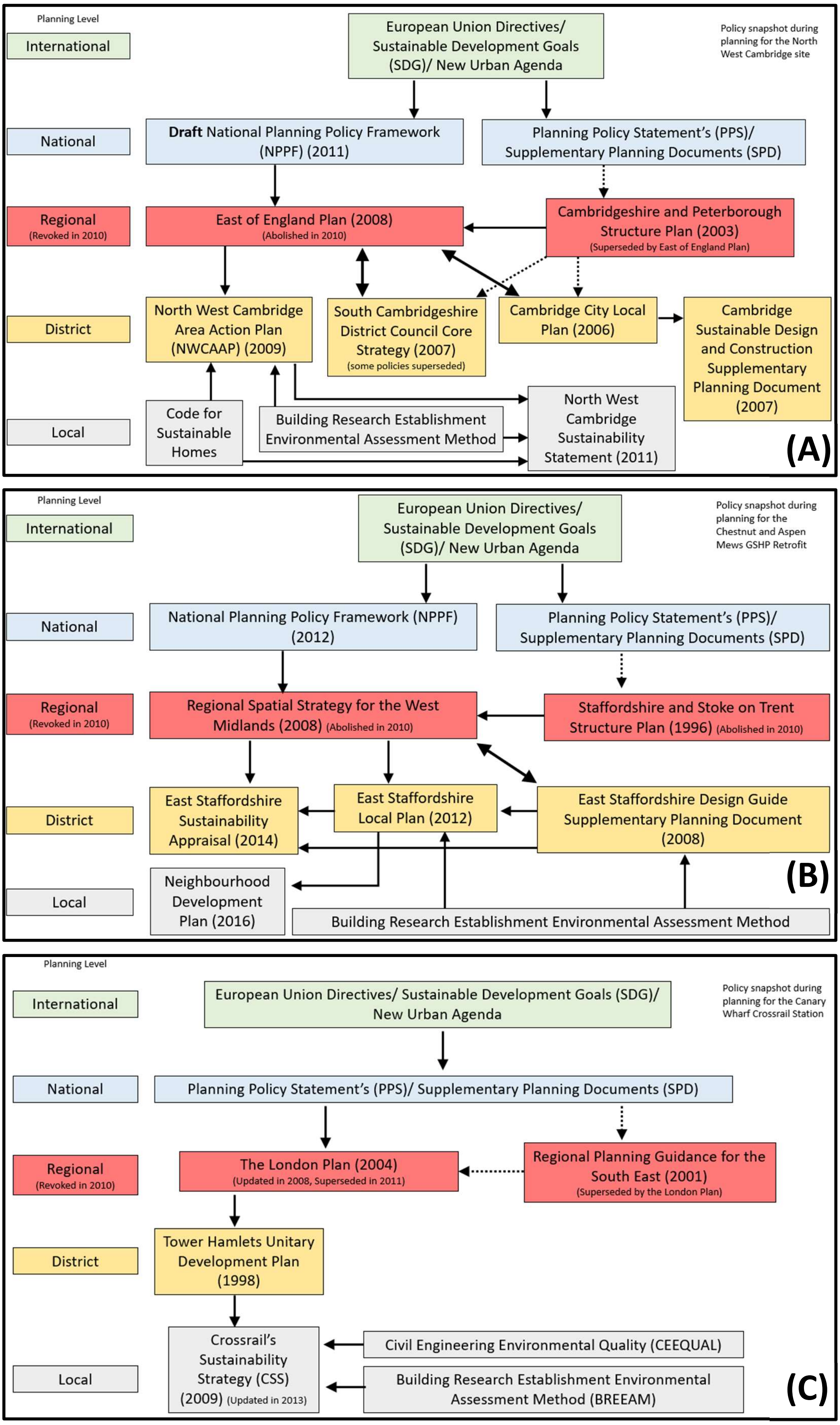


Figure 3.11 – Structure of UK planning governance and the relevant documentation at different planning levels at the planning phase of case study sites. A = Groundwater (NW Cambridge), B = Ground Heat (Chestnut and Aspen Mews), C = Subsurface space (Canary Wharf Crossrail Station).

The key documents relevant to the respective planning levels are illustrated in Figure 3.11. Where applicable, non-statutory documents such as resilience or sustainability assessment frameworks (e.g. BREEAM or CEEQUAL) are also shown within Figure 3.11 at the site-specific level. This was to demonstrate the inclusion or exclusion of geo-resources in existing urban sustainability and resilience assessments, particularly as some planning authorities requested proof of sustainability through assessment schemes. BREEAM was heavily encouraged by planning authorities for post-construction reviews. Documents connected to planning policy which include references to geo-resources were analysed as part of the analytical narrative for each case study.

3.5.2 Document Examination Strategy

Based on this structure, an extensive review of planning policy and associated documents that existed across the different levels and were associated with the case study sites was conducted. The types of documents analysed ranged from site specific sustainability statements, to regional geo-resource plans, to international sustainability strategies. A selection of key documents that were reviewed in this process are shown in Table 3.17. To ensure thematic consistency with the case study sites and the other analytical techniques, documents were chosen due to their significance to the site-specific urban sustainability discourse and/or their geo-resource use.

Year	Document	Relevance
2003	Water Act	National legislation for abstracting water in the UK.
2008	East of England Plan	Regional-level guidance for sustainable urban development (including water resources).
2006	Cambridge Local Plan	District-level guidance for sustainable urban development (including water resources).
2011	Renewable Heat Incentive	Government scheme to increase the uptake of renewable heat technologies.
2010	West Midlands Local Authority - Low Carbon Economy Programme	Measures the progress on implementing low carbon solutions in the region.
2013	East Staffordshire Borough Climate Change Strategy and Implementation Plan	Addresses actions for the region to reduce its impact on climate change (including alternative energy options).
2012	National Planning Policy Framework	National guidance for urban development.
2000	London East-West Study	Discusses some aspects of managing the subsurface in central London.
2009	Crossrail's Sustainability Strategy	Sets out development targets for achieving sustainability.

Cambridge   Burton   London

Table 3.17 – A selection of the key documents that were reviewed for each case study document examination.

Within these documents, searches were carried out for keywords associated with the case-study-specific geo-resources and sustainability search terms. Example keyword searches for each case study are shown in Figure 3.12.

Keyword	Cambridge	Burton	London	Keyword	Cambridge	Burton	London
sustain	x	x	x	geothermal		x	
sustainable	x	x	x	thermal		x	
sustainability	x	x	x	ground heat		x	
resilience	x	x	x	heat		x	
resilient	x	x	x	subsurface	x	x	x
resiliency	x	x	x	ground	x	x	x
groundwater	x	x	x	underground	x	x	x
water	x	x	x	subterranean	x	x	x
wastewater	x	x		belowground	x		x
source		x		space			x

Figure 3.12 – Example keyword searches for each case study document examination.

This technique did not assess how regularly geo-resources terms are used within documents, but examined whether geo-resources themes are integrated and if their inclusion is supplemented by clear and effective guidance for their utilisation in urban settings. Therefore, the results were presented as an analytical narrative, lending itself to the characteristics of a summative content analysis, which shared the goal to go "beyond mere word counts to include latent content analysis" (Hsieh and Shannon, 2005).

This technique also aligned with the aims of other established qualitative approaches and utilised some of their procedures such as hermeneutic content analysis (HCA)[5] and thematic analysis[6]. The document examination undertaken for this project shares some characteristics of HCA as interpretation is required where the methods for employing geo-resources may be ambiguous within urban guidance documents. Furthermore, the document examination approach is comparable to thematic analysis as keywords equate to themes. The keywords

[5] Hermeneutic content analysis (HCA) covers a broad range of content analysis methods (Bergman, 2015). The technique is known as the "science of interpretation" (Allen and Jensen, 1990) and is commonly used to understand religious writings (Jasper, 2004, p. 7). HCA "involves description but considers understanding and reflection of material" (Vieira and de Queiroz, 2017).
[6] Thematic analysis follows a similar approach to hermeneutic analysis but involves extracting text which conforms to one of the three levels of themes set by the researcher: basic, organising and global (Attride-Stirling, 2001).

were processed in a similar manner to the basic themes in thematic analysis. The importance and influence of these keywords was considered in the wider framework of geo-resource utilisation within urban design and sustainable development. This is akin to the process of relating basic themes to organising themes, and then global themes as part of thematic analysis.

The final product was a detailed examination of the inclusivity of geo-resources within case study documents, and provided an indication of the perception of geo-resources across the different levels of governance in England. This contributed valuable information towards identifying which sectors have the most influence in managing urban development, and what flaws in the current system need addressing to enhance urban sustainability and resilience through the use of geo-resources.

3.5.3 Data Collection, Access Statement and Limitations

Similarly to the qualitative interview approach, this method is limited by the subjectivity of the technique. This method relies upon the interpretation of the researcher to identify the themes within each document. The expertise of the researcher minimises the risks associated with this limitation however it should still be acknowledged.

This approach relied upon the relevant documents being readily accessible in order to conduct the analysis. Although in many cases documents were easy to source there were some which were private, unobtainable or incomplete. For example, the 1998 Unitary Development Plan for the Tower Hamlets Borough was acknowledged as a key guidance document within the Canary Wharf Crossrail Station planning report. However, it was confirmed by the Borough Council that this document was not held in their records and was therefore unavailable for use in this study.

Finally, although a thorough investigation was undertaken and key documents were incorporated, it cannot be assumed that all of the relevant documentation for each case study site was uncovered for this research. Furthermore, any new articles produced since the document examination will be missing from this analysis and may necessitate a revision to these findings.

3.6 The Case Study Sites

Three case study sites were selected as they demonstrate geo-resource utilisation in urban development in the UK. The purpose and background to each site has been summarised below.

3.6.1 Case Study Site One – North West Cambridge Development (Groundwater)

On average across England, almost a third of public water supply comes from groundwater resources (British Geological Survey, 2015b). The amount of groundwater available to support public water supply is measured frequently and has allowed hydrogeologists to project the change in groundwater availability in the future. A map produced by the Environment Agency illustrates that the case study area is in an area suffering from serious levels of water stress (Environment Agency, 2007). Ravilious (2017) states that “Cambridge Water and Cholderton Water rely entirely on the water found in the chalk and sandstone rock formations of the south-east”. Cambridge Water, the supplier of public water for the region explain that “in total, 97% of the water supplied by Cambridge Water comes from boreholes drilled into the chalk strata south of Cambridge” (Cambridge Water, 2018).

The North West Cambridge development is part of the University of Cambridge, and it was designed to be a long-lasting and resource efficient development. The site includes; 1500 new homes, 1500 private houses, 100,000 square meters of academic and research development space, a hotel, a care home, sports centre, playing field and public open space (North West Cambridge, 2018). The development aspires to achieve sustainability, including “a site-wide requirement for Code for Sustainable Homes Level 5 for the housing, as well as a minimum rating of BREEAM Excellent for all other buildings” (Wilson, 2018). To meet this challenge the daily potable water use needs to be less than 80 litres per head per day, 69 litres less than the national average (Consumer Council for Water, 2020). This target requires innovative design measures to be implemented on site and is partially fulfilled by the site-wide non-potable water supply network.

Surface water from across the site is diverted into swales and ditches which drain into lakes located on the site. Water is then directed through reed beds (which are the initial step in the treatment process) into a treatment plant before being drawn into the non-potable water system that supplies buildings across the site. The non-potable system does not interact with the potable system, however is laid in parallel to the supply. This design is innovative and the largest recycled water-system in place in the UK (Wilson, 2018).

This dual water network design at North West Cambridge has been chosen for a case study as:

1. It can demonstrate the various views of development stakeholder groups.
2. It is advanced in the UK as an approach to meet water demand (i.e. using two separate water supply networks from different water sources).
3. The region is highly dependent on groundwater to meet water supply needs, and therefore has high dependency on urban design solutions for new developments to reduce demand and reduce the pressure on groundwater supplies, making it an ideal model for testing a new geo-resource resilience approach.

3.6.2 Case Study Site Two – Chestnut and Aspen Mews, Burton on Trent (Ground Heat)

As technology has advanced, ground heat energy in the shallow subsurface has been recognised for its potential as a renewable heat source for domestic and commercial buildings. The number of Ground Source Heat Pump (GSHP) installations has been rising in the UK for a number of years, and the benefits of these systems are well explored including; economic aspects, environmental considerations, energy saving and energy supply security (Karytsas and Theodoropoulou, 2014).

A residential area of Burton on Trent was recently updated when a social housing company retrofitted 60 properties across two blocks of flats with GSHPs. The scheme involved the installation of 40 communal closed loop boreholes connected to individual ground source heat pumps in every flat. Tenants have reaped savings of between £350 and £750 on their yearly heating bills due to the investment in this recent technology (Kensa Heat Pumps, 2015a).

This GSHP scheme has been chosen for a case study because:

1. Information on the project has been made available from stakeholder groups. Due to the private and competitive nature of GSHP consultation, information has been challenging to acquire for other potential case study sites.
2. It is an example that can demonstrate the impacts of GSHP installations and give an indication of the efficiency of the scheme beyond the initiation phase (as it was completed in 2015).

3. Its status as a retrofit to an existing building presents more opportunity to utilise this approach in established urban areas (as well as new developments).

3.6.3 Case Study Site Three – Canary Wharf Crossrail Station, Crossrail (Subsurface Space)

The use of underground space for infrastructure such as car parking and commercial sites is common in many cities. The subsurface as a spatial resource also encompasses buried utilities, sustainable drainage systems, and private extensions such as iceberg houses, which due to the increasing popularity in London, have required local authorities to implement new subsurface development policies.

One of the most recent sizable developments of the subsurface has occurred in London. Crossrail, a subsidiary of Transport for London, has involved the construction of 26 miles of tunnels underneath London's busy streets (Crossrail Ltd, 2017a). The overall construction project makes use of geo-resources in numerous ways. With regards to water, water saving measures have been implemented both in the construction phase and in the operational phase of the network. For example, "low volume flush and leak detection systems for stations and portal washroom facilities as well as rainwater harvesting at the Old Oak Common depot which will be used to wash the new trains" (Crossrail Ltd, 2017c). In addition, of the 7.9 million tonnes of excavated material from the construction of Crossrail, 97% of the material was re-used or recycled. Much of the material was transported by water to Wallasea Island to contribute to the creation of a new RSPB wetland habitat (Crossrail Ltd, 2017d). However, as the main focus of this case study is to assess the benefits of utilising subsurface space, the tunnelled sections are the focus of this study, and in particular, Canary Wharf Crossrail Station.

Canary Wharf station is of primary interest due to its use of the subsurface for space and its interactions with other uses of the subsurface. The station itself is five stories below a mixed-use subterranean space and is constructed within a body of water (West India Dock). The station was originally named the Isle of Dogs Station, and therefore many of the planning reports are written under this title. The urban design of the station building is unique with "a 310 metre-long timber lattice roof, sheltering a striking roof-top garden, [which] lets in light and rain for natural irrigation" (Crossrail Ltd, 2017b).

The subsurface development at Canary Wharf Crossrail Station has been chosen for a case study because:

1. It is a recent development employing the latest technology with regards to underground space use, and therefore can present the most current challenges of underground construction.
2. It has employed many cross-sectorial stakeholders locally on site but also regionally across London, representing a well-rounded account.
3. Many documents are publicly accessible including development plans and sustainability reports across the Crossrail network.

3.7 Summary

By conducting multiple case studies, results can be analysed within individual settings but also across themes. In this case an exploration was made into the use of geo-resources as a whole as well as for groundwater, ground heat and subsurface space respectively.

Performing the three analytical procedures detailed above for each case study site resulted a comprehensive set of results which enabled a discussion surrounding the perception and utilisation of geo-resources, and their impact for building sustainable and resilient urban areas. The following chapters present the findings of the three case studies: NW Cambridge (groundwater) (Chapter 4), Chestnut and Aspen Mews (ground heat) (Chapter 5), and Canary Wharf Crossrail Station (subsurface space) (Chapter 6).

4 - Investigating Groundwater and Urban Design at the North West Cambridge Development

Water is a crucial resource for existence, and human settlement has undeniably altered its cyclic behaviour on a universal scale (Sterling et al.,2013). From Chapter 2, practice examples of marrying water with sustainable development are discussed, and it is highlighted that groundwater, a key part of the water cycle, is a complex but well-managed resource that is carefully monitored in the UK. In England, abstraction is managed by the Environment Agency (EA) so that the use of groundwater – an important contributor to water supplies - can be regulated from a central authority.

The City of Cambridge is one region that relies entirely on groundwater as 100% of the regions drinking water is sourced from local chalk and greensand aquifers (Cambridge Water, 2019). With such a high dependency on groundwater in the region, there lies an opportunity to relieve the pressure on groundwater and enhance urban sustainability and resilience simultaneously. Through the combination of sustainable drainage infrastructure and an innovative dual water supply network, a novel approach has been implemented at the North West Cambridge (NW Cambridge) development to increase urban sustainability and in-turn enhance the resilience of groundwater supplies. This development aligns with the pursued definition of resilience (as discussed in Chapter 2) where it raises the threshold for the community at NW Cambridge to survive, adapt and grow in response to any events that may impact the longevity of the site from a water resources perspective. As the region is highly dependent on groundwater to meet regional demand, obtaining water from a non-potable system diversifies the water sources, creating more options to support the water supply network.

This chapter explores the techniques through which pressures on groundwater resources have been alleviated at the NW Cambridge site. The capacity of the dual water network is unique in the UK (Wilson, 2018), and therefore this site offered an opportunity to study the value that geo-resources and urban design can bring when working harmoniously together. The potential use of groundwater was first assessed by a site-specific geo-resource mapping tool. Following this, the facilitators and obstacles in implementing the scheme have been investigated through a series of stakeholder interviews and an examination of planning policy and groundwater guidance documents. Combined, the data collected from these methods demonstrate the perception and potential use of groundwater in enhancing urban sustainability and resilience.

4.1 Introduction

The NW Cambridge development is located west of the city of Cambridge (National Grid Reference TL 42635 59965) (Figure 4.1), and straddles two council boundaries: Cambridge City Council in the East, and Cambridgeshire District Council in the West.

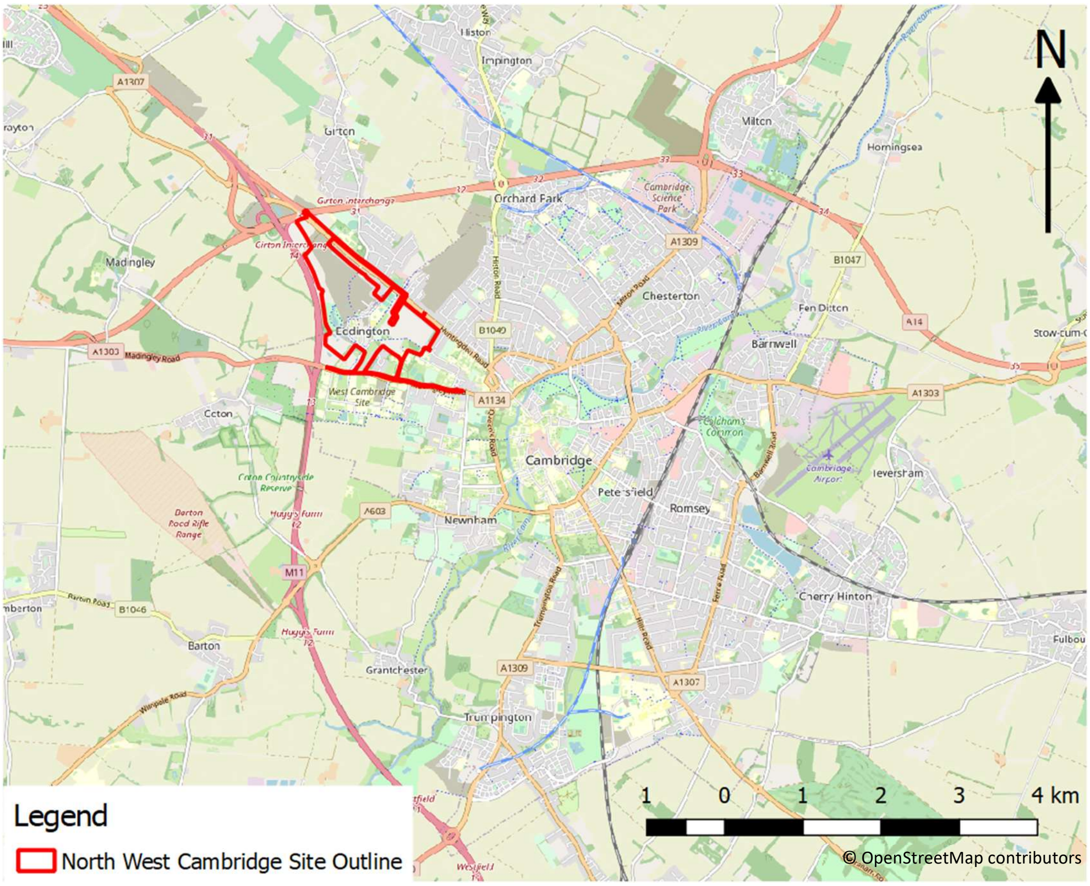


Figure 4.1 – Site location plan for the North West (NW) Cambridge development.

The 150 hectare site is owned by the University of Cambridge and divided into five areas, with Eddington at the local centre. Once finished the site will contain 3000 new homes, new amenities for the local community and new research facilities for the University (North West Cambridge Development, 2017). Outline planning was submitted for the site in September 2011, and granted in February 2013. The site is divided into eight phases with 26 development parcels (North West Cambridge, 2013). Phase one of the development includes residential housing, a primary school and a nursery as well as the associated transport infrastructure. Eddington (the local centre in phase one of the development) is described as a "natural meeting point with a range of retail, leisure and community facilities" (North West Cambridge Development, 2017). The infrastructure design for Phase 2 has been completed and the business case will be presented this year (2020) (West and North-West Estates Board, 2019).

There is a high standard for sustainability planned across many aspects of the development. For example, the sustainability statement, submitted in 2011 as part of the planning application, noted that "sustainability principles have been used to guide the design and development of the sustainability strategy for the Proposed Development" (AECOM, 2011, p.4). Sustainability approaches for the site also include a district heating system, solar panels and an underground waste storage system which embraces the use of underground space.

Another of these sustainability features is the UK's largest rainwater harvesting Sustainable Drainage System (SuDS). The water collected from this system is circulated site wide for use in toilets, washing machines and gardens (Figure 4.2).

TABLE 4 - STANDARD SPECIFICATION OF WATER USE FOLLOWING APPLICATION OF 'DELIVERABLE' WATER EFFICIENCY MEASURES		
Feature	**Water use estimation litres/person/day (including normalisation factor)**	**Water Demand Type**
WC	12.3	Non-potable
Taps (excluding kitchen taps)	7.2	Potable
Bath	15.5	Potable
Shower	23.9	Potable
Kitchen sink taps	11.8	Potable
Washing machine	14.3	Non-potable
Dishwasher	3.3	Potable
Garden	5.0	Non-potable
Total Potable Demand/person	**61.7**	
Total Non-Potable Demand/person	**31.6**	
Total Demand/person	**93.3**	

Figure 4.2 – Potential usage of potable and non-potable water based on the Code for Sustainable Homes Level 5 efficiency targets (URSb, 2013, p.9).

The scheme was designed to reduce the pressure on the potable water system by providing 31.6 litres per person per day of the total 93.3 litres per person per day estimated used across the site (URS, 2013b). The water use target across the development is 80 litres per person per day, which is nearly half of the UK average at 150 litres per person per day which would have amounted to a total of 1,035,000 litres of water every day for a development of 3000 houses (South Staffs Water, 2010). Water use is closely monitored to review whether these estimations are accurate, and whether the target of 80 litres per person per day is being attained.

When only considering the 3000 residential dwellings at NW Cambridge with an average occupancy of 2.3 people per home (Cambridge Water, 2019), the estimated water use will be approximately 552,000 litres of water every day across the development. When compared to the average water usage per person for Cambridge (137 litres per person per day, (Cambridge Water, 2019)) this equates to a saving of 393,300 litres per person per day (which means 41% less water should be used at NW Cambridge than the average for Cambridge for the equivalent number of houses).

This saving is crucial given that it is predicted that the amount of water available for use will reduce by 800,000 litres per day for the Cambridge region by the year 2045 due to climate change (Cambridge Water, 2019). The scheme delivers a water saving of approximately 400,000 litres per day equivalent to 50% of the estimated savings required under future climate projections (Cambridge Water, 2019). Even though the urban extent of the NW Cambridge development is small, and the amount of water consumption is small when compared to the usage across the region supplied by Cambridge Water, the site is delivering a large proportion of the water efficiency measures that are likely to be needed in the future. If the water scheme at NW Cambridge was replicated elsewhere in the region, the estimated savings would significantly mitigate the predicted impact of climate change for the area.

The implemented design works as a water sensitive urban design (WSUD) scheme[1]. Surface water is collected via a SuDS network, treating it and then redistributing it via a non-potable site wide network which works in parallel to the potable water supply (Figure 4.3). The system intercepts surface water from across the development and directs it into ditches and swales which discharge into surface reservoirs (the lagoons on the western edge of the site). The swales and ditches are aligned with the pre-development water catchment area, and follow the natural topography of the site, directing most water from the centre towards the western edge. Once in the lagoons, water is filtered through reed beds and a water treatment plant before being pumped back to buildings via a network of pipes parallel to the potable water network. Storm water leaves the lagoons via culverts which join the local

[1] "Water sensitive urban design (WSUD) denotes an approach to the planning and design of urban development, namely the integration of urban water systems with the natural water systems that are part of the hydrological cycle" (Barton and Argue, 2007, p.31).

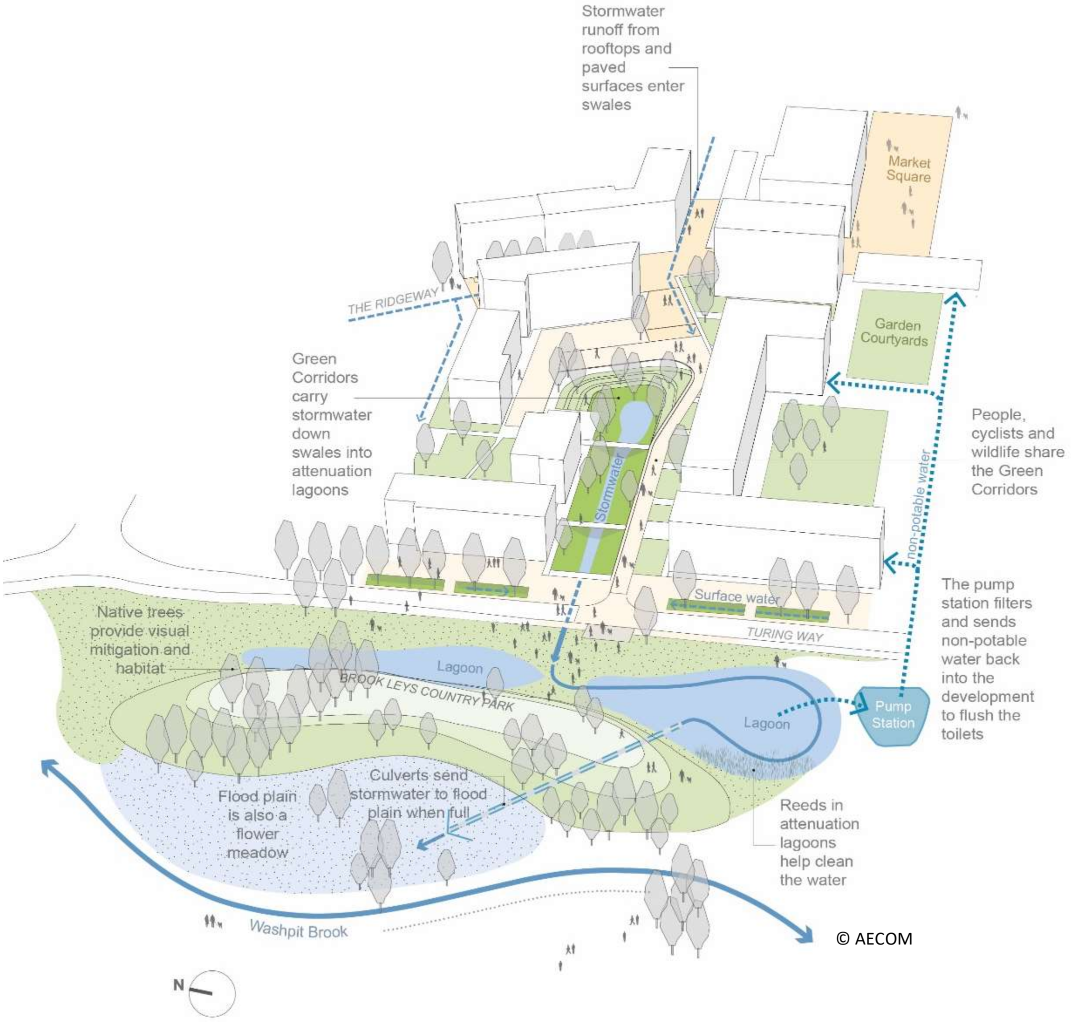


Figure 4.3 – Non-potable water supply network at the NW Cambridge site (AECOM, no date, cited in Wilson, 2018).

stream west of the site (the Washpit Brook) (Figure 4.3). By controlling the rate of flow in this way, the optimal balance can be struck to maximise water efficiency and maintain stable environmental conditions downstream. The non-potable network operates separately to the potable water supply in order to minimise any risks of cross-contamination.

Implementing such an extensive WSUD scheme has a range of potential benefits as shown in Figure 4.4. The water network at NW Cambridge fulfils many of these outcomes including the creation of a public open space from the surface SuDS (green corridors, swales, lagoon area) and the creation of wildlife habitats and corridors supporting biodiversity in the area. With the far-reaching benefits of WSUD being so desirable for creating sustainable urban developments, it is essential to explore how the water-saving scheme at NW Cambridge came about, and how the vision was achieved.

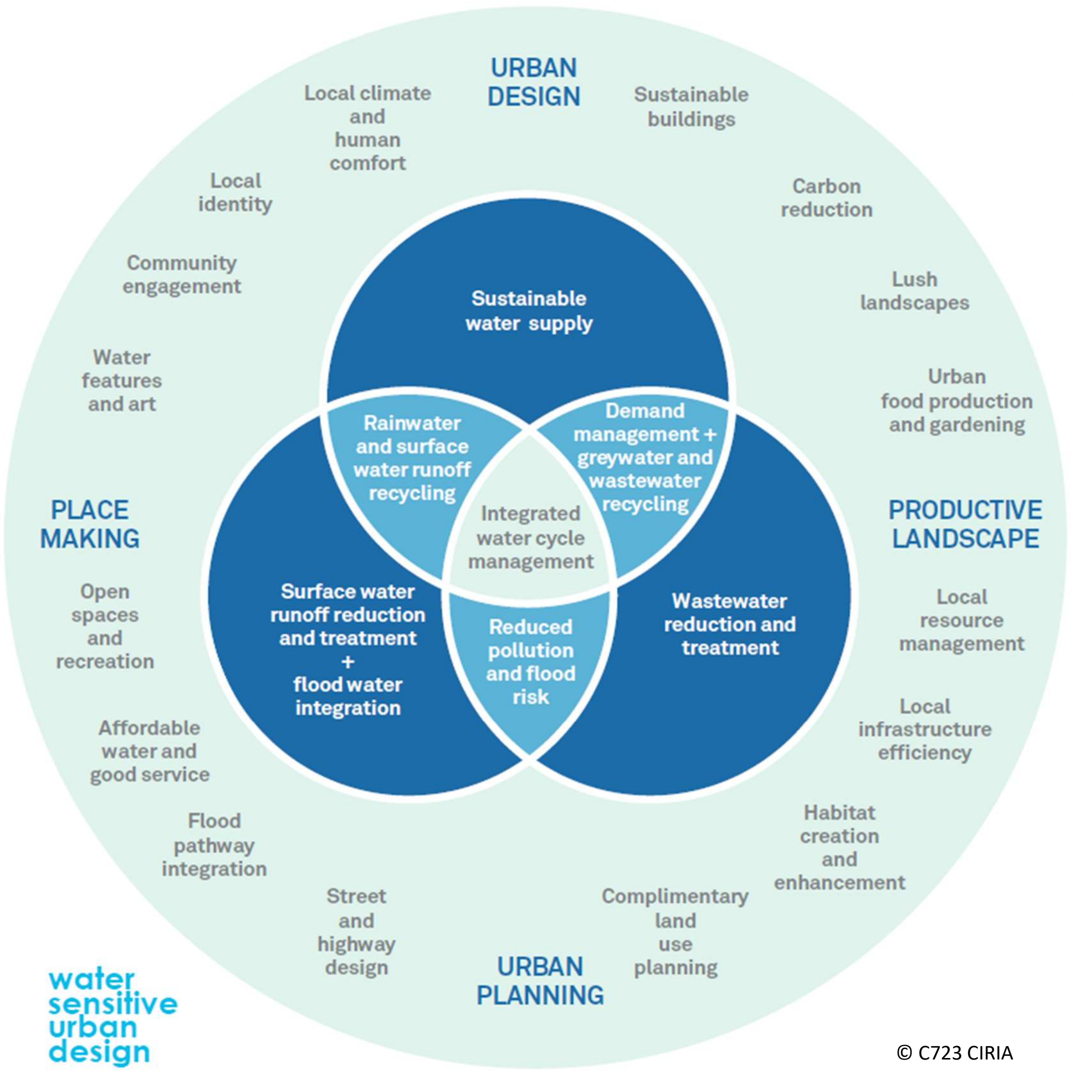


Figure 4.4 – The inter-related aspects of water sensitive urban design (Morgan et al., 2013).

4.2 Site Characteristics

4.2.1 Geological Setting and Hazards

The geological setting of the site determines the potential availability of groundwater for urban exploitation. Borehole and map records held by the British Geological Survey (BGS) indicate that part of the site is underlain by superficial Head (gravel) deposits, typically 2.3 – 3m thick (boreholes refs: TL46SW135 and TL45NW49), which occur from north to south in the central and eastern areas of the site. The Head deposits are underlain by the Gault Formation; a mudstone bedrock which occurs across the majority of the site, other than in the eastern corner of the site where the overlying West Melbury Marly Chalk Formation is present. The Gault Formation is underlain in turn by the Lower Greensand Formation, Oxford Clay Formation and the Corallian Group.

Reports indicate that the majority of the site comprises topsoil underlain by sand and gravel which varies in thickness from 1 – 5m in the north, to less than 1m in the south (URS, 2013a). In discrete areas, made ground, rather than topsoil, was encountered thought to be related to previous development and a former landfill[2]. The Gault (Clay) Formation was proven immediately beneath the superficial sand and gravel deposits, and the Lower Greensand Formation was encountered underlying the Gault Formation from 42 - 51m below ground level (boreholes refs:TL45NW118 and TL45NW49).

A significant implication of this is that due to the low permeability of Gault clays, infiltration may be limited across the site. Furthermore, the limited thickness of sand and gravel deposits also impedes infiltration and water storage potential, which means that regardless of planning policy or design, direct groundwater utilisation on site may be restricted. However, the Lower Greensand Aquifer may be suitable for supporting water supplies from a geological perspective should other conditions (such as environmental and economic) allow exploitation.

Although the focus of this study is to demonstrate geo-resource potential (specifically for groundwater), it is worth noting the geo-hazards which could affect the utilisation of geo-resources on site. There are locations on site that are at some risk from collapsible deposits, landslides and running sands. In addition, the pervasive Gault Formation underlying the site has a high plasticity, and the West Melbury Marly Chalk Formation (underlying the eastern-most area of the site) has the potential to create solution features under the correct conditions. Specialist design for the infrastructure and foundations may be required in the impacted areas.

4.2.2 Hydrogeological and hydrological setting

Cambridge lies within a water-stressed region, or to be exact, Cambridge Water has a moderate stress potential which was given a 'not serious' status from an assessment by the EA (Environment Agency, 2013). However, as Cambridge Water is fully dependant on groundwater to meet water demand in the region (Cambridge Water, 2019), there is an inherent vulnerability that necessitates careful water management.

The hydrogeological and hydrological setting for the development provides the environmental context for the exploitability of groundwater. The Washpit Brook, a tributary

[2] Some features (such as potential contaminated land, groundwater quality, landfills, protected sites, etc) are not included within the groundwater potential mapping tool created for the site. These features could be captured in a later version of the tool as environmental facets.

of the River Great Ouse is the nearest surface water feature running along the western boundary of the site. The western area of the site drains into the Washpit Brook via land ditches. The eastern part of the site drains into a separate catchment and the BinBrook. In the north western corner of the site (bounded by the Washpit Brook) there is a small area classified as Flood Zone 2. Besides this there are no other flood zones on the site. Records indicate that there are no active water abstraction licences within 500m of the area (URS 2013a).

The superficial Head gravel on site are classified as a secondary undifferentiated aquifer. The Environment Agency describes this classification as a rock characterised by both “permeable layers capable of supporting [local] water supplies”, but also “lower permeability layers which may store and yield limited amounts of groundwater” (Environment Agency, 2017a). The underlying Gault Formation is classified as an unproductive rock, however it may be confining the underlying Principal aquifer of Lower Greensand Formation which may be a reliable water source if it is proven to be of sufficient and consistent thickness. The site is not within a Groundwater Source Protection Zone (SPZ).

Under the imposed planning conditions for the potable water supply strategy, “no infiltration of surface water drainage into the ground is permitted other than with the express written consent of the Local Planning Authority” (URS, 2013b, p.1). This is a standard planning condition that introduces the requirement for a site assessment to be undertaken to evaluate the suitability of the location for infiltration before any infiltration mechanism is implemented. It is important to integrate this into the water management system across the development.

The URS site investigation struck water within the superficial sand and gravels in two boreholes at 0.9m and 2.2m below ground level (URS, 2013a). Follow up groundwater monitoring indicated inconsistent groundwater levels in the monitoring wells. This finding as well as information on the known geological conditions indicates perched water in the superficial deposits on site which is “strongly influenced by seasonal fluctuations in rainfall, and in the shorter term can be affected by antecedent weather conditions” (URS, 2013a, p.12).

The site demonstrates how sustainability schemes can increase the resilience of groundwater supplies to increase urban sustainability. The design of the system evolved over time based on the feedback from multiple stakeholders as well as physical restrictions and policy constraints. The following sections present an innovative groundwater-mapping method which assesses the potential for the utilisation of groundwater on site. This is followed by an exploration of the enablers and problems encountered with the scheme from a series of stakeholder interviews and document examination.

4.3 Groundwater Potential Mapping Tool

To establish the potential of utilising groundwater directly at the NW Cambridge site, a groundwater potential mapping tool was created from a geological perspective which provides a rating (ranging from excellent to very poor) for the site area.

The methodology undertaken to create the mapping tool was discussed in chapter 3. The map produced comprises five components representative of the properties that affect groundwater utilisation (Table 4.1). Table 4.2 summarises the datasets, their purpose and level of reworking that was undertaken before the datasets were incorporated into the mapping tool.

Factor	**Dataset**	**Justification**
Am I on a productive aquifer?	Aquifer Designation	Indicates the calculated thickness of superficial deposits from archived borehole logs. This can therefore indicate where deposits are less than 10m thick and therefore not considered suitable for a groundwater supply.
Does the underlying bedrock have good productivity?	Aquifer Potential	Indicates the sustainable yields of groundwater in litres per second. Also indicates the presence of a concealed aquifer at depth.
Is the water resource vulnerable to contamination?	Groundwater Vulnerability	Indicates the perceived risk to groundwater that development is likely to have.
Is there shallow groundwater that may impact construction?	Depth to Source	Indicates the depth to the shallowest aquifer and therefore gives an indication of the accessibility of the groundwater supply.

Is made ground absent from the site?	Artificial Geology	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.

Table 4.1 – Key factors affecting groundwater utilisation potential, the related dataset and justification for its use.

Dataset Name	**Background**	**Reworking**
Basic Superficial Deposits Thickness Model (BSTM)	Mathematical model of thicknesses of superficial deposits derived from borehole data	Less than 10m thickness is unlikely to provide adequate water as the saturated thickness of the aquifer is insufficient. Therefore any superficial deposits less than 10m of recorded thickness have been removed from the BSTM data.
Superficial aquifer designation/ Bedrock aquifer designation	"Joint Environment Agency and British Geological Survey dataset identifying the different aquifers of England and Wales"*	The reduced BSTM data was used to isolate the superficial aquifer designation data where deposits were greater than 10m thick. The bedrock aquifer designation data was not edited.
Aquifer Potential	"A map that shows the distribution of bedrock aquifers (at outcrop and concealed) that can provide sustainable yields"**	The aquifer potential data was not edited.
Groundwater Vulnerability	Joint Environment Agency and British Geological Survey dataset providing information on groundwater vulnerability. Some three-dimensional data are used within this map (e.g. superficial thickness).	Combined groundwater vulnerability map used. Worst case vulnerability classification used from the bedrock and superficial aquifer vulnerability designations.

Depth to Source	Mathematical model showing the depth from the ground surface to the top of an aquifer.	Used instead of the groundwater levels dataset as Depth to Source measures depth to aquifer whereas the groundwater levels dataset could record phreatic/perched water table or aquifers that have limited productivity.
Artificial Geology	An extract of the BGS Geology map, providing a visualisation of known artificial deposits.	Areas within the site boundaries were created where no artificial ground was recorded.

Table 4.2 – Utilised datasets for the groundwater potential mapping tool, background information and reworking undertaken for use in the tool.
* British Geological Survey, (2015)
**Abesser and Lewis (2015)

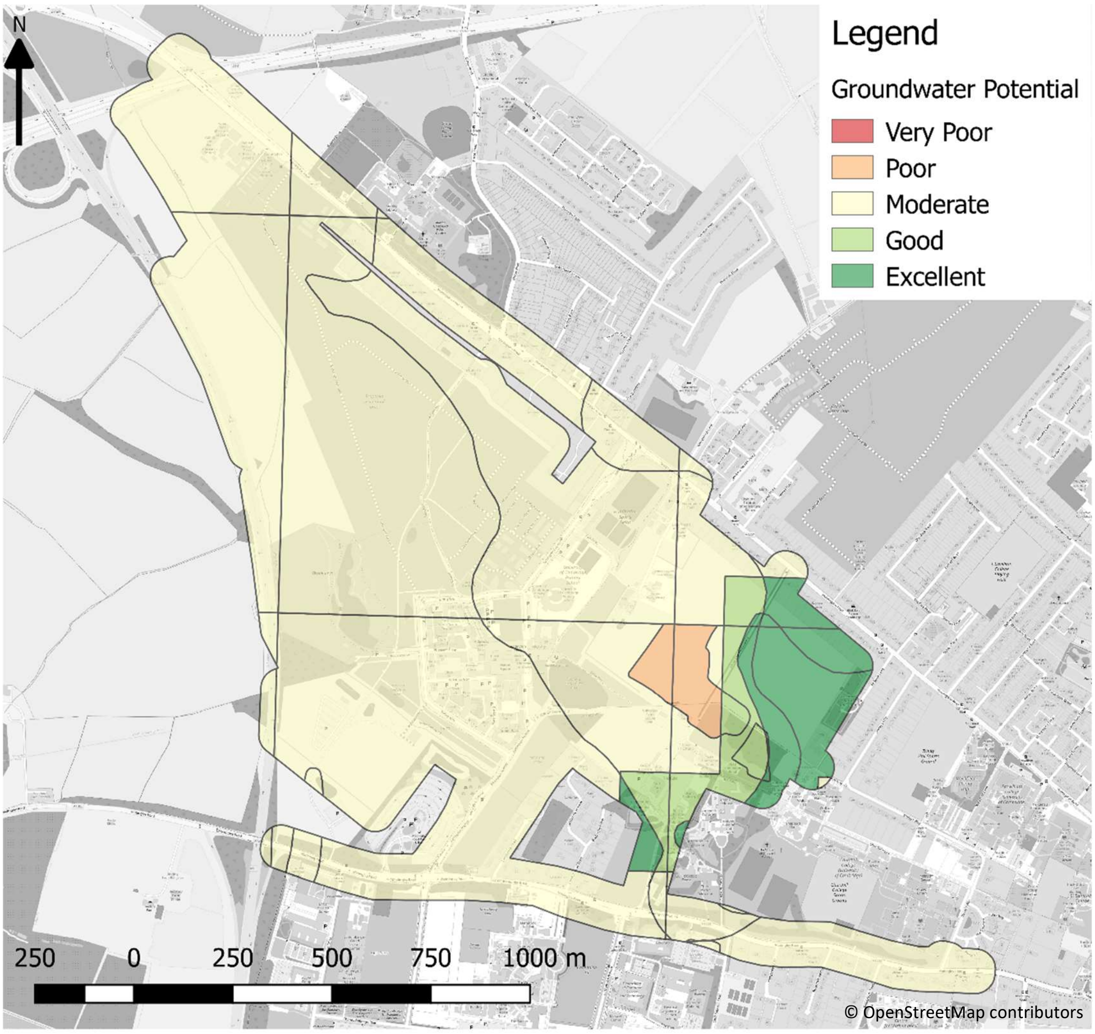


Figure 4.5 – Groundwater Potential Map for the NW Cambridge development.

The groundwater potential map (Figure 4.5) showed an 'excellent' area for potential groundwater utilisation in the eastern corner of the site, which equated to 6% of the total site area. There was a 'good' area for groundwater potential adjacent to this, covering 4% of the total site area, and 2% of the site area with a 'poor' groundwater potential towards the centre. The remainder of the site (89%) was classified as 'moderate' for groundwater potential[3]. The following characterisation of groundwater potential ratings was based on the most common factors. Different combinations of factors may result in the same ratings on site.

The areas achieving an 'excellent' groundwater potential had no artificial cover, a principal aquifer at outcrop (>6L/s) and a concealed aquifer less than 50m below ground level. The area also had a high groundwater vulnerability.

[3] The percentages may not add up to 100% due to rounding.

The areas with a 'good' groundwater potential had similar characteristics to 'excellent' areas, except that the 'good' areas had an unproductive aquifer recorded at outcrop whereas the 'excellent' areas had a principal aquifer at outcrop. There was a clear discrepancy here, as unproductive strata could not equate to a principal aquifer. This issue was due to data misalignment, where the aquifer designation dataset (projected as polygons) did not line up with the aquifer potential dataset (projected as a grid). To accommodate this incongruity, the regions with 'good' groundwater potential were considered to have the same groundwater potential as the 'moderate' areas of the site.

The groundwater potential map suggested that most of the site had a 'moderate' groundwater potential. This was characterised by: no artificial cover, an unproductive surface geology (no aquifer and no recorded groundwater vulnerability), with a concealed aquifer less than 50m below ground level. Some 'moderate' regions also had high groundwater vulnerability, where superficial deposits less than 10m in thickness overlayed the bedrock.

Finally, the 'poor' areas of groundwater potential had similar characteristic to 'moderate' areas, except that the 'poor' regions contained areas of worked ground.

As this assessment was performed retrospectively for the NW Cambridge development, these results were used to validate the approach implemented on site. From a geological perspective, there was overall a 'moderate' potential for direct utilisation of groundwater across the development.

4.3.1 Map Validation

The data behind the geo-resource classifications was assessed against external factual reports and records which related to the factors supporting the classification (Table 4.3). This verified the accuracy of the groundwater potential map.

Ref No.	Groundwater potential mapping result		Groundwater potential mapping factor	External information/data source	External information/data comment	Age of data
1	Excellent	6%	No recorded presence of made ground	On Site - Bunkers Hill - TL46SW135	0.3m of soil over 2.3m of gravels over Gault Clay (no made ground recorded)	March, 1977
2	Good	4%		On Site - Madingley Road, Park and Ride Dev - TL45NW220	0.5m of topsoil over clay to 2.4m below existing ground level (begl) (no made ground recorded)	February, 1994
3	Moderate	89%		On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	0.15m of soil over 3.0m of gravels over Gault Clay (no made ground recorded)	February, 1963
4	Poor	2%	Worked ground	OS Plan (Partial) 1:1,250 (Old-Maps.co.uk, 2019)	Gravel pit recorded over area of worked ground	1967-1968
5	Excellent	6%	A good aquifer (>6l/s) is present at outcrop	URS Phase 2 Geo-environmental Interpretive Report	"There are no active groundwater abstractions within 500m of the site" (URS, 2013a, p.8).	June, 2013
6	Good	4%		Cambridge Geological Map Sheet 188	Fragments of chalk (principal aquifer material) were reported within strata, however no	1881-1883

				On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	chalk layer. The chalk (principal aquifer) outcropping to the east of the site is not laterally persistent according to the geological map. Observatory Gravels are recorded within the area of superficial geology.	February, 1963
7	Excellent	6%	A concealed aquifer at depth (of no more than 50m below ground level)	Cam and Ely Ouse Abstraction Licensing Strategy. On Site and nearby WellMaster water well data On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	Groundwater is not available for licensing for abstraction. Water well data confirms the presence of water between 8m and 31m below ground level. Lower Greensand Formation (aquifer) is encountered 42m below ground level.	June, 2017 1900's February, 1963
8	Good	4%				
9	Moderate	89%				
10	Poor	2%				
11	Excellent	6%	A principal aquifer is present at surface (which may be overlain by superficial deposits less than 10m in thickness)	URS Phase 2 Geo-environmental Interpretive Report Cambridge Geological Map Sheet 188	Fragments of chalk (principal aquifer material) were reported within strata, however no chalk layer. The chalk (principal aquifer) outcropping to the east of the site is not laterally persistent according to the geological map.	June, 2013 1881-1883

					The chalk has not been confirmed by available exploratory hole logs.	
12	Good	4%	An unproductive aquifer is present at surface (which may be overlain by superficial deposits less than 10m in thickness)	On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	0.15m of soil over 3.0m of gravels over Gault Clay to 42m below ground level. (Where superficial deposits are not present, unproductive clay is persistent to depth)	February, 1963
13	Moderate	89%				
14	Poor	2%				
15	Moderate	89%	An unproductive groundwater vulnerability is present at surface	On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	0.15m of soil over 3.0m of gravels over Gault Clay to 42m below ground level. (Where superficial deposits are not present, clay is persistent to depth across the majority of the site.)	February, 1963
16	Excellent	6%	High groundwater vulnerability is recorded at surface	URS Phase 2 Geo-environmental Interpretive Report	Where superficial deposits are present on site, or the chalk bedrock outcrops at the surface, high vulnerability has been recorded.	June, 2013
17	Good	4%				
18	Poor	2%				

				On Site - Wyboston, Cambridge and Soham Boreholes - TL45NW49	Fragments of chalk (principal aquifer material) were reported within strata, however no chalk layer. Observatory Gravels are recorded within the area of superficial geology.	February, 1963

Table 4.3 – Validation information for factors used in groundwater potential map.

In general, Table 4.3 shows that the information and data reviewed for the NW Cambridge site supported the findings of the groundwater potential map.

For the areas on the groundwater potential map that achieved 'excellent', 'moderate' or 'good' where no made ground was recorded, three on site boreholes supported this assessment. For areas with a 'poor' rating where worked ground was a contributing factor to the groundwater potential, Ordnance Survey mapping confirmed the presence of a gravel pit between 1967-1968 (Old-Maps.co.uk, 2019).

Across the site, a concealed aquifer was reported at a depth of 50m or shallower. The principal aquifer (Lower Greensand Formation) was encountered at a depth of 42m below ground level in an on-site borehole. Additionally, on-site and nearby water well data indicated the presence of groundwater between 8m and 31m below ground level. These factors supported the validity of the groundwater potential map.

For 'excellent' areas of groundwater potential, a potentially productive (>6l/s) principal aquifer was present at outcrop according to the groundwater potential map. However, external information confirmed that no groundwater abstraction points existed within 500m of the site boundary (URS, 2013a). This opposed the findings of the groundwater potential map where the eastern corner had an 'excellent' potential (indicating that it may have been feasible to have a groundwater abstraction point within the local area). This may have been due to several factors.

Firstly, the data used in the groundwater potential map considered the properties of the geological unit and it did not account for the predicted or encountered thickness or prevalence of a unit. Upon inspection, the geological map sheet of the area confirmed that the chalk unit giving the 'excellent' groundwater potential in the eastern area of the site was shallow and discontinuous, and therefore, was unlikely to be viable for groundwater abstraction in this location.

Secondly, the interpretation did not consider the regional groundwater resource availability context. External mapping information showed that groundwater is not available for licensed abstraction within the Cam and Ely Ouse catchment (Environment Agency, 2017b) (i.e. the groundwater is already fully allocated up to the limit of impacting the environment). Although this finding opposed the groundwater potential map (as this level of interpretation was not incorporated into its design) it instead re-enforced one of the drivers for the NW

Cambridge non-potable water network; that water stress in the region required sustainable and innovative urban design.

From this process, the groundwater potential map was generally considered to be an accurate interpretation of the groundwater situation across the site, although its limitations need to be considered during its use. The map provides an indication of the areas of the site where groundwater utilisation could be investigated, and is not a final model to be used for the installation of any infrastructure.

4.3.2 Translation into Urban Design Criteria

NW Cambridge utilised many documents which addressed sustainable and resilient urban design criteria. Relevant planning policy, urban design guidance and sustainability and resilience agendas were translated into an urban design geo-resource (UDG) matrix for the NW Cambridge site. The matrix connects the groundwater potential map with the urban design agenda for sustainability and resilience (and/or water utilisation) specific to the case study setting. It demonstrates how water can be utilised to meet different urban agendas and allows users to target specific urban criteria. The following documents were included in the UDG matrix:

- UK Government Design Guide,
- National Planning Policy Framework (NPPF),
- Planning Policy Statement 1: Delivering Sustainable Development (plus Supplement: Planning and Climate Change)
- East of England Plan,
- Cambridge Local Plan,
- Cambridge Sustainable Development Guidelines,
- North West Cambridge Area Action Plan (NWCAAP),
- Cambridge City Council Sustainable Design and Construction Supplementary Planning Document,
- BREEAM sustainability assessment method.

These documents played an important guiding role for the development of the NW Cambridge site (and are discussed in detail in Section 4.5). It is especially important that technical solutions to water utilisation meet the urban design criteria in planning policy. Therefore, the relationship between these issues are presented in the UDG matrix (Appendix I).

As explained in the methodology (section 3.6.6), the UDG matrix (Appendix I) presents elements of sustainable urban infrastructure utilising water across the horizontal axis, and sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Figure 4.6 demonstrates two approaches to using the UDG matrix. Firstly, by reading horizontally, the user can prioritise urban criteria (relevant to the NW Cambridge site) and see which water uses may fulfil a particular criteria. Alternatively, by reading vertically, if pursuing a specific method of water use, the user can see how implementing it may fulfil certain criteria. A selection from the UDG matrix is presented in Figure 4.6.

Disregarding the actual water network infrastructure implemented at NW Cambridge, the following assessment was determined for the potential use of water from considering the UDG matrix:

As the areas of 'excellent' conditions for groundwater potential are not supported by the map validation information, it would be prudent to consider utilising surface waters alongside a regular potable water supply to contribute towards resilient urban design and sustainable infrastructure at NW Cambridge. It can be drawn from the UDG matrix that some of the most effective methods which should be investigated for the development include; simple rainwater harvesting, advanced rainwater harvesting, grey-water recycling, underground attenuation and storage, water saving devices, drought tolerant planting, and the installation of water monitors and meters where possible. Many of the 'moderate' regions have unproductive strata which may be impermeable, leading to increased surface runoff. This ground property could be utilised to redirect surface water into a water harvesting network.

4.3.3 Groundwater Potential Mapping Tool Limitations

The map works by only considering the groundwater immediately beneath the site, however groundwater is part of a much wider water cycle in the surrounding catchment. Regional groundwater movement impacts the availability of water and suitable for abstraction, as well as the direction of local groundwater flow.

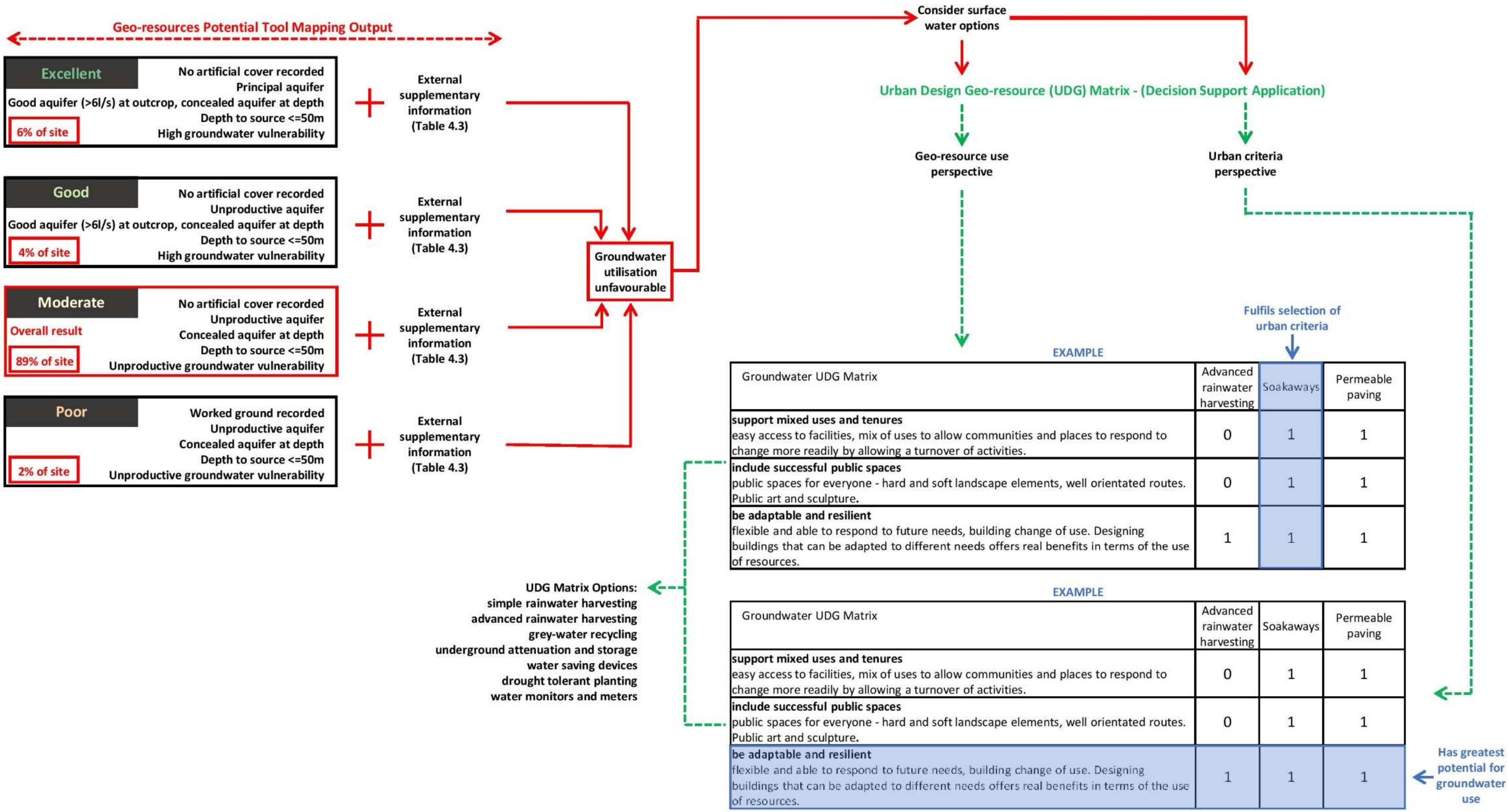


Figure 4.6 – Flow diagram summarising the method of applying the groundwater potential map output to the Urban Design Geo-resource (UDG) matrix.

Other external factors such as abstraction licensing must also be considered. It was reported that groundwater was not available for licensing (Environment Agency, 2017b), and in this circumstance, it was deemed better to rely on Sustainable Drainage Systems (SuDS) to capture surface water for re-use in buildings in order to support the wider water system.

Furthermore, other external factors (such as economic and environmental) must be considered as it is more than just the geological factors which determine the viability of groundwater utilisation.

The compiled datasets were created using diverse processes with different data sources. As previously mentioned, misalignment occurred where data was combined from different mapping methods. This issue may require datasets to be reviewed to explore whether a more aligned version could be possible.

Further limitations of the general geo-resources mapping tools are discussed in the methodology chapter of this study (chapter 3).

4.3.4 Groundwater Potential Mapping Tool Section Summary

In order to reduce the demand from the potable water supply at NW Cambridge, the site wide non-potable water network was implemented along with a series of SuDS to redirect rainwater, as well as the installation of water saving devices in new buildings. In line with the CIRIA SuDS Manual (Woods-Ballard et al., 2007), water management strategies were implemented for source control, site control and regional control. The SuDS features implemented on site included: permeable paving, swales, advanced rainwater harvesting network, detention basins, and water saving fixtures and fittings.

The map output from the groundwater potential mapping tool suggested that direct groundwater utilisation may be possible from a geological perspective in distinct areas of the site. However, upon validation, external information was found to contradict the map and indicated that groundwater in the area was already fully allocated up to the limit of impacting the environment, and therefore was unavailable for direct abstraction at NW Cambridge. The urban criteria within the UDG matrix indicated that advanced rainwater harvesting (i.e. a dual water network) was one of the most compatible with the urban design actioned at the NW Cambridge site.

The implemented SuDS at NW Cambridge which are included within the UDG matrix align well with the findings of the groundwater potential mapping tool. The applied water management approaches maximise the contribution that water can make to the sustainability and resilience agenda of the development as well as the surrounding region.

4.4 Case Study Stakeholder Interviews

The groundwater potential mapping tool demonstrated how the water management scheme at NW Cambridge has increased both urban and groundwater sustainability and resilience at NW Cambridge. To investigate the main drivers, enablers and challenges for implementing this system, a series of interviews were undertaken with stakeholder representatives of the NW Cambridge development.

NW Cambridge presented an opportunity to explore the impacts of managed water usage, and the affect this had for building resilient infrastructure and sustainable urban environments. The successful implementation of this system required collaboration by many stakeholder groups which had to consider the project brief, local strategies for water management, policy guidance and the environmental setting.

Representatives from Greater Cambridge Shared Planning Services, the University of Cambridge, the Urban Design Consultancy (AECOM), South Staffs Water (owner of Cambridge Water) and a resident of Eddington agreed to be interviewed to express their views and experience of the sustainability agenda and the dual water network implemented on site. The representatives from these groups were selected because they understood the sustainability agenda and/or the specific geo-resource (water) use and had experience of the application at NW Cambridge.

Following full transcription of interviews, the responses were coded to correlate findings across stakeholder groups. In the following section, the main enablers and drivers that facilitated the water network at NW Cambridge, as well as barriers to the implementation of the scheme are the focus of discussion. The potential failures that may occur (which are not specific to the NW Cambridge water network) are also discussed.

4.4.1 Interviewee Response

4.4.1.1 Enablers

Once coded into themes, thirty six enablers were identified across the stakeholder groups. Within this there was only one enabler that all stakeholder groups identified – optimised costs. Affordable infrastructure for sustainable development was a clear and common enabler, which closely links to project feasibility. The community member noted that cost must be a priority for developers but also for end users, "if sustainable living can be made as cheap as possible in the short term and long term, this would be desirable" (Resident, 2018). When asked about enabling factors for the development at NW Cambridge, the interviewee representing local planning services identified early planning as an incentive for minimising costs, implying this was generally an aim for parties involved in early planning phases. This message was also relayed when discussing the implementation of BREEAM assessments; "if you're going for sustainable development, it has to be embedded from the client brief, otherwise you're missing opportunities to make cost effective decisions." (Greater Cambridge Shared Planning Services, 2019). In the same light, the engineering design company for the development stated that "if a development looks good, is made from high quality material…it can help developers to market their approaches. But developers are in it for the money. That's what they need to do, so sometimes they'll engineer as much as possible which means less material and less waste" (Design Consultancy, 2018). The University of Cambridge also shared its approach with regards to finance noting that "many housing developments at this scale are about people making money, and making money is not what NW Cambridge is about. It is about meeting a strategic need for the university. Money is important no doubt about it, we have had to be careful with how to spend money, but the university was committed to doing something and has delivered it" (Client, 2019). The water supplier for the development further commented that "the whole of the development is seen as the exemplar site for sustainability. With the developer being such a unique client, they have the money and foresight to achieve it" (Water Supplier, 2019).

Other common enablers identified by multiple stakeholder groups include:

- Effective partnerships
- Schemes supported by policy
- Feasible schemes
- Schemes which offer solutions to multiple site issues
- Site owners/developers with sustainability high on their agenda

Identifying these main enablers for the development at NW Cambridge paves the way for future developments and infers which stakeholder groups may need to take action (and at what phase in the design process) to drive sustainable and resilient urban design through the utilisation of water (and geo-resources). For example, for schemes to be supported by policy, government authorities at all levels (national, regional and local) should ensure that a clear sustainability policy is in place for new developments which explicitly states the design requirements that resilient infrastructure should have, and the opportunities that exist from a geo-resources perspective. In addition, the alliance of motivated and knowledgeable stakeholders contributes to the viability of schemes such as the water network at NW Cambridge, provided this is supplemented by effective communication across all parties (Ascott and Kenny, 2019). These factors are synchronous with the findings of Jelphs and Dickinson (2008) whose model of effective partnerships relies on the interplay of shared commitments, role clarity, cooperation and interprofessional trust (which from the interviews was key to the success of the water network at NW Cambridge).

The majority of the stakeholder groups said that the water network at NW Cambridge was the result of a series of fortuitous circumstances, including but not limited to; a University determined to deliver an exemplar site for sustainability, a water supplier willing to work innovatively with them to bring a feasible water management scheme never attempted before on this scale in the UK, and a set of local policies in place to set the standard for sustainable water use across the site. These actions have enhanced urban resilience in the sense that the stakeholders have provided capacity for the water system at NW Cambridge to survive and adapt should stresses and shocks occur which impact the site.

4.4.1.2 Drivers

Twenty eight codes were identified across from the stakeholder groups transcripts as drivers for the implementation of the water scheme at the NW Cambridge development. The most mentioned drivers across the stakeholder interviews were:

- Having sustainability high on the agenda
- Having a driven/ambitious developer
- Creating a water efficient system

All of the stakeholder groups set/abide by sustainability standards within their own respective industries, and from the interviews it was clear that all of them place sustainability high on their individual company agendas. Having this shared goal for NW Cambridge would naturally be identified as a driver for the dual water network scheme. Additionally, the representatives from the local planning authority, engineering design consultancy, water supplier, and the University of Cambridge itself all attributed the client (University of Cambridge) as a driver for the scheme, due to their ambition to deliver sustainable development in all aspects of the NW Cambridge site.

The other main driver identified by the local community representative, client, engineering design consultancy and utility supplier was the need to create a water efficient system. This driver is linked to other factors, such as "water was high on the sustainability agenda for many reasons, but not least was for our carbon footprint. The less water used, the less energy used" (Client, 2019). Additionally, the engineering design consultancy firm representative said that "there was a need to do this to reduce the conventional water use and get down to the 80 litres per head per day. It wasn't just a case of getting water efficient devices into people's properties. We needed to rethink and challenge what you could re-use water for and where the other water sources were" (Design Consultancy, 2018).

It is likely that both comments were said in reference to documents which aim to minimise the carbon footprint and water consumption in new developments. This demonstrates that strict and detailed guidelines on infrastructure design within compulsory documents can be used to steer urban design towards sustainable and resilient trajectories.

4.4.1.3 Barriers

Forty-one themes were identified as potential barriers for the implementation of sustainable and resilient urban design through the utilisation of water. When discussing the main barriers, all of the stakeholders mentioned cost as an issue. The local community member said that "low development costs are most important…costs can be a big preventive" (Resident, 2018). The local authority concurred, noting that "if you think about [sustainable design options] early on enough in the project, it helps to keep costs down" (Greater Cambridge Shared Planning Services, 2019). The engineering design company highlighted that regular house builders are in the business to make money and though this is not the case for the NW Cambridge site, it is a common barrier to exploring sustainable urban design and geo-resource utilisation. The water supplier for the development commented that "cost is the reason why [similar strategies] have not been explored/implemented more widely" (Utility Supplier, 2019), and that financially incentivising schemes on a national scale may result in increased uptake.

After cost, the most frequent barriers identified across the stakeholder groups included:

- Safety concerns/ infrastructure risks/ liability
- Weakened/loss of policy for the built environment
- Different levels of interest in sustainable design across the country
- Lack of long-term vested interest in developments

Each of these areas need addressing to see the widespread implementation of urban design which is more sustainable and resilient from the utilisation of water. However, none of these issues have quick fix solutions.

For the NW Cambridge site, the safety concerns identified by the community member were whether recycled water was safe for use; "is re-used water safe? Are there any safety issues with using recycled water?" (Resident, 2018). This is associated with the unfamiliarity of a dual water network. The representative of the engineering design company considered risk in terms of the wider implementation of the network, stating that "if you go to a meeting with professionals, the risk of having a dual water network always comes up". Furthermore, the risks associated with liability were also mentioned, some stakeholders can be "very concerned and reluctant, and ultimately, it's all about risk. If their name is on the discharge into a water course and something goes wrong…the greater the chance of them being sued. They need to manage the risk using sufficient treatment upstream, or sufficient mitigation to make the risk low". Multiple water companies were approached to consider the non-potable network, perhaps in anticipation that some organisations may be less willing to take a risk on a non-potable water network than others. The engineering design company representative also said that "we were fortunate in the long term to get; a water company partner, the University who adopted the SuDS, and a water company who was willing to adopt the non-potable network, a lot of the big companies won't do that for managing their own risk" (Design Consultancy, 2018).

This type of barrier can only be overcome with contractual conditions, and more stakeholders willing to undertake innovative urban designs to achieve sustainable development. Fine-tuning the approaches (no matter what their outcome) and learning from experience is the only way that the risk around geo-resource use for sustainable urban design can be overcome.

The local planning authority for the NW Cambridge site recognise that "national policy has weakened in the last few years when it comes to the built environment". In terms of setting water efficiency standards, national policy limited the level of water efficiency that local authorities can ask for to 110 litres per person per day, even though some think there are grounds for water limits to be lower than this in some cases. In NW Cambridge, despite support from the utility provider and the Environment Agency, the limit was non-negotiable. The local planning authority said that "in areas of water stress, not being able to go beyond that 110 litres is a real barrier in not being able to promote that sort of approach" (Greater Cambridge Shared Planning Services, 2019). This was relayed by the engineering design company, who say that "currently planning authorities are weak. When you look at planning in London, we require them [development] to be much higher in quality than regulation allows, but the rates on returns are so high in London that no one is able to challenge the planning authority. If you go somewhere more rural, the planning authority don't have the power to challenge the developer to do better designs for fear of being challenged legally over permissions. We are seeing planners agree because they feel fortunate to get development coming their way, and that they get solutions from, such as affordable housing" (Design Consultancy, 2018). This highlighted one of the largest issues for sustainable development and planning, namely that it is driven by national level decision making. A recent report suggested that the planning system is inadequate in many ways and that "the Government should announce a clean break with the land use planning system introduced in 1947 that largely continues in the same form today" (Airey and Doughty, 2020, p.10). There are ongoing plans to reform the planning system in the UK which will impact the way that geo-resources (such as water) are approached. In particular, the proposal to introduce a lone statutory test to measure sustainable development (Grimwood et al., 2020). However, in the current economic climate with the national housing shortage, these attitudes towards development, and the policies used to govern their sustainability standard are unlikely to change quickly.

Furthermore, there are different levels of interest in sustainable design and geo-resource use across the country. National policy sets a basic requirement for sustainable development and expects regional and local authorities to adapt this to the context of their area. However, the interpretation of national policy is subjective, and as stated by the engineering design company, it depends on the pressure on local authorities to accept planning applications that contributes towards the demand for housing set by the government.

Several stakeholders indicated that a volume house builder may not have a long-term vested interest in the potential contribution that their site could make to sustainable urban development. Suggestions on how to change this approach have included: making codes of practise and policy more constrictive – particularly for urban design parameters, and resources efficiency measures. This is one option that planning departments could action. However, the interviewee representing local planning services suggested that projects such as the NW Cambridge dual water network are not implemented often partly due to “not having the right policies in place that require it to happen” (Greater Cambridge Shared Planning Services, 2019). Alternatively, the representative of the utility supplier suggested that for these kind of schemes “it is around driving developer behaviour, there must be a financial incentive rather than just relying on developers to want to be sustainable” (Water Supplier, 2019). For example, in another area of geo-resource utilisation, the Renewable Heat Incentive (RHI) scheme encourages the implementation of renewable heat technologies via financial incentives (OFGEM, 2019). If successful, a similar strategy could be investigated for the uptake of other sustainable development infrastructure such as water-management schemes which promote and incentivise sustainable and resilient urban design.

4.4.1.4 Failures

Although not specific to NW Cambridge, it was highlighted by the stakeholder interviewees that events can occur which may lead to the failure of urban design infrastructure that utilises water (and other geo-resources). Two ideas were suggested that could have this result.

Firstly, one stakeholder representative described an anonymous project that had incorporated water recycling into its design, and later went out of use following a breakdown in communication between stakeholder groups. In the context of urban resilience, Ascott and Kenny (2019, p.477) suggested that “a multidisciplinary ‘journey’ towards resilience must begin with improved communication, where stakeholders seek to understand and contribute to each other’s respective priorities”. A lack of understanding of the functionality of different parts of any system may result in technical failure, rendering the system unusable. Furthermore, Morel and Diener (2006, p.51) highlighted that “the main reasons for system failure are caused by a lack of maintenance and understanding of the operational principles of the treatment chain. During project implementation, it is therefore of utmost importance to focus not only on technical equipment and infrastructure but also to include information and training of the different key stakeholders”. Although describing greywater systems in an international context, this statement is also applicable for systems in the UK, and if accepted as a requirement for the implementation of innovative infrastructure, may ensure the longevity of urban design infrastructure that utilises geo-resources.

This potential failure also highlights issues surrounding the decentralisation of services, in particular that the responsibility for maintenance and upkeep may be devolved to local organisations and communities. This issue was also observed where certain conditions had to be met for Cambridge Water to adopt the water system at NW Cambridge.

Secondly, one stakeholder representative suggested that an increased uptake of geo-resource infrastructure to enhance sustainability and build urban resilience may induce a rebound effect, where end users use more resources thinking that because it is generated from a sustainable resource, more of it can be used with no significant effect. There is little evidence to suggest that this has a significant risk of this occurring, and even less that this may lead to the demise of infrastructure that utilises geo-resources.

4.4.2 Stakeholder Interviews Section Summary

The different stakeholder groups see a range of opportunities from the implementation of the water recycling network at NW Cambridge. Ultimately it was the ambition of the University of Cambridge to see their vision of a sustainable water supply for the site that saw the network delivered, although this would not have been possible without the expertise and backing of all other stakeholder groups.

The local authorities saw NW Cambridge as an opportunity to push for high water efficiency standards, beyond the standard set by national policy. In doing this it set an exemplar site that other developments in the region could aspire to. The engineering design consultants saw the NW Cambridge proposal as a series of fortuitous circumstances coming together including: strong local policy, a high-status developer, a willing water company to partner with, and an innovative solution for water security. The water company saw this not only as an opportunity to collaborate with a prestigious university, but also the chance to be associated with the largest rainwater harvesting scheme in the UK. For the residents, the rainwater harvesting scheme was not a prominent driver for their decision to move there, however the increased interest in sustainable living may have a lasting impact on water conservation.

The primary enabler for the project identified by all stakeholders was feasible costs. Although the University of Cambridge stated that cost was secondary to some aspects of project design and sustainability infrastructure. This message was also reiterated by the other stakeholders who may not have been as restricted financially for this project than they are in other situations.

The dual water network is yet to be implemented across all phases of the development, and the impact that having a non-potable water supply has on overall water consumption for the site is yet to be evaluated. The interviewee representing local planning services (2019) said that "to date however, it is proving successful and is generating a lot of interest in how you can utilise surface water runoff to meet a resource need. For so long people have seen surface water as something you need to get rid of, but no it's a resource, so let's use it. It would be great to see that lesson implemented more in new developments." The University of Cambridge reinforce that the site has received international interest for its approach to sustainable urban design and to see this level of interest in the scheme is a sure sign that stakeholders are interested in understanding the potential benefits that utilising geo-resources may have for potential future ventures.

The standard that the dual water network has set in water use for sustainable and resilient urban settings is both pioneering and motivating. From the interviews there was keen interest from multiple stakeholders to replicate the scheme elsewhere and continue to enhance and implement innovative urban design. This may be particularly true where geo-resource use can directly meet some of the challenges of urbanisation (such as addressing water stress and reducing demand on natural resources). However, it is planning policy, urban design guidance and financial incentives which can influence the frequency that schemes such as the dual water network at NW Cambridge are implemented.

In order to explore the role of planning policy, urban design guidance and sustainability and resilience assessment at NW Cambridge, the following section explores recurring themes to groundwater utilisation spanning documents across different planning scales (from an international to local scale). The presence (or absence) of water (and groundwater) as a resource to be managed is also considered in a sustainability and resilience context.

4.5 Planning Policy, Urban Design Guidance and Sustainability Assessment Analysis

4.5.1 Introduction

The relationship between building sustainable and resilient urban environments (managing demand) and creating sustainable water resources (managing supply) is interdependent. To achieve sustainable urban infrastructure requires the sustainable use of water, and to achieve sustainable water resources requires the sustainable utilisation of water within urban infrastructure. Therefore, documentation for protecting groundwater is as important to consider as the documentation promoting sustainable urban development.

When sustainability and resilience first surfaced as driving concepts for urban development, water management was included as a foundation block in many strategies. For example, the first UN Conference on Human Settlement and Sustainable Urban Development (Habitat I) held in 1976 produced the Vancouver Action Plan which included a section on water supply. Water management and approaches for providing safe access to clean water was one of the goals set in this agenda (United Nations, 1976).

In order to determine how groundwater can be utilised in urban design most effectively, (and whether this has been influential over the development at NW Cambridge) the relevant planning policies, urban design guidance and sustainability and resilience agendas have been explored across multiple scales. The key messages relevant to water within these documents are presented in Table 4.4, as well as the cross-cutting themes which are discussed in greater detail below. These are:

- Protection
- Efficiency of Use
- Governance and Planning
- Sustainable Drainage Systems (SuDS)
- Water Management

Case Study 1 – Water, North West Cambridge		
Level	**Document**	**Key Message/Impact Relevant to Case Study**
International	Sustainable Development Goals (SDGs)	Goal 6 – **increase water efficiency**, **implement water management**, **protect** the environment
International	Water Framework Directive (WFD)	aims to improve and **protect** water quality
National	Water Environment Regulations (2003)	a strong focus on the **protection of groundwater** from pollutants and environmental hazards, which is the principal message
National	Draft National Planning Policy Framework (NPPF)	**incorporated Sustainable Drainage Systems (SuDS)**
National	National Standards for Sustainable Drainage (Department for Environment, Food and Rural Affairs, 2015b)	guides deliver details of the **factors affecting the implementation of SuDS**.
National	Non-Statutory Technical Standards for Sustainable Drainage: Practice Guidance	guides deliver details of the factors affecting the **implementation of SuDS.**
National	Planning Policy Statement 1: Delivering Sustainable Development (PPS1)	**protection** and **efficient use of water resources** through avenues such as **regional planning** and **SuDS**
National	PPS1 supplementary guidance 'Planning and Climate Change'	**regional and local planning authorities to set clear advice** for sustainable development which includes different **facets of water management**
National	Draft Planning Policy Statement: Planning for a Low Carbon Future in a Changing Climate	**role that planning authorities can play** to boost **efficient water usage** and set **water management standards**, also highlights the costs and benefits of **implementing sustainable drainage**
National	Codes of Practice (BS 8515 Rainwater harvesting systems: Code of Practice)	Sets a **minimum standard for SuDS**
Regional	East of England Plan 2008 (abolished in 2010)	emphasised **collaborative planning** across organisations for optimised **water management**, emphasised the **use of SuDS** and **water efficiently**, reducing the demand on water resources and reducing waste, and **successful communication** between organisations to do this.
District	Cambridge Local Plan	Promotes specific aspects of **SuDS**, assigns responsibility for the different facets of **water management**,

District	Cambridge City Council Sustainable Design and Construction Supplementary Planning Document (SDC) 1. Sustainable Development Checklist	**water conservation approaches** are encouraged, sets a **water use target**, and encourages a range of **SuDS strategies** 1. relating to **SuDS** and th5e reduction of water consumption
District	South Cambridgeshire District Council Core Strategy	No reference to water, suggests the careful use and re-use of resources
District	Draft Cambridge Sustainable Development Guidelines (CSDG) Supplementary Planning Guidance	**Increased water efficiency and minimising waste,** also encourages the use of **various types of SuDS**. detailed suggestions for **water conservation and water re-use**
Local	North West Cambridge Area Action Plan (NWCAAP) 1. Policy NW24: Climate Change and Sustainable Design and Construction 2. Policy NW25: Surface Water Drainage	1. Demands **water conservation measures to reduce water use and waste**, as well as **protection of the surrounding environment**. 2. **SuDS on site** should control the run-off volumes.
Site Specific	BioRegional One Planet Living principles 1. Principle 2	1. **Minimise water consumption by water efficiency** and recycling measures.
Site Specific	Development Planning Conditions 1. 26 2. 27 3. 29 and 30	1. Implement a **water management plan** to maximise water efficiency. 2. Optimise **design and management of SuDS**. 3. Provide sufficient water supply and drainage.
National	Code for Sustainable Homes	Implement **water conservation measures** (reduce consumption by installing water efficient designs and water recycling systems). The smaller the water consumption, the higher the number of credits and sustainability level achieved. Category 2 – install **water efficient fixtures** indoors and **SuDS** outdoors. Category 4 – **control surface water runoff**
National	Building Research Establishment Environmental Assessment Method	**Water consumption and water monitoring** are included in accreditation. Assesses water efficiency of different measures and role of monitoring water use.

Grey = protection, Blue=efficiency of use, Green = governance and planning, Yellow = SuDS, Pink = water management

Table 4.4 – Key planning policy, urban design guidance and sustainability and assessment documents impacting the NW Cambridge development with their content related to water summarised and categorised into themes.

4.5.2 Protection

Aspects of protection were observed primarily within international agendas, national level planning regulations, urban design documents, and a sustainability assessment scheme (Code for Sustainable Homes).

One standpoint of this was protecting the groundwater from potentially harmful elements which could impact its use. This was observed as a target in Sustainable Development Goal (SDG) six, but also in the Water Framework Directive (WFD) which relayed this message through the Water Environment Regulations (2003). The WFD had a strong focus on the protection of groundwater from pollutants and environmental hazards. As well as this, Planning Policy Statement 1: Delivering Sustainable Development (PPS1) discussed the protection of water resources (from contamination) through avenues such as development plan policies (Office of the Deputy Prime Minister, 2005).

In addition, the Code for Sustainable Homes (CSH) Category 4: Surface Water Runoff in the CSH aimed to "design surface water drainage for housing developments which avoid, reduce and delay the discharge of rainfall run-off to watercourses and public sewers using SuDS techniques" (Department for Communities and Local Government, 2010b, p.124). This measure involved providing protection of infrastructure and watercourses from the effects of flooding where a new development is undertaken and is compulsory under the CSH to fulfil regardless of the sustainability rating being pursued.

More locally, the North West Cambridge Area Action Plan (NWCAAP), part of the local plan, stated that "care must be taken to ensure that water reuse and recycling does not have an adverse effect on biodiversity, or the wider water environment, in accordance with the requirements of the Water Framework Directive (WFD)" (Cambridge City Council and South Cambridgeshire District Council, 2009, p.40).

Besides this, the lower levels of governance (regional, district and local) did not significantly focus on the protection of water or groundwater within the context of sustainable urban design. However, water resource protection may have been included in wider independent documentation or grouped with other general environmental or resource management plans.

4.5.3 Efficiency of Use

The efficient use of water resources was discussed widely across multiple scales of sustainability agendas, planning regulations, urban design documents, and sustainability assessment schemes.

Water efficiency was included within SDG six as a comprehensive target, but more detail was observed in documents at a national level and below. At a national scale, Planning Policy Statement 1: Delivering Sustainable Development (PPS1) referred to efficiency as “enabling more sustainable consumption and production and using non-renewable resources in ways that do not endanger the resource or cause serious damage or pollution” (Office of the Deputy Prime Minister, 2005, p.9). Furthermore, the document put onus on planning authorities to encourage developments which reuse existing resources and not utilise unexploited ones. Specific reference was made to the sustainable use of water in this framework under the ‘prudent use of natural resources’.

This message was reiterated at District Level Planning, where the Cambridge City Council Sustainable Design and Construction Supplementary Planning Document (SDC) included a section on natural resources (Cambridge City Council, 2007). There was also a Sustainable Development Checklist within the SDC that must also be completed under the Cambridge Local Plan. Under section 3.2 of the SDC, water conservation approaches were encouraged for new developments. Suggested actions included: installing water efficient fittings, rainwater harvesting systems or greywater recycling systems. In addition, the document set a desirable target of 105 litres per capita per day for water use, which was in line with achieving three stars under the Code for Sustainable Homes (Cambridge City Council, 2007). This document was reviewed (and the SDC completed) early on in project feasibility studies, and therefore the connection between water efficiency and urban design for sustainable development was apparent from the onset.

Also at a district level, the Cambridge Sustainable Development Guidelines (CSDG) (2003) was a Supplementary Planning Guidance Document referenced to in Policy 3/1 of the Cambridge Local Plan. A draft version of the guidelines confirmed that CSDG is targeted at informing people who were “involved in planning and delivering development in Cambridge” (Land Use Consultants cited in Cambridge City Council, 2002, p.7). Within this was a section on conserving water resources, where sustainable development in this context meant "using natural resources (e.g. energy, water, construction materials, etc.) more efficiently, and minimising waste" (Land Use Consultants cited in Cambridge City Council, 2002, p.11). The draft guidance in the CSDG provided the most detailed information for schemes which use water conservation and water re-use to enhance sustainable development, primarily through infrastructure suggestions incorporated in urban design.

As well as this, one of the main local level policy documents guiding the site proposals was the North West Cambridge Area Action Plan (NWCAAP) (Cambridge City Council and South Cambridgeshire District Council, 2009). Policy NW24 (Climate Change and Sustainable Design and Construction) stated that water conservation measures will be incorporated into the NW Cambridge development. These included water saving mechanisms and greywater recycling systems which would have the effect of reducing water use and waste across the site.

In addition, the NW Cambridge development set its own sustainable development guiding principles based on the BioRegional One Planet Living principles (AECOM, 2011). As part of this there were thirteen principles which address the different facets of sustainability across the NW Cambridge site. Principle 2 of the Cambridge Sustainability Statement was based on the water management for the site to "ensure that freshwater consumption at the proposed development is reduced through water efficiency and the collection and recycling of rainwater and wastewater" (AECOM, 2011, p.7). Developing site-specific sustainability principles for a single development is a not common occurrence for most developments, particularly for smaller sites where sustainability and resilience measures are often only fulfilled for planning approval.

Also, for the NW Cambridge site several planning conditions involved water resource management and sustainability, the main ones being 26, 27 (surface water drainage), 29 and 30 (water supplies) (South Cambridgeshire District Council, 2013) (which are also discussed in section 4.5.4). The reference to water efficiency within site specific documentation emphasised its importance to sustainable and resilient urban design and development.

In the context of sustainability assessment schemes, the CSH emphasised the importance of water efficiency within its measures. The NWCAAP worked on the basis that "all dwellings built up to 2013 (for up to 50 dwellings) are required to meet Code for Sustainable Homes level 4 (Code 4) or higher. The 51st and subsequent dwellings prior to 2013 and all dwelling constructed post 2013 are required to meet Code 5 or higher" (AECOM, 2011, p.39). In addition, in order to meet CSH Level 5 for residential development, water conservation measures at NW Cambridge needed to be implemented which reduce water usage to 80 litres per head per day or less (Cambridge City Council and South Cambridgeshire District Council, 2009).

More specifically, the CSH aimed to "reduce the consumption of potable water in the home from all sources, including borehole well water, through the use of water efficient fittings, appliances and water recycling systems" (Department for Communities and Local Government, 2010b, p.82). The assessment criteria for water was based on the amount of water consumed per person per day in litres. The smaller the water consumption, the higher the number of credits and sustainability level achieved. The highest levels (5 and 6) required less than 80 litres per person per day to be consumed under indoor water use (ibid).

Furthermore, Category 2: Water in the CSH only stated the documentation required to demonstrate compliance with achieving specific levels. It did not directly suggest implementing methods to conserve water, however it offered definitions of some viable options. For example, under indoor water use, it described low-flush WCs, grey-water recycling and flow restrictors. Under outdoor water use, it described, rainwater butts and central rainwater collection systems. Following this to demonstrate compliance during the design stage, the "location, details and type of appliances/ fittings that use water in the dwelling including any specific water reduction equipment with the capacity / flow rate of equipment" (Department for Communities and Local Government, 2010b, p.83) were reported, and the "location, size and details of any rainwater and greywater collection systems provided for use in the dwelling" (ibid) were described.

Similarly, the BREEAM assessment evaluated water consumption. An excellent rating required a minimum of one credit (12.5% improvement over baseline building water consumption) and for water monitoring the one available credit was achieved by meeting the relevant assessment criteria (BRE Global Limited, 2014). Under water consumption, the BREEAM scheme identified the water efficiency of different mechanisms (such as showers, toilets, greywater systems, etc) and equated this to a performance scale. The water monitoring category had a set of fixed criteria that must be fulfilled to achieve the available credit (ibid).

The BREEAM summary included in the NW Cambridge Sustainability Statement stated that water consumption and water metering were mandatory on site. In addition, water recycling and irrigation systems would be implemented in the majority of infrastructures (except offices) as well as greywater recycling and rainwater collection systems as part of site-wide water management (AECOM, 2011).

From the information provided in the BREEAM Technical Manual, the water network and its associated fittings at NW Cambridge exceeded the requirements to achieve an 'excellent' BREEAM rating. This exemplified the fact that the sustainability achievements of NW Cambridge went far beyond the local, regional and national policies that are compulsory on the site.

4.5.4 Governance and Planning

The role of governance and planning for the use of water in enhancing urban sustainability and resilience was most apparent in the higher levels of documentation.

Planning Policy Statement 1 (PPS1) mentioned the role of different planning levels in implementing sustainable urban approaches, with the PPS1 supplementary guidance 'Planning and Climate Change' reinforcing the notion that national, regional and local planning authorities need to set clear advice to regularly deliver sustainable development (Department for Communities and Local Government, 2007). In addition, the draft Planning Policy Statement: Planning for a Low Carbon Future in a Changing Climate stated that regional and local planning authorities should boost efficient water usage and set water management standards to enhance resilience, particularly in regions where water is already stressed (Department for Communities and Local Government, 2010a). This responsibility was delegated to regional strategies, which for the NW Cambridge site fell under the East of England Plan (2008).

The East of England Plan set a regional framework for Local Plans and gave spatial context to national Planning Policy Statements. It was abolished in 2010 following the revocation of regional planning after a change in UK government. The plan placed a significant emphasis on utilising water efficiently and enhancing sustainability across the region. It presented ideas for reducing the demand on water resources and reducing waste, and placed significant emphasis on communication between organisations to facilitate this (Government Office for the East of England, 2008). The East of England Plan (Government Office for the East of England, 2008) renewed the guidance from the Cambridgeshire and Peterborough Structure Plan, however in 2011 the enactment of the Localism Bill meant that planning authorities were no longer obliged to produce Regional Spatial Strategies. As a result, a planning unit was formed by Cambridgeshire and Peterborough to maintain a sense of regional planning.

The Sustainability Statement for NW Cambridge stated that as the East of England Plan was not officially abolished during the early phases and its principles were followed for the development (AECOM, 2011). Under the East of England Plan policies were set out in relation to water use and sustainable development on site. It emphasised collaborative planning across organisations for optimised water management planning, stating that "the Environment Agency and water companies should work with OFWAT, EERA and the neighbouring regional assemblies, local authorities, delivery agencies and others to ensure timely provision of the appropriate additional infrastructure for water supply" (Government Office for the East of England, 2008, p.67).

At a district scale, the Cambridge Local Plan assigned responsibility for the different facets of water schemes, stating that "in designing sustainable drainage systems, developers must provide for the maintenance of such schemes…Cambridge Water and Anglian Water are responsible for water supply and sewage treatment within Cambridge. The Environment Agency is responsible for water resource management" (Cambridge City Council, 2006, p.65).

Higher levels of documentation often assigned responsibility to lower levels and provide brief inexact statements to address the role of water in urban sustainability and resilience. As shown by their observed presence throughout the documentation, governance and planning played a significant role in enabling the utilisation of water at NW Cambridge.

4.5.5 Sustainable Drainage Systems (SuDS)

The processes behind the implementation of SuDS as part of the dual water network at NW Cambridge are a complex web of technical management, design creativity and stakeholder communication, which was guided by documentation such as those discussed here. SuDS are embedded in planning policy, urban design guidance and sustainability assessment schemes from national to local levels in the UK. SuDS can play a crucial role in utilising water to augment sustainable urban environments, and the inclusion of SuDS at NW Cambridge demonstrates this in action.

At the time of development of the NW Cambridge site, the National Planning Policy Framework (NPPF) was only available in draft format, and therefore the primary focus from a planning perspective was on Planning Policy Statements. However, it was stated in the sustainability statement that “at the heart of the NPPF is to be the presumption in favour of sustainable development” (AECOM, 2011, p.2), demonstrating its emphasis on holistic sustainability and resilience measures. In 2012 the NPPF incorporated Sustainable Drainage Systems (SuDS) (Department for Communities and Local Government, 2012) and was supplemented by SuDS guidance such as the National Standards for Sustainable Drainage (Department for Environment, Food and Rural Affairs, 2015b), and the Non-Statutory Technical Standards for Sustainable Drainage: Practice Guidance (Local Authority SuDS Officer Organisation, 2016). Both guides delivered details of the factors affecting the implementation of SuDS.

Of the critical planning policies impacting the development of the NW Cambridge site, the previously mentioned PPS1 considered water efficiency through the use of SuDS and promoted their general uptake (Office of the Deputy Prime Minister, 2005). In addition, the draft Planning Policy Statement: Planning for a Low Carbon Future in a Changing Climate highlighted the costs and benefits of implementing sustainable drainage (Figure 4.7).

Criteria in policy	Costs	Benefits
Use sustainable drainage systems, paying attention to the potential contribution to be gained to water harvesting from impermeable surfaces and layouts that accommodate waste water recycling	There may be additional costs to developers in providing SUDs, although in some instances SUDs systems may be cheaper than conventional drainage.	The use of SUDS should lead to reduced likelihood of flooding; and where water harvesting is incorporated in the design of a development may lead to benefits in areas of water stress or shortage. This has strong links with other policies; the draft Floods and Water Management Bill includes a provision to make SUDs mandatory where practicable.

Figure 4.7 – Planning application assessment measure relevant to SuDS (Department for Communities and Local Government, 2010a, p.61).

Furthermore, the SuDS system feeding the dual water network at NW Cambridge adhered to Codes of Practise in compliance with UK planning law. For example, BS 8515 Rainwater harvesting systems: Code of Practice was followed for the site-wide water recycling network at NW Cambridge. This ensured that the scheme was installed to a minimum standard for rainwater harvesting systems in the UK. These codes of practise set the requirements that must be met although they can be written for non-compulsory sustainable infrastructure (i.e. meeting a certain quality is compulsory, however implementing a design is not).

The regional East of England Plan (2008) further encouraged the use of SuDS to improve the connection between water and the built environment. However, it was the district and local level documentation which provided details on SuDS implementation for promoting sustainable urban settings. For instance, at a district level the planning authorities believed that the Cambridge Local Plan was an opportunity for innovative design to pave the way towards sustainable development. The plan was clear in promoting the use of SuDS such as "swales, lagoons, permeable paving, green roofs and reed beds, depending upon the nature of the proposed development and site characteristics" (Cambridge City Council, 2006, p.65).

In addition, the Cambridge City Council Sustainable Design and Construction Supplementary Planning Document (SDC) addressed SuDS separately to water use. This implies that technical expertise was needed to make the connections between water, SuDS and urban design, and draw out their relevance to implement coherent solutions. More specifically, there were seven questions presented in the SDC relating to SuDS, two of which is related to the SuDS Design Accreditation and Information Checklist (presented in the SDC). Under this checklist, technical data for the SuDS system was required which included: design return periods, permitted rates and volumes of runoff. In addition, there was a requirement to provide technical information on: the existing environmental conditions, site parameters, hydraulic conditions, structural properties, and design specific SuDS parameters. The other five questions from the SDC checklist ensured technical data has been collected to build sustainable infrastructure (capable of meeting the sustainability criteria discussed in the Cambridge Local Plan and the design principles section of the SPD), and checked that a maintenance plan was provided for the SuDS features in the future. In the bigger picture, these ensured that SuDS abided by the higher levels of guidance and legislation surrounding sustainable development. This was also evident in the water section of the SDC Checklist, which focused on setting targets for water consumption and addressing how these targets could be achieved (Cambridge City Council, 2007).

Nevertheless, the SDC only provided guidance to development stakeholders on the policies set out in the Cambridge Local Plan (2006), detailing the actions that must be adhered to. In this there is some commentary relating to the use of water as a resource to build sustainability. This is through the delivery of SuDS, where it is stated that an added benefit to rainwater harvesting is reduced demand on potable water networks. The Cambridge Local

Plan stated that “it is preferable to manage surface water runoff on site where possible through the use of sustainable drainage techniques” (Cambridge City Council, 2006, p.65). In addition, open space “could also be used for the storage/recycling of water to benefit flood protection and encourage sustainable drainage systems” (Cambridge City Council, 2006, p.37). This may have been a significant enabler for the green infrastructure implemented at NW Cambridge.

The Cambridge Sustainable Development Guidelines (CSDG) (2003) also encouraged the use of various types of SuDS in relation to water utilisation and sustainable development at NW Cambridge (Land Use Consultants cited in Cambridge City Council, 2002). For example, permeable paving, water recycling, swales and balancing ponds to manage water across the site. It further suggested that developers should collaborate with local authorities as well as wider regulatory bodies (such as the EA) to protect the environment from flooding and pollution using SuDS. This notion was also repeated in the NWCAAP, where Policy NW25 (Surface Water Drainage) set a clear precedent that the SuDS on site should control the run-off volumes to mitigate any risks associated with flooding and to prevent any negative impact local wildlife.

Finally, Condition 27 of the granted planning permission required the specifics of the SuDS features on site to be disclosed, including accountabilities, ownership and management strategies. Conditions 29 and 30 related to water supply and discharge, requiring evidence that sufficient water supply and drainage has been devised for the development. The criteria set by planning authorities controlled the quality and quantity of water management approaches for the site, as well as the level of incorporated sustainability that is mandatory for new developments.

From the perspective of sustainability assessment methods, the CSH referred to the SuDS management train which is an implemented sequence to achieve acceptable surface water runoff rates. This included techniques for; source control (soakaways, porous paving, green roofs, etc), site/local control (swales, detention basins, soakaways, etc) and regional control (wetlands and larger basins).

As previously stated, under the CSH the highest levels of sustainability required less than 80 litres per person per day to be consumed. Under category 2, SuDS were suggested to fulfil the outdoor requirement and meet the desirable level of sustainability. The University of Cambridge decided to go above and beyond the requirement by implementing the site wide

SuDS and dual water network. AECOM (involved throughout the design and implementation of the development at NW Cambridge) calculated that they could reduce the demand on the potable water network by a third by utilising a non-potable water network. The predicted potable water usage was just over 60 litres per person per day; well under the 80 litres per head per day required to achieve CSH Level 5.

SuDS play a significant role in water management systems, and their widespread implementation in the UK demonstrates this. The encouragement and regulations around SuDS implementation that is observed in national, regional, district and local documentation showed that SuDS are widely accepted as a means of utilising water to enhance urban sustainability and resilience. Their regular occurrence within documentation generated a general knowledge of SuDS amongst urban stakeholders and demonstrates a possible route for implementing other geo-resources in the UK to enhance urban sustainability and resilience.

4.5.6 Water Management

Water management is a broad term which allows water networks to be managed in an urban context. References are made to it in global itineraries, but also in national, regional, district and local levels although the amount of detail around the concept increases closer to local levels where contextual information is available to describe the water management scheme at NW Cambridge.

Unified approaches to water management are encouraged in SDG six through avenues such as international collaboration. At a national level, the PPS1 supplementary guidance 'Planning and Climate Change' and the Draft Planning Policy Statement: Planning for a Low Carbon Future in a Changing Climate suggested that governing bodies should address water management for sustainable development to tackle the impacts of climate change (Department for Communities and Local Government, 2007; Department for Communities and Local Government, 2010a). Also, as a broad statement at a regional scale, the East of England Plan (2008), noted that water management can be optimised through collaborative planning and increased use of SuDS to enhance water efficiency (Government Office for the East of England, 2008). At a more local scale, the policies set out in the Cambridge Local Plan set a clear precedent that sustainably is important in achieving planning consent, and that water management had a role to play in this through techniques such as SuDS (as discussed above). In fact, condition 26 of planning permission required the production of a site-wide water management approach that was approved by the local planning authority. This was partly to guarantee “efficient use and management of water within the site” (South Cambridgeshire District Council, 2013, p.13).

4.5.7 Document Examination Section Summary

Cambridge as a region is heavily dependent on groundwater resources to meet water demand, and in recognition of this, regional and local planning authorities enforced water management techniques to encourage sustainable schemes. The water system devised for the NW Cambridge development not only demonstrated compliance with planning policy, but also delivered on aspirational sustainability beyond codes of practice and legislation in many instances.

This document examination investigated the guidance that exists through cross-cutting themes observed on different levels of planning policy, urban design guidance and sustainability assessment approaches. National policy and guidance focus on water efficiency, and demonstrated a strong connection to urban design through SuDS implementation. Regional and district policy added context to the national agenda, giving area-specific guidance and directing urban stakeholders towards future-proofing concepts (such as water efficiency measures and minimising waste of natural resources). Site level documents compiled policy and urban design guidance and discussed the urban design features for the site which will meet the criteria set out at higher scales.

This examination demonstrated that groundwater is well-regulated in the UK by effective planning policy, and that there is an established connection between sustainable and resilient urban design and water-saving features. No conflicting guidance was observed within the policy examined, although the general trend of increasing detail (from broad concepts at national level through to more context specific methods at local levels) may have facilitated this. There was a clear focus on water efficiency and SuDS across the different levels of planning policy. More detailed guidance was available from granular levels of governance, particularly district and local level authorities. This is because local circumstances can be considered within guidance to provide the most relevant information to development stakeholders.

Furthermore, ownership of groundwater is a complicated issue due to its invisibility, its interaction with surface water systems and the complexity of subsurface environments. However, the responsibilities of water management are much easier to define through governance and planning. The NW Cambridge development set out stakeholder expectations and responsibilities in its earliest phases, and this demonstrated some key factors for success of the scheme: collaboration, clear guidance, and communication between driven stakeholder groups.

4.6 NW Cambridge Case Study Conclusion

The NW Cambridge development is home to the UK's largest rainwater harvesting scheme, built to enhance the resilience of the site and improve the sustainability of the area. Groundwater in the region surrounding Cambridge is not available for consumptive licensing (Environment Agency, 2017b) and therefore careful water management is required across the region to ensure resource security for the future. This case study has demonstrated the way that groundwater is both perceived and utilised as a geo-resource in the context of sustainable and resilient urban development.

The groundwater potential mapping tool and UDG matrix identify where and how groundwater can be explored for utilisation, and what urban structures should be considered to maximise the potential contribution that water in urban design can have for meeting planning policy and urban design guidance. If done in the feasibility or early design phases of a construction project, these tools could steer stakeholders towards urban design with a geo-resources perspective, to consider their options and site geo-resource potential from the onset of a project.

The groundwater potential mapping tool identified areas within the NW Cambridge development with different potentials for groundwater utilisation. There are areas on site with excellent potential for direct groundwater utilisation from a geological perspective, however there are regional restrictions preventing the overexploitation of groundwater, and therefore stopping its abstraction on site. The implemented water management scheme (including the non-potable water network, water-efficient fixtures and SuDS infrastructure) delivers sustainable design across the site and meets various water use and sustainable development goals in line with local, regional and national documents. The site specific UDG matrix demonstrates to stakeholders how the scheme has satisfied criteria from local to national planning policy and guidance. Retrospectively, this may have facilitated targeted ground investigations and contributed towards optimised urban design on site which maximises the sustainability and resilience potential of the development from a water perspective.

The interview series confirmed that there were a combination of motivations for the NW Cambridge water management scheme. One regular point for its success was the enthusiasm of the client (University of Cambridge) to construct a holistic sustainable development that fulfils the University's needs for expansion but also demonstrates an exemplar case of sustainable urban growth. The capital cost of these types of schemes was identified as a key barrier for building infrastructure focussed primarily on delivering sustainability. The stakeholder groups of NW Cambridge all considered the dual water network a success in terms of achieving the aims that the system was designed to meet. An assessment of the long-term functionality and effects of the network will require information to be gathered over time, however it was suggested that the potable water consumption could be reduced by up to 50% due to the use of the non-potable water supply.

Furthermore, planning policy, urban design guidance and sustainability and resilience assessments were found to be generally inclusive of water and/or groundwater management. The national and international documents gave fewer instructions on how to implement sustainable development or utilise water for sustainable urban design, however they encouraged sustainable development and often devolved responsibility to regional and local authorities to provide appropriate guidance. There was a clear association between the efficient use of water within urban infrastructure and sustainable development agendas. The infrastructure at NW Cambridge was most aligned to regional and local policies. The most detailed information was at local levels where it is most relevant to provide context-specific implementation guidance. Planning policy for the region set a clear precedent for water conservation in terms of reduced consumption and increased recycling. Some of this was enforced under planning conditions, and some was encouraged under urban design guidance, however all of these documents facilitated the sustainable use of water and/or sustainable and resilient urban design.

This groundwater case study contrasts with those for ground heat and subsurface space as it does not utilise the geological resource (groundwater) directly but implements an urban design feature which impacts the sustainability and resilience of the resource over a wider area. This demonstrates the importance of the temporal component and regional context for the utilisation of groundwater. The groundwater potential mapping tool is dependent on whether groundwater is available for consumption, which fluctuates on a much smaller timescale than ground heat or subsurface space utilisation. This groundwater case study assesses groundwater utilisation from a geological sense however requires active updates to reflect changes to regulation for the region. This may in part be responsible for the complete omission of groundwater use for the design and planning components of the NW Cambridge site.

The next chapter investigates the perception and use of ground heat in creating sustainable urban design. A comparison of the case study findings is presented in Chapter 7 which evaluates geo-resource use for enhancing urban sustainability and resilience.

5 - Investigating Ground Heat Utilisation at Chestnut and Aspen Mews, Burton on Trent

Developments in technology have allowed the utilisation of ground heat as a renewable energy source in both large scale commercial buildings as well as domestic housing. Ground heat has the potential to support clean urban growth, as part of a suite of renewable energy sources, over traditional energy supply. However, establishing ground heat potential on a case by case basis can be complex due to the number of factors affecting its suitability such as: thermal properties, ground temperature, groundwater and geological characteristics.

As discussed in Chapter 2, resilience is adaptive and transformative, and by installing a ground source heat pump (GSHP), should an event occur that compromises traditional energy supply routes, the decentralised and renewable nature of ground source heat can increase the chance of a site being able to maintain a stable state and preserve an existing normality. GSHPs are becoming increasingly common in the UK, and therefore assessing the situation and design of existing GSHPs is important to determine their potential for building resilient infrastructure and sustainable urban environments. The rate of uptake is variable across the UK and is determined in part by the suitability of ground conditions and the success of existing schemes.

This chapter explores how ground heat has been used as an alternative to mains gas heating at Chestnut and Aspen Mews, and the sustainability and resilience this delivers by utilising a decentralised resource. The site was selected as an example of a vertical closed loop GSHP network which demonstrated how ground heat can be utilised in existing buildings as part of a retrofit[1]. The successful implementation of the GSHP system at Chestnut and Aspen Mews required collaboration by several stakeholder groups (design consultants, installers, client/investor, end users), which had to consider the project requirements, local context, policy guidance and the environmental setting. Furthermore, the novelty of ground heat as an accessible geo-resource means that it has only been introduced into planning guidance and policy in recent times.

As with case study one, the potential use of ground heat at Chestnut and Aspen Mews was assessed using a geo-resources potential mapping tool. Following this, a series of stakeholder interviews and an examination of planning policy, urban design and ground heat guidance,

[1] There are other mechanisms which have different contextual settings to consider, for example horizontal closed or vertical open systems which have different implementation requirements which are not part of this case study.

as well as sustainability and resilience assessments explored the enablers, drivers and difficulties encountered in implementing the ground source heating system at Chestnut and Aspen Mews. These techniques demonstrate the perception and potential use of ground heat in enhancing urban sustainability and resilience.

5.1 Introduction

Chestnut and Aspen Mews comprise 60 properties across two low rise three-storey flats which are owned and managed by Trent and Dove Housing and leased out to tenants. They are located south east of Burton Upon Trent town centre in East Staffordshire (National Grid Reference SK 25678 20853) (Figure 5.1).

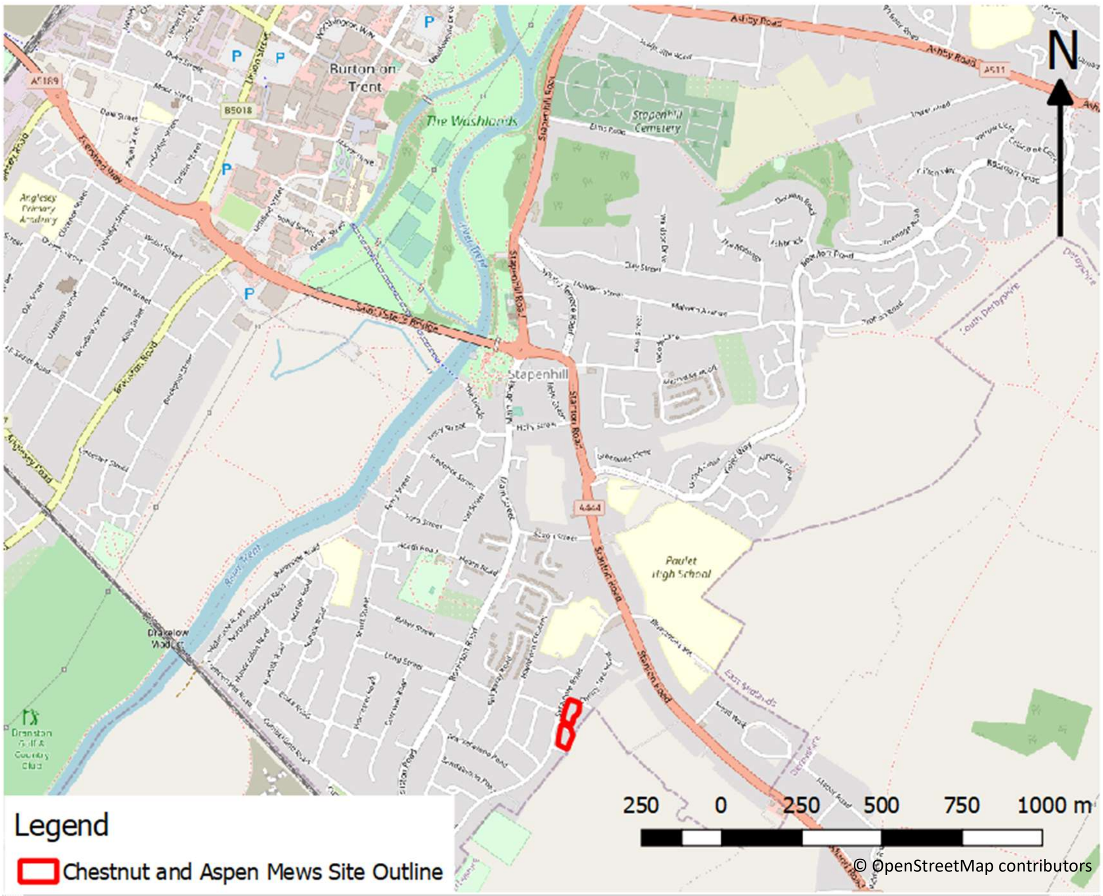


Figure 5.1 – Site location plan for Chestnut and Aspen Mews, Burton on Trent.

The site is approximately 0.5 hectares in size which includes the green space surrounding the buildings where the boreholes were installed. The flats were originally built between 1963 and 1968, and the retrofit of the vertical closed loop GSHP system was undertaken in 2015.

The retrofitted GSHP network installed at Chestnut and Aspen Mews is a micro district ground source heating system (i.e. a communal ground array supplies heating to individual properties). The system has 40 communal boreholes installed to a depth of between 112m and 152m below ground level and is connected by 12 near-surface ground arrays. The ground arrays link to the heat exchangers which are connected to Kensa's Heat Pumps (6kW Shoebox Twin design) which are installed in each individual flat. The boreholes have a minimum

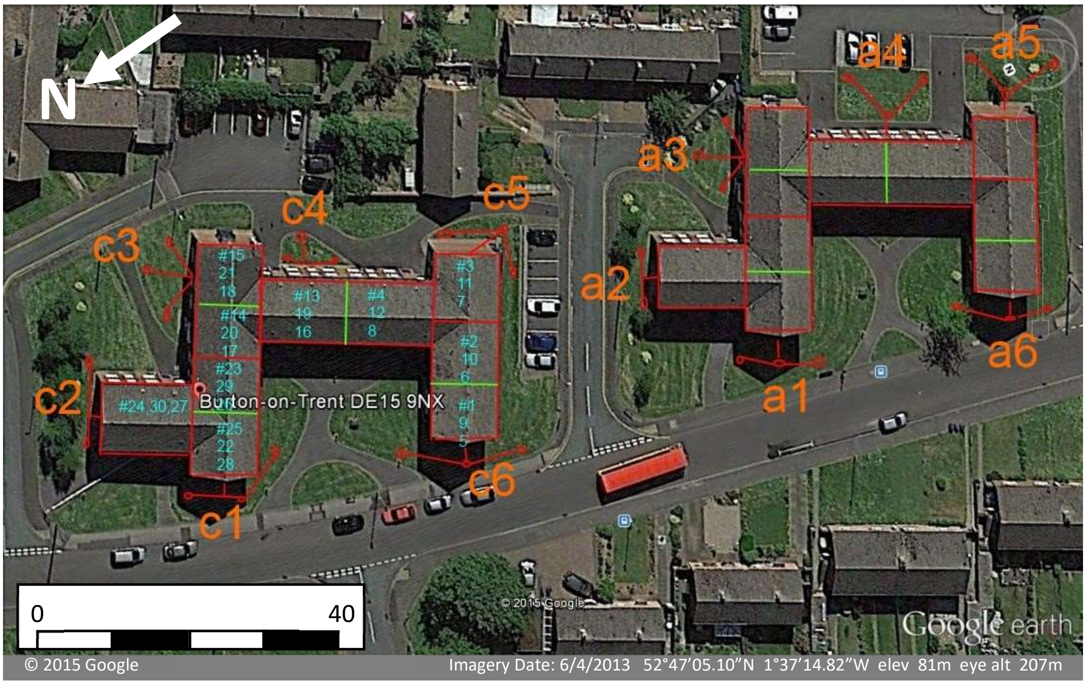


Figure 5.2 – Borehole location plan for Chestnut and Aspen Mews (c boreholes = Chestnut Mews, a boreholes = Aspen Mews).

spacing of 6-8m and are located in the landscaped areas surrounding the two blocks of flats (Figure 5.2).

The infrastructure associated with GSHPs typically have low maintenance requirements. The pumps may provide reliable heating for 20 years or more (Omer, 2006), and the borehole array should function for up to 100 years (Kensa blueprint document, 2016). The installation in Burton is a typical GSHP closed loop set up containing three main components:

- the loop (containing a water and antifreeze solution that circulates the ground via the borehole absorbing the heat),
- the pump (transferring the heat into the distribution circuit),
- the heat distribution system (radiators and hot water cylinders).

The utilisation of ground heat at Chestnut and Aspen Mews is presented in a simplified schematic below (Figure 5.3). To summarise, the loop flows through the ground and into the subsurface via a borehole. The loop returns to the surface having extracted heat from the surrounding rocks. Heat is converted to a useable form (via a heat pump) and circulated for domestic use via a distribution system.

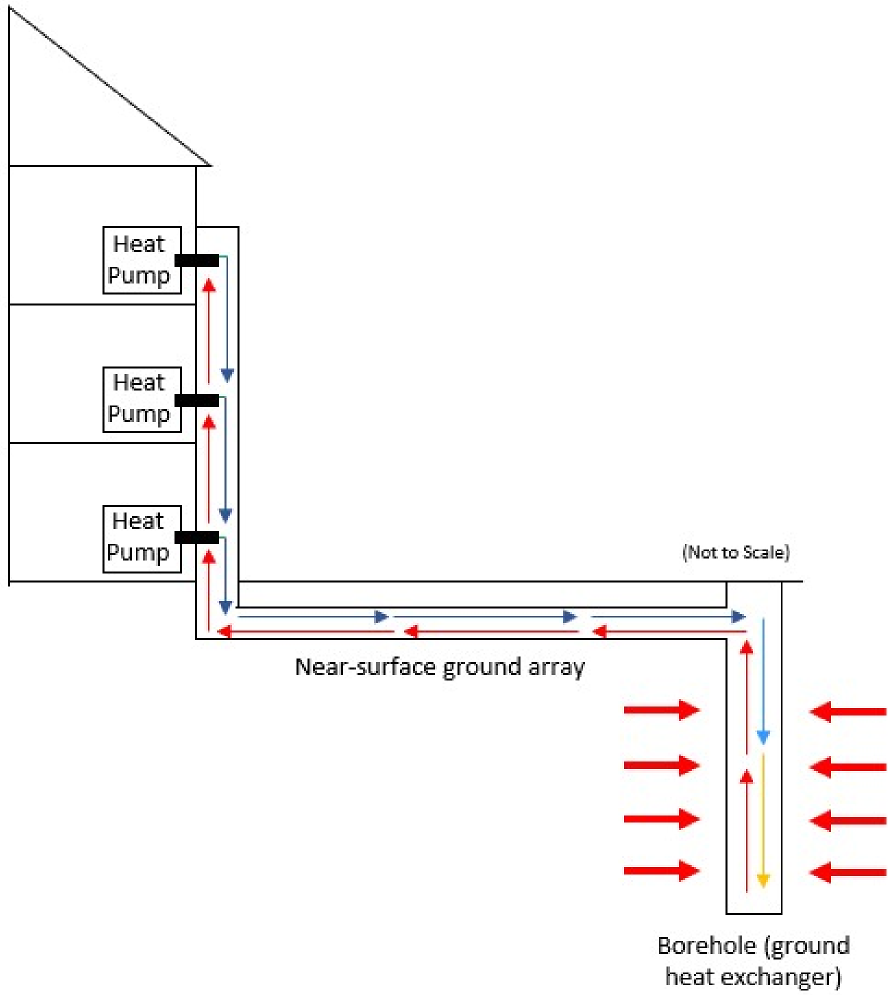


Figure 5.3 – Schematic of the GSHP system at Chestnut and Aspen Mews.

The boreholes were drilled to a depth pre-determined by modelling calculations which account for "heat pump performance including minimum coefficient of performance (COP) requirements and estimated seasonal performance factor (SPF), fluid temperature constraints, geology, the thermal conductivity of the ground, flow rate, loop configuration and its hydraulic implications, local climate and landscaping" (GSHP Association, 2011, p.11).

The geological conditions are particularly important as these heavily impact the performance of GSHP systems. This includes thermal conductivity, thermal diffusivity, ground and sub-surface temperatures, geological formations and thickness, presence of weathered geology, rock strength, groundwater levels, aquifer properties and the presence of mine workings. These are discussed in detail by Busby et al., (2009) and summarised in Table 5.1.

Geological Factor	Importance
Thermal conductivity	"The capacity of a material to conduct or transmit heat" (Busby et al., 2009, p.296). This varies with rock type and conditions and impacts heat exchange performance.
Thermal diffusivity	"The rate at which heat is conducted through a medium" (Busby et al., 2009, p.296). This varies with rock type and conditions and impacts heat exchange performance.
Ground and sub-surface temperatures	The temperature difference between the sub-surface and the fluid within the loop is the temperature gradient. The higher the gradient the more efficient the GSHP system may be.
Geological formations and thickness	Boreholes may encounter several rock types. Superficial deposits have wide-ranging thermal properties. Bedrock formations also have variable rock properties which will impact GSHP performance.
Presence of weathered geology	Rock properties (and thermal properties) will be altered in weathered formations.
Rock strength	Impacts the excavation methods for GSHP installation.
Groundwater levels	Presence enhances thermal properties (significantly in superficial deposits) and therefore impacts GSHP performance. Downwards groundwater flow can reduce subsurface temperatures. Upwards flow can increase surface temperatures. In both cases flow impacts GSHP performance.
Aquifer properties	Most important for open loop GSHPs but also vital for closed loop – "porosity, permeability, hydraulic conductivity, transmissivity and storage coefficient" (Busby et al., 2009, p.303) will influence the impact of groundwater on GSHPs. Artesian conditions can complicate construction.

Presence of mine workings	Hazardous to borehole drilling.

Table 5.1 – Geological conditions impacting the performance of GSHP systems (based on Busby et al., 2009).

5.2 Site Characteristics

5.2.1 Geological Setting and Hazards

Records held by the British Geological Survey (BGS) (2016a) indicated that the site has no superficial deposits or made ground presence. However due to the urban setting of the site, localised made ground may be anticipated. According to the geological maps, most of the site is underlain by the Tarporley Siltstone Formation; a siltstone, mudstone and sandstone bedrock which is part of the Mercia Mudstone Group. The Helsby Sandstone Formation is present in the south eastern corner of the site (a formation part of the Sherwood Sandstone Group) (British Geological Survey, 2016a).

On-site borehole logs confirm the variable geological conditions encountered on site. Multiple boreholes were drilled in close proximity at locations C1-C6 and A1-A6. The interpreted log of the first borehole at each location are presented in Figure 5.4 and Figure 5.5 respectively. All boreholes were examined when evaluating changes with depth. The approximate cross-sectional lines for all boreholes are shown in Figure 5.6.

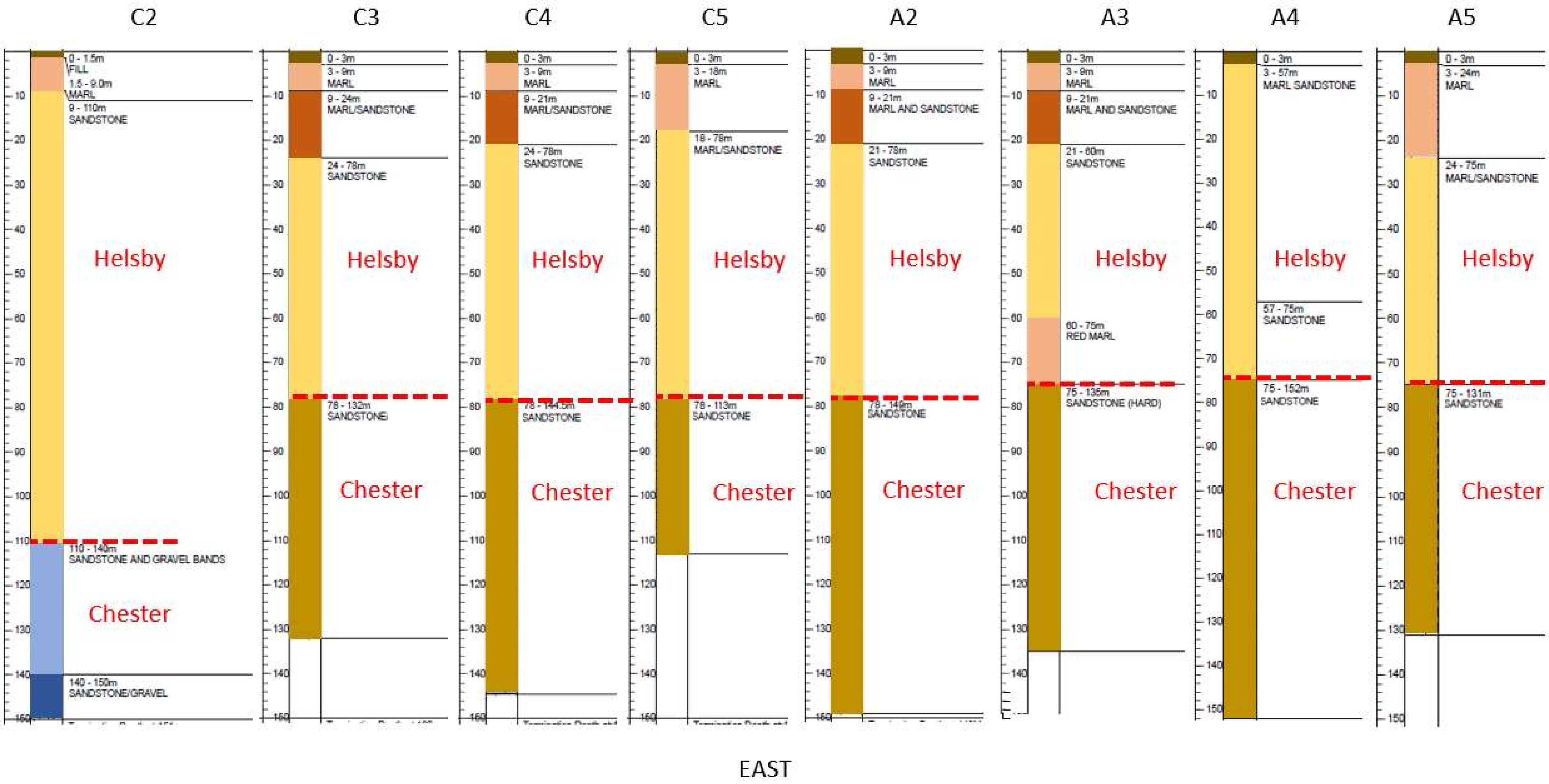


Figure 5.4 – Interpreted borehole geology from the eastern side of Chestnut and Aspen Mews.

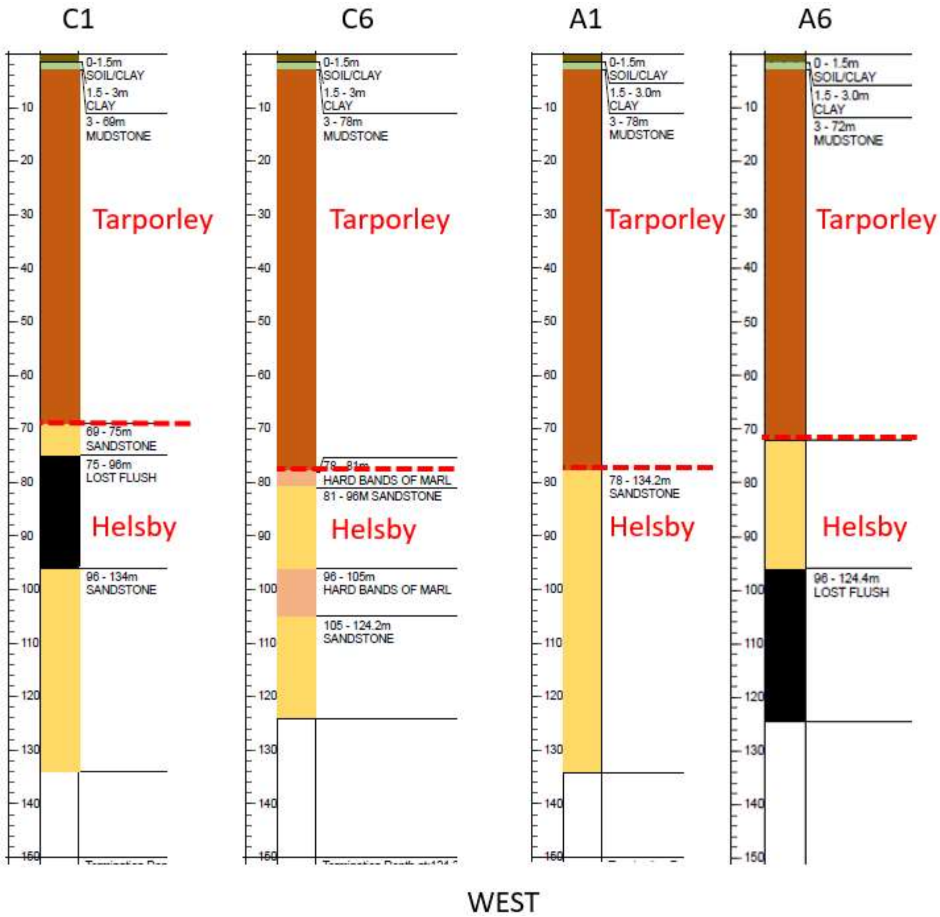


Figure 5.5 – Interpreted borehole geology from the western side of Chestnut and Aspen Mews.

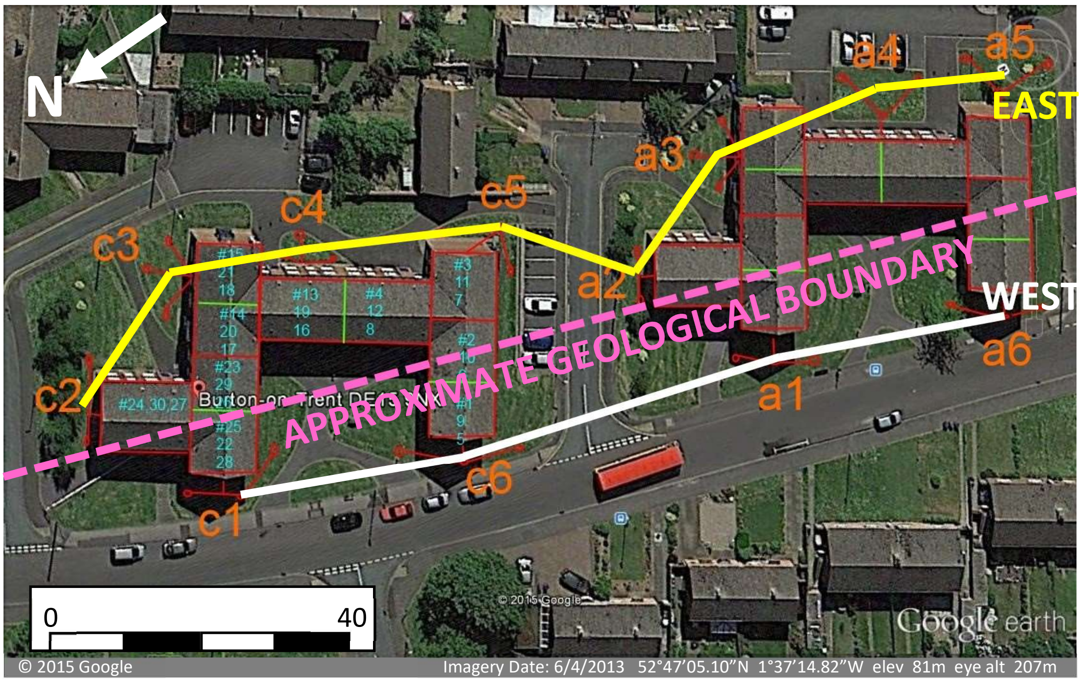


Figure 5.6 – Approximate cross-sectional lines for borehole logs and the approximate geological boundary across the Chestnut and Aspen Mews site.

Shallow conditions in the eastern boreholes (logs C3, C4, C5, A2, A3, A4 and A5) are typically interbedded clayey silty sandstones and sandy mudstones to approximately 80m below ground level. Although not named within the logs this description was consistent with the Helsby Sandstone Formation, which is present in the south eastern corner according to the geological map. Below this a variation in the sandstone was observed, indicating a change into the underlying Chester Formation.

Boreholes drilled in the western half of the site (logs C1, C6, A1 and A6) typically contained mudstone to a depth of 50m-75m below ground level, the thickness of these deposits indicate the presence of Tarporley Siltstone across the western half of the site. Below this a sandstone unit was recorded with localised marl bands and loss of flush. This may be the underlying Helsby Sandstone Formation as observed on the geological map.

There is a distinct change in geological conditions dividing the site in a broadly north-south orientation as shown in Figure 5.6. This closely resembles the geological setting expected for the site (British Geological Survey, 2001).

A borehole approximately 600m to the south west reported glacial till to 1.3m depth overlying weathered mudstone and Mercia Mudstone (SK22SE511). Rockhead (siltstone) was encountered at 2.3m below ground level (SK22SE511). Another borehole (SK21NE7) approximately 950m to the south east suggested that the Mercia Mudstone is underlain by the Chester Formation (at 21.3m begl) and beneath this was the Pennine Lower Coal Measures Formation (at 136.8m begl).

Geological formations have wide-ranging thermal properties which will impact the performance of GSHP systems, however the variation in thermal conductivity is due to the influence of other factors such as water saturation and rock consolidation (Santa et al., 2020). One factor alone cannot define the viability of a GSHP system. Modelling a combination of site-specific geological data is required to explore ground heat utilisation potential.

Although the focus of this study is to demonstrate the geo-resource potential of the site in relation to the use of ground heat, the geo-hazards which could affect the utilisation of ground heat should also be recognised. For instance, BGS datasets indicate that there is a slightly increased risk of compressible ground 50m north of the site, and running sands may pose an issue if the water table rises rapidly (British Geological Survey, 2014).

5.2.2 Hydrogeological and hydrological setting

The hydrogeological and hydrological setting for the development provides the environmental context for the exploitability of ground heat. Chiasson et al., (2000) stated that "the thermal properties of soils and rocks are functions of mineral content, porosity, and degree of saturation", emphasising the importance of establishing the hydrogeological setting on site.

Groundwater levels are approximately 18m to 26m below ground level (British Geological Survey, 2015a), and the groundwater vulnerability is classified as high (Environment Agency, 2017c). For the closed loop GSHP installed at Chestnut and Aspen Mews, this means that the loops are circulating within saturated strata of mudstone and sandstone. The impact this has on the thermal properties of the rocks (and therefore GSHP efficiency) is dependent on the porosity, density and level of consolidation as well as water content (Busby et al., 2009). One study found that for sedimentary rocks "the increase in thermal conductivity after water saturation was found to be considerable in many cases, varying between 6% and 55% for sandstones and between 3% and 17% for shales when compared to data obtained in the dry state" (Nagaraju and Roy, 2014).

The Tarporley Siltstone is classified as a Secondary B aquifer. The Environment Agency describes this classification as a "predominantly lower permeability layers which may store and yield limited amounts of groundwater due to localised features such as fissures, thin permeable horizons and weathering. These are generally the water-bearing parts of the former non-aquifers" (Environment Agency, 2017a). The Helsby Sandstone Formation and the underlying Chester Formation (at approximately 80m depth) are classified as Principal aquifers which have "high intergranular and/or fracture permeability - meaning they usually provide a high level of water storage" (Environment Agency, 2017a). The Pennine Lower Coal Measures beneath the Chester Formation is classified as a Secondary A aquifer; "permeable layers capable of supporting water supplies at a local rather than strategic scale" (Environment Agency, 2017a). The site is not within a Groundwater Source Protection Zone (SPZ).

As shown, the aquifer designations provide general information on some of the formation properties. These could be used in combination with other factors to determine GSHP efficiency.

The implementation of a GSHP system at Chestnut and Aspen Mews showcases the value of ground heat for increasing urban sustainability. In order to assess the ground heat potential across the site, a mapping tool was implemented for the location. The following sections explore the value of ground heat from this tool, followed by an examination of the enablers and barriers encountered from a series of stakeholder interviews and a document examination.

5.3 Ground Heat Potential Mapping Tool

In order to retrospectively assess the potential of utilising ground heat at Chestnut and Aspen Mews, a mapping tool was devised from a geological perspective which provides a rating (from excellent to very poor) across the site area. This rating gave an indication of the geological suitability of utilising ground heat on site, specifically for vertical closed loop GSHP systems.

The methodology undertaken to create the mapping tool was described in chapter 3. The map produced comprised five components which represent some of the principle properties that affect ground heat utilisation (Table 5.2). Table 5.3 summarises the datasets, their purpose and level of reworking that was undertaken before incorporating the datasets into the mapping tool.

Factor	**Dataset**	**Justification**
Am I on a productive aquifer?	Aquifer Designation	Indicates the water-bearing properties of geological units. The ability of the subsurface to store and transfer groundwater will affect the efficiency of a GSHP system.
Is the water resource vulnerable to contamination?	Groundwater Vulnerability	Indicates the perceived risk to groundwater. Drilling into an aquifer to install a GSHP borehole may create a potential contamination pathway.
Is there shallow groundwater which can impact thermal conductivity?	Depth to Source	Indicates the depth to the shallowest aquifer (which many coincide with the water table). Saturated ground tends to increase thermal

		conductivity influencing the efficiency of a GSHP system.
Is the subsurface easy to excavate?	(Civils) Excavatability	Indicates the anticipated equipment required to excavate the ground. Important as a proxy for the potential cost of drilling and borehole/pump infrastructure.
Is made ground absent from the site?	Artificial Geology	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.

Table 5.2 - Key factors affecting ground heat utilisation potential, the related dataset and justification for its use.

Dataset Name	**Background**	**Reworking**
Basic Superficial Deposits Thickness Model (BSTM)	Mathematical model of known thicknesses of superficial deposits	Superficial deposits with less than 10m of recorded thickness have been removed from the BSTM data because "unsaturated zone is likely to be effectively less than 10 m thick"* (p.302) meaning the impacts of groundwater will be more comparable. Also, vertical closed loop heat exchangers are typically installed "between 15m and 120m deep"** (p.7). The superficial aquifer designation was then clipped to this and combined with the bedrock aquifer designation.
Superficial aquifer designation/	"Joint Environment Agency and British Geological Survey dataset	The reduced BSTM data was used to isolate the superficial aquifer designation data where deposits were greater than

Bedrock aquifer designation	identifying the different aquifers of England and Wales" *** (p.10).	10m thick. The bedrock aquifer designation data was not reworked.
Ability to excavate the ground – 'Excavatability'	British Geological Survey dataset based on geotechnical property information.	A new column was created due to cases when data was 'na' for typical strength or typical density excavation type. The new column 'typ_ex' presents data from the filled column to maximise map coverage.
Groundwater Vulnerability	Joint Environment Agency and British Geological Survey dataset providing information on groundwater vulnerability.	Combined groundwater vulnerability map used. Worst case vulnerability classification used from the bedrock and superficial aquifer vulnerability designations, following the precautionary principle.
Depth to Source	Mathematical model showing the depth from the ground surface to the top of an aquifer.	Used instead of the 'depth to groundwater' dataset as Depth to Source measures depth to aquifer whereas the groundwater levels dataset could record phreatic/perched water table at shallower elevations.
Artificial Geology	An extract of the BGS Geology map, providing a visualisation of known artificial deposits	Areas within the site boundaries were created where no artificial ground was recorded.

Table 5.3 - Utilised datasets for the ground heat potential mapping tool, background information and reworking undertaken for use in the tool.
* Busby et al., 2009,
**Energy Saving Trust, 2007
***British Geological Survey, 2015b

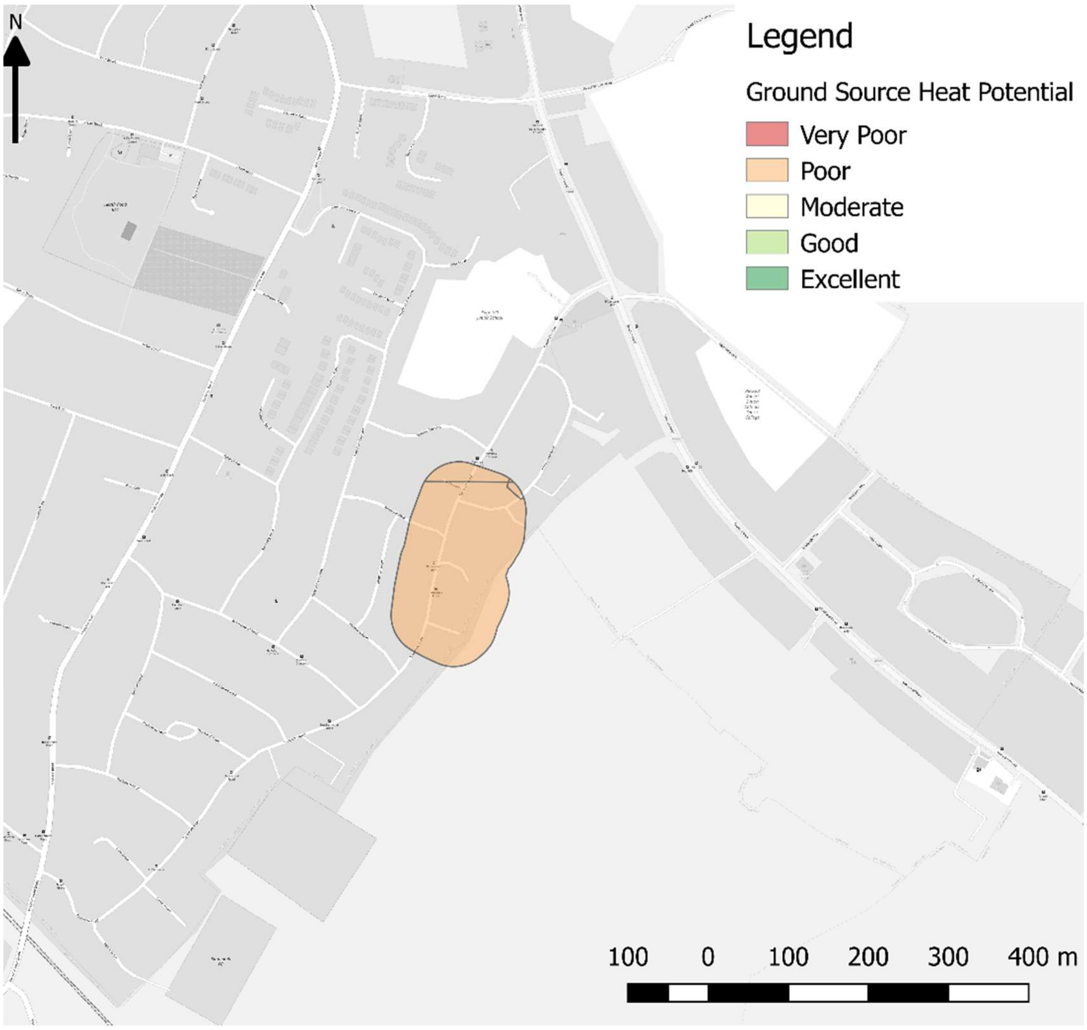


Figure 5.7 – Ground heat potential map for Chestnut and Aspen Mews.

The ground heat potential map (Figure 5.7) showed that the whole site has a 'poor' potential for ground heat utilisation due to the following features:

- Made ground recorded in the north eastern corner of the site.
- A Secondary B aquifer present at surface across the site (which may be overlain by superficial deposits less than 10m in thickness).
- High groundwater vulnerability recorded at surface across the site.
- Anticipated need for power tools to excavate the ground on the site.

These characteristics showed that the 'poor' potential was a result of ground constraints on site, rather than the resource availability.

5.3.1 Map Validation

The data behind the geo-resource classifications was assessed against external factual reports and records which related to the factors supporting the classification (Table 5.4). This verified the findings of the ground heat potential map.

Table 5.4 shows that the information and data reviewed for potential ground heat utilisation at the Chestnut and Aspen Mews site supported the findings of the ground heat potential map. Made ground was observed on site, a Secondary B aquifer was observed at shallow depth (as well as sandstone intervals) (presenting high groundwater vulnerability), and rockhead was observed at shallow depth (exhibiting tougher subsurface conditions for excavation), which all supported a ‘poor’ potential for utilising ground heat at Chestnut and Aspen Mews.

Ref No.	Ground heat potential mapping result	Ground heat potential mapping factor	External information/data source	External information/data comment	Age of data
1	Poor	Made ground in the north eastern corner of the site	Old Maps – OS Plan – Burton on Trent 1883, 1953 and 1958-1968 (Old-maps.co.uk, 2020a-c). On site borehole – Chestnut Mews (C2/1)	Brick yard recorded North of the site in 1883. By 1953 the brick yard was an old clay pit. On the 1958-1968 map the site had been redeveloped into a school. No made ground recorded across the remainder of the site. Made ground recorded within one of the boreholes in the northernmost cluster of boreholes to a depth of 1.5m below ground level.	Map extracts from 1883 – 1968 2015
2	Poor	A Secondary B aquifer is present at surface (which may be overlain by superficial	On site boreholes – Chestnut and Aspen Mews (all logs C1 - C6 and A1 – A6)	The top 3m is typically unrecorded on the borehole logs. Shallow conditions in the eastern boreholes (C2, C3, C4, C5, A2, A3, A4 and A5) are typically interbedded clayey silty sandstones and sandy mudstones to approximately 80m below ground	2015

		deposits less than 10m in thickness)		level. The western boreholes (C1, C6, A1 and A6) typically contain mudstone to a depth of 50 – 75m below ground level. All on site boreholes include sandstone intervals of varying thickness and depth with an inconsistent amount of clay contents.	
			Off Site borehole circa 500m north east of site – Violet Lane – SK22SE29 (BH1 marked on map)	The Lower Keuper Sandstone Formation (now known as the Helsby Sandstone Formation) which underlies the Tarporley Siltstone Formation is recorded from surface at this borehole. This principal aquifer underlies the Tarporley Siltstone Formation stratigraphically.	October, 1960
			Off Site trial pit excavations circa 580m south west of the site – Sycamore Road – SK22SE513	Weathered Mercia Mudstone (parent unit of the Tarporley Siltstone Formation) is recorded beneath made ground and glacial till from 2m-3.4m below ground level.	December, 1991
			BGS Lexicon of Named Rock Units – Tarporley Siltstone Formation	The Sherwood Sandstone Group and Mercia Mudstone Group intertwine in many regions, and	2019

				as the exact boundaries are inexact, they are often drawn ambiguously.	
			The physical properties of minor aquifers in England and Wales, Technical Report WD/00/04 Environment Agency R&D Publication 68	The Mercia Mudstone Group is largely impermeable, however the Tarporley Siltstone Member (anticipated on site strata) may form a minor aquifer.	2000
3	Poor	High groundwater vulnerability recorded at surface across the site	On site boreholes – Chestnut and Aspen Mews (all logs C1 - C6 and A1 – A6) Nearby WellMaster data and water levels in Boreholes: Violet Lane – SK22SE29 Bretby West no. 2 – SK22SE23	All on site boreholes include sandstone intervals of varying thickness and depth with an inconsistent amount of clay contents. This may be the underlying Helsby Sandstone Formation (a principal aquifer), which would be at high groundwater vulnerability. Wellmaster records 'No aquifer' present in nearby boreholes. No water level data is recorded in the nearby available borehole logs.	2015 Logs records from: 1960 1955

			Trial Pit Excavation Logs: Sycamore Road – SK22SE513 Sycamore Road - SK22SE511	Excavations on Sycamore road are dry and stable to a depth of 2.8m below ground level.	December, 1991
			The physical properties of minor aquifers in England and Wales, Technical Report WD/00/04 Environment Agency R&D Publication 68 (Jones et al., 2000)	There is a transitional boundary between the Sherwood Sandstone Group (Helsby Sandstone Formation and Chester Formation) and Mercia Mudstone Group (Tarporley Siltstone Formation) in many regions, and the exact boundaries between units are difficult to distinguish. Sandstone and siltstone horizons within the Mercia Mudstone "may contain and transmit limited quantities of groundwater through fractures" (Jones et al., 2000).	2000
4	Poor	Anticipated need for power tools to excavate	On site boreholes – Chestnut and Aspen Mews (logs C1 - C6 and A1 – A6)	Marl or marl and sandstone are recorded from 3m below ground level, and frequently report hard drilling, (particularly within sandstone layers). The need to change the drill bit to a 'rock roller' or 'rockbit' at depth (typically around 75m below	2015

		ground on the site	Off Site trial pit excavations circa 580m south west of the site -Excavation Logs: Sycamore Road – SK22SE513 Sycamore Road - SK22SE511 Sycamore Road - SK22SE514 Sycamore Road - SK22SE504 Sycamore Road - SK22SE512 Sycamore Road - SK22SE507	ground level) is commonly noted. Very weak to moderately weak mudstone/ siltstone rockhead recorded between 0.9 and 2.65m below ground level.	December, 1991

Table 5.4 – Validation information for factors used in ground heat potential map.

5.3.2 Translation into Urban Design Criteria

The Chestnut and Aspen Mews retrofit was designed in line with documents that focused on urban sustainability and resilience. Relevant planning policy, urban design guidance and sustainability and resilience agendas were translated into an urban design geo-resource (UDG) matrix for the Chestnut and Aspen Mews site (Appendix I). The matrix connected the ground heat potential map with the urban design agenda for sustainability and resilience (and/or ground heat utilisation) specific to the case study setting. It demonstrated how ground heat can be utilised to meet different urban agendas and allowed users to target specific urban criteria. The following documents were included in the UDG matrix:

- UK Government Design Guide,
- National Planning Policy Framework (NPPF),
- Regional Spatial Strategy for the West Midlands,
- East Staffordshire Local Plan,
- East Staffordshire Sustainability Appraisal,
- East Staffordshire Design Guide Supplementary Planning Document,
- BREEAM sustainability assessment method.

These documents influenced the GSHP retrofit project at Chestnut and Aspen Mews (and are discussed in detail in subsequent sections). It is especially important that ground source heat technologies (GSHT) meet urban design criteria and planning policy as this encourages their uptake. Therefore, the relationship between these issues are presented in the UDG matrix (Appendix I).

As explained in the methodology (section 3.6.6), the UDG matrix (Appendix I) presents elements of sustainable urban infrastructure utilising ground heat across the horizontal axis, and sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Figure 5.8 demonstrates two approaches to using the UDG matrix. Firstly, by reading horizontally, the user can prioritise urban criteria (relevant to the Chestnut and Aspen Mews site) and see which approaches of ground heat use may fulfil particular criteria. Alternatively, by reading vertically, if pursuing a specific method of ground heat use, the user can see how implementing it may fulfil certain criteria. A selection from the UDG matrix is presented in Figure 5.8.

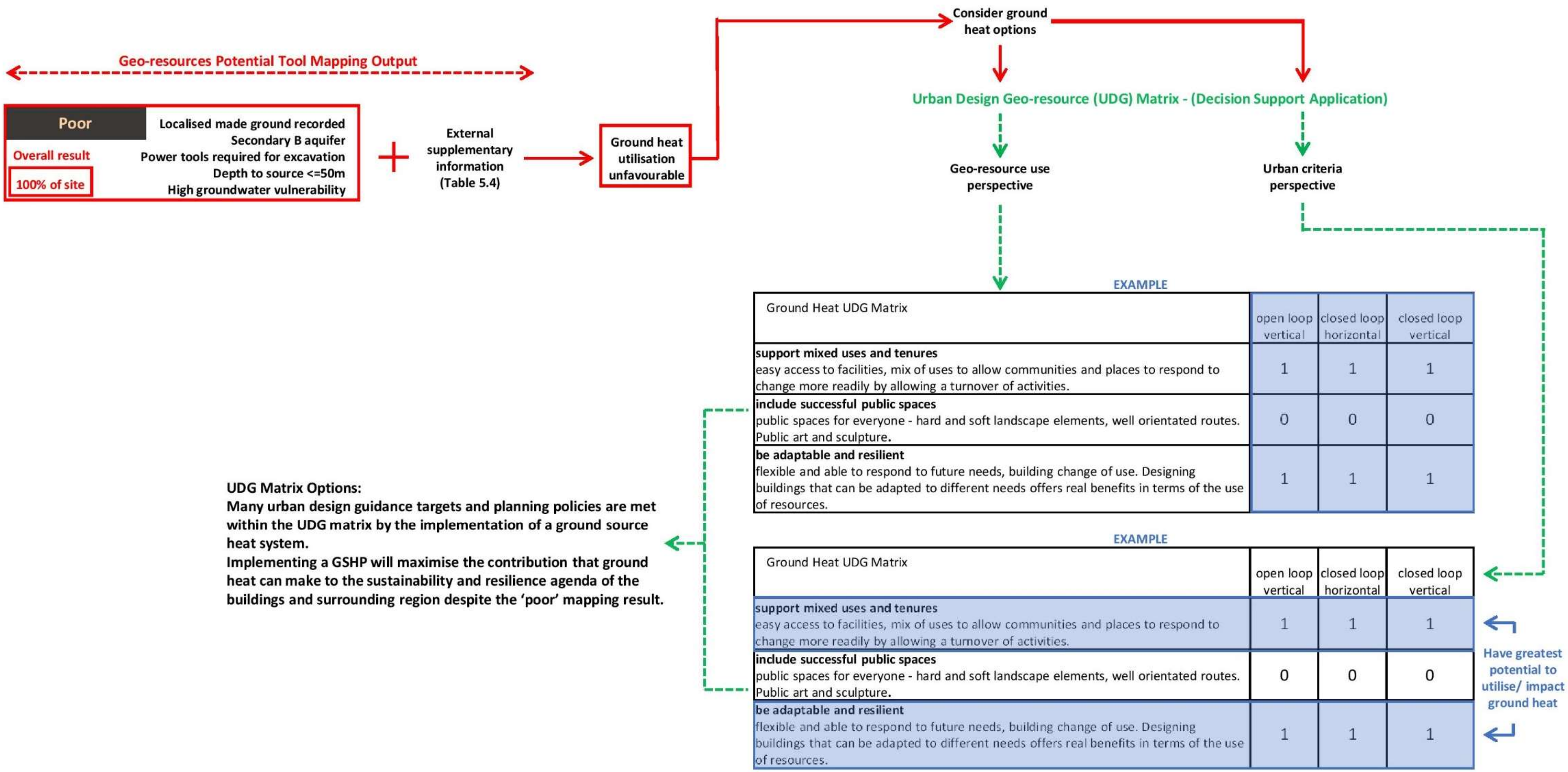


Figure 5.8 – Flow diagram summarising the method of applying the ground heat potential map output to the Urban Design Geo-resource (UDG) matrix.

Given the results of the ground heat potential map, and disregarding the actual ground source heating system implemented at Chestnut and Aspen Mews, the following assessment was determined from considering the UDG matrix:

As the whole site has 'poor' potential for ground heat utilisation, a GSHP scheme may encounter difficulties associated with ground constraints at Chestnut and Aspen Mews. However, constructing a GSHP system on this site would increase the buildings independence by diversifying the heat supply resource that end users depend upon. Furthermore, it would provide the buildings with more capacity to adapt should circumstances surrounding energy supply change in the future. In addition, the installation increases the functionality of an otherwise empty above ground space and subsurface space, all of which contribute towards sustainability and resilience for the site.

Despite the 'poor' result from the ground heat potential map, many urban design guidance targets and planning policies are met within the UDG matrix by the implementation of a GSHP at Chestnut and Aspen Mews (Appendix I). Implementing a GSHP will maximise the contribution that ground heat can make to the sustainability and resilience agenda of the buildings and surrounding region where possible.

As this assessment has been completed retrospectively for the retrofit project at Chestnut and Aspen Mews, these results can provide verification of the approach taken on site. Notwithstanding the potential difficulties that may have been encountered from the ground constraints, the success of the scheme is evidence that even with a 'poor' potential for ground heat utilisation, other factors (beyond geological considerations) may overcome the geological challenges and permit geo-resource use to enhance urban sustainability and resilience.

5.3.3 Ground Heat Potential Mapping Tool Limitations

A key issue with mapping ground heat potential was accurately accounting for subsurface temperatures. There was no data available which is granular enough to estimate potential heat yields on a site-by-site basis without detailed site-specific investigations (which can deliver information such as subsurface temperatures). For example, thermal conductivity data was available for geological formations however without the knowledge gained from intrusive site investigations (such as the nature of the deposit, bulk porosity of the soil, degree of saturation, etc), the information can at best suggest an approximate range of thermal conductivity, which did not offer accurate enough information to be incorporated into the tool.

Without thermal data, it should be acknowledged that there may be some discrepancy between the geological characteristics and the mapping result (‘poor’ ground heat potential). Given this, it is arguable that the map did not give an accurate enough result for ground heat and that site conditions offered a ‘moderate’ potential for ground heat utilisation, not ‘poor’. The initial iteration of the ground heat potential mapping tool has highlighted where improvements can be made, and in an ideal scenario a second iteration of the tool would be run that included this data, or the model scoring would be reassessed and adjusted based on subsurface temperatures from the nearest available average. However, there are more generalised projects focussed on addressing this (such as the BGS GSHP Screening Tool or the European ThermoMap Project). Furthermore, it is possible to estimate subsurface temperatures in Britain due to its geological stability and well documented geological settings, however there are many factors which can impact the actual temperatures which will be encountered at depth. Busby et al. (2011) highlighted some of these issues including: the multidimensional natures of heat flow, groundwater movements, and heat influence from other sources such as urban areas or natural radioactive decay.

As previously discussed, there is no central record kept of existing ground source heating systems, and therefore another limitation of this model was the unknown influence that existing systems may have on the GSHP installation at Chestnut and Aspen Mews. This factor will change over time, and therefore a temporal aspect for the tool should be considered for any future iterations.

Other external factors such as abstraction licensing must also be considered for open loop systems (although this was not the design implemented at Chestnut and Aspen Mews). For use in ground source heat pumps, both an abstraction and discharge licence must be obtained from the Environment Agency. Furthermore, regional groundwater flows also impact the occurrence of water, and local abstractions may influence the direction of flow and water availability.

In addition, as discussed in Chapter 3, the score rating was based on the national range of scores that can be achieved from the ground heat potential mapping tool. Any results from the ground heat potential map may need to be refined by more granular information should ground heat utilisation be pursued. Furthermore, other factors (such as economic and environmental) must be considered as it is more than just the geological factors which determine the viability of ground heat utilisation.

The map should be considered an indication for where ground heat utilisation might be investigated, however it is an exploratory model and not a final model to be used for the installation of any infrastructure. Furthermore, with no scope to implement a second iteration of the map, it should be noted that the other aspects of this assessment (including thermal conductivity, diffusivity and sub-surface temperatures) should be incorporated into the map when appropriate datasets become available.

Finally, the UDG matrix illustrated the relationship between ground heat utilisation and the relevant planning policy, urban design guidance and sustainability and resilience assessments for Chestnut and Aspen Mews. However, as there was often no difference acknowledged between the different types of GSHT's within regulating and guiding documents, the relationship between GSHT's and the regulating and guiding documents often showed the same result in the UDG matrix. This can only be rectified by the publication of individual regulations and guidance documents for the different types of GSHT for use in the UDG matrix.

Further limitations of the general geo-resources mapping tools are discussed in the methodology chapter of this study (chapter 3).

5.3.4 Ground Heat Potential Mapping Tool Section Summary

GSHPs boast a range of benefits such as; cheaper running costs over direct electricity, safer (due to no requirements for combustion or risk of gas emissions), renewable and local energy source, producing fewer emissions, have a longer lifespan than combustion boilers and have the potential to provide cooling (GSHP Association, 2019). The GSHP retrofit project at Chestnut and Aspen Mews was devised to be beneficial to multiple stakeholders, chiefly to provide long-term income for the proprietor and achieve long-term savings on heating bills for tenants.

The ground heat potential mapping tool revealed a 'poor' potential for ground heat utilisation at Chestnut and Aspen Mews. The validation process supported the findings of the map, endorsing the 'poor' potential for ground heat use, primarily due to ground constraints. The UDG matrix demonstrated that GSHT was appropriate for achieving many urban design and planning policy agendas relevant to the site and sustainability and resilience agendas. However, there are limiting factors affecting the ground heat potential tool, as well as external factors relating to its application (such as social and economic feasibility) that are not accounted for and must be considered with the results from the tool.

5.4 Case Study Stakeholder Interviews

Sustainability and resilience were unapplied concepts for UK cities when Chestnut and Aspen Mews were constructed in the mid 1960's. When the micro district GSHP network was installed in 2015, the effect would have been significant in increasing the relative energy resilience that the buildings possessed, and also would have enhanced sustainability for the area. The installation meant that the buildings were no longer dependent on distant power plants, but instead were utilising local, renewable ground heat from the immediate vicinity.

Each property was fitted with an individual heat pump which allowed residents to control the heat for their individual flats. Kensa's report of the project declared that tenants were satisfied with the GSHP installations, and was supported by quotations made by tenants (Kensa Heat Pumps, 2015b).

Ground heat is not a resource that is often considered in policy outside of the context of energy efficiency, however the local plan revealed that in 2015 21.5% of the Borough population lived in fuel poverty (East Staffordshire Borough Council, 2015). Shallow ground heat is a resource that can be utilised to tackle fuel poverty as well as meet sustainability and resilience agendas according to reported tenant savings (Kensa Heat Pumps, 2015b). The reports produced post-installation of the GSHP scheme focus on the economic savings and tenant satisfaction, which were the main aspirations for the project. There was not a significant focus on sustainability or resilience in documentation highlighting the benefits of the project. This was also evident in several of the stakeholder interviews undertaken for this case study.

In assessing how to successfully implement ground source heating schemes in the UK, the drivers, enablers as well as potential barriers and failures were explored through a series of stakeholder interviews.

In any development proposal, a series of stakeholders must be consulted at different stages of implementation. For the Chestnut and Aspen Mews retrofit project there were three main stakeholders: the client (funder of the project and owners of the infrastructure), the contractor/installer and the consultant/design team. A representative of the local council was also interviewed to gauge their understanding and perception of ground source heating, even though the local authorities played no role in the retrofit project. The end user was also considered for interviewing about the ground source heat utilisation, however, as the end users were short-term tenants, starting a dialogue was difficult and challenged further by the circumstances of the occupants. Therefore, the end users were not interviewed and commentary from phase one of the Trent and Dove GSHP retrofitting scheme was included where needed, although the potential biased from this should be noted as the document was authored by the client.

Representatives from East Staffordshire Borough Council, Trent and Dove Housing Association, Kensa Heat Pumps Ltd and Genius Energy Lab were interviewed alongside a representative of Geothermal International who although detached from the case study site presented views from comparable developments. The representatives from these groups were selected because they understood the sustainability agenda, were experts involved with ground heat utilisation, or had experience of the application of these areas.

Following full transcription of interviews, the responses were coded to correlate findings across stakeholder groups. In the following section, the main enablers, drivers and barriers of the scheme are the focus of discussion.

5.4.1 Interview Response

5.4.1.1 Enablers

Once coded into themes, eleven enablers were identified across the stakeholder groups. Within this, one enabler was commonly identified and highlighted across the majority of the stakeholder groups – government subsidy. The installation of ground source heating infrastructure has been supported by a government financial scheme (the Renewable Heat Incentive (RHI)) since 2014 (discussed in detail in section 5.5.5). There were two streams to the RHI; domestic and non-domestic. In this case, the design of the retrofit at Chestnut and Aspen Mews meant that it qualified for the non-domestic tariff. The representative of the investor at Chestnut and Aspen Mews stated that the income from government subsidy was important in enabling the project to go ahead, but also that funding options change regularly and can often be withdrawn. Furthermore, they questioned the impact that this kind of approach may have on the housing shortage observed across much of England.

The heat pump consultant commented that the RHI is an important scheme for providing sufficient returns on investment to motivate stakeholders to install ground source heat pumps within their developments. However, the consultant also stated that after 2021 the RHI will be discontinued, and the government may take a more enforcement-based approach to encourage the uptake of renewable heat infrastructure "for example tougher building regulations [and] more planning regulations" (Consultant, 2018). The recent announcement of reforms to the planning system may facilitate this, particularly if planning decisions change from being discretionary to a rules-based system as suggested (Grimwood et al., 2020).

The representative of the contractor at Chestnut and Aspen Mews maintained a connection with the RHI by contributing to its development. The company also observed carbon emission reduction programmes such as the Energy Company Obligation (ECO) which provided further financial support to qualifying applicants. When asked about project enablers, the interviewee's immediate response was that "funding was the key one. If it wasn't for the combination of RHI and ECO funding streams it wouldn't have happened. We could make the case around sustainability and fuel poverty benefits and maintenance requirements…but these on their own would not have been enough given the fairly significant upfront capital costs. The income was critical" (Contractor, 2019). The impact of the RHI on the feasibility of the installation was further highlighted in the companies project report, which stated that by designing a scheme qualifying for the non-domestic RHI, the project qualified for "upfront grant funding via the ECO and 20 years of income via the Non-Domestic Renewable Heat Incentive (RHI)" (Kensa Heat Pumps, 2015b).

Other enablers identified by individual stakeholders included:

- Economic feasibility
- Good stakeholder communication and mutual motivation
- Technologically feasible designs
- Long term investors
- Focussed policy
- Optimal subsurface conditions

Identifying these main enablers for the retrofit at Chestnut and Aspen Mews implied what actions were needed to implement ground source heating solutions more widely. It was clear from discussions that the focal mechanism for the implementation of ground source heating systems was government subsidy with clear qualifying criteria and income rates. However, there was a perceived risk associated with inconsistent RHI payments, for example following the change to RHI tariffs there was widespread closure of many solar panel installation companies (General Project Manager, 2019). For more stakeholders to invest in ground source heating systems, a long-term financial contribution or offsetting scheme was inferred to enable GSHPs or similar infrastructure.

Creating a strong sense of purpose and a reliable method of communication was also identified in addition to monetary support. Although in some cases this could be by motivated clients, it may be more effective if enforced by clear planning policy.

Government authorities at all levels (national, regional and local) should ensure that a clear sustainability policy is in place for new developments which explicitly states the requirements that resilient infrastructure should have, and the opportunities that exist from a geo-resources perspective. In addition, ensuring the collaboration of well-trained stakeholders with expert knowledge is key, and achieving an inclusive, consistent and open line of communication across and between stakeholder groups is core to effective partnerships.

5.4.1.2 Drivers

Fourteen codes were identified across the stakeholder groups as drivers for implementation of the Chestnut and Aspen Mews retrofit scheme. The most frequently mentioned driver across the stakeholder interviews was policy.

Planning policy for closed loop ground source heating systems is insufficient across different scale of governance (discussed in Section 5.5.4). However, the role of ground source heating within low emission agendas and climate change action plans is an influential driver for the implementation of GSHPs. This was evident from the answers given by the local authorities who when asked about their alignment with sustainability and resilience in policy stated that the "local plan contains a policy relating to low carbon and renewable energy, however this mainly refers to the use of other legislation [such as] building regs" (Local Authority, 2019). Even down to neighbourhood scale planning, it is identified that for high quality design, developments should be "energy efficient and aims to reduce carbon emissions" (Stapenhill Parish Council and Neighbourhood Plan Steering Group, 2016, p.23). The discussion with the ground source heating consultant largely presented policy as a problem for the implementation of GSHPs, but it was suggested that the knowledge from ground source heating experts is gradually being translated into effective policy.

Other drivers disclosed in the stakeholder interviews included:

- To reduce building problems and building maintenance

- To create effective heating schemes
- To provide health benefits for end users
- Known benefits from similar projects

In the interview with the contractor, it was commented upon that the retrofitted heat pumps out-performed the old storage heaters significantly, and that GSHPs are a more effective solution than gas boilers for heating the apartments: “It was identified that switching storage heaters to ground source heat pumps would make a running cost saving to the resident and also heat a home to a more comfortable level” (Contractor, 2019). Fuel poverty in the area meant that tenants were frequently only heating one room in their flats, causing numerous issues with the buildings and tenant wellbeing (Contractor, 2019). ‘Reducing excess winter deaths’ was a tagline associated with the retrofitting project from its conception and was stated as a key driver for the client. This aim was relayed by the contractor representative who identified this as a driver during the interview.

Furthermore, phase one of the scheme (entirely separate from the Chestnut and Aspen Mews retrofit) was completed by the same stakeholders before the proposal to install GSHPs at Chestnut and Aspen Mews. Having retrofitted GSHPs in other properties in the region, and knowing the working methods of the other stakeholders, it was likely to be a smooth process to repeat the project for Chestnut and Aspen Mews. During the interviews, both the client and contractor representatives noted that a good relationship and knowledge of other stakeholders working processes was helpful whilst implementing the project at Chestnut and Aspen Mews, and was a driver for repeating the works.

As financer for the installation of the GSHP network at Chestnut and Aspen Mews, the client was the main driver for the project, and their motivations were most important in executing the works. The interviewee confirmed that tenant wellbeing and setting a blueprint for GSHP installation were key factors for the proprietors. The grant covering capital costs as well as the long term RHI payments were also incentives (Kensa Heat Pumps, 2015b). This suggests that building proprietors (new build or existing) should be targeted for increased implementation of ground source heat technologies in England and acting on their individual needs would impact ground source heating uptake rate.

5.4.1.3 Barriers

Nineteen themes were identified as potential barriers for the implementation of sustainable and resilient urban design through the utilisation of ground source heating. The most discussed impediment was the perception that ground source heating systems have significant risk associated with their implementation. There were several views of risk associated with ground source heat utilisation. The general project manager described a scenario where mistakes made in early GSHP installations impacted the opinion of development contractors; “for example flint backfill rupturing a PVC pipe meaning low or no pressure in the [GSHP] system. Some of these triggered bad impressions of ground source heating to contractors, when in fact it was miscommunication which caused the bad impression” (General Project Manager, 2019). This highlights a common occurrence where a lack of knowledge or willingness to ask leads to a defective or broken system. There are many more general misconceptions of ground source heat pumps which may be hindering widespread implementation. Franck (2017) identified several including:

- Planning permission is always needed
- Heat pumps take up considerable space
- Heat pumps have maintenance issues
- Heat pumps are not suitable for old homes

These misconceptions if accepted by development stakeholders will have a negative impact on the rate of uptake of GSHPs. Unfortunately, until stakeholders have an active interest in the use of GSHPs there is often very little opportunity to counteract these ideas. Additionally, GSHP systems are novel, and “people are wary of new technology and what it might lead to” (General Project Manager, 2019).

The interviews highlighted that the most frequent deterrent to ground heat utilisation is the high-risk perception that many people have. Several interpretations of this were mentioned in interviews, one of which was the potential failure associated with inaccurate calculations for assessing the efficiency and capacity of GSHP systems. For example, misunderstanding the groundwater flow, subsurface saturation or thermal diffusivity of materials may impact the efficiency of the GSHP system. The consultant (2018) mentioned that “smaller GSHPs [are at] a bigger risk as if you get the calculations for the house design wrong. There is little that can be done to correct it as it has a finite source”. Additionally, the consultant said that open loop systems have higher risks associated with them due to their reliance on groundwater levels: “if the water output is not as high as expected, this may require a re-evaluation of the potential output from a GSHP system" (Consultant, 2018). These risks can be minimised by expert involvement in GSHP design. Subsurface conditions (including groundwater assessments) will be addressed during the intrusive ground works which although will require funding, will cost significantly less than installing a ground source heating system that will not function.

There was another perceived risk around financing GSHPs. The client representative said that as the investor of the scheme they were carrying all the risk. In addition, they perceived the government subsidy strategy as flawed due to its application process and the possibility that the funding may be withdrawn within a few years. The contractor commented on the financial risk of the Chestnut and Aspen Mews retrofit project, stating that despite the success of phase one, "there was still the perceived risk of investing two to three times more per flat than they would have done if they were just going to replace the systems like for like" (Contractor, 2019). The relative novelty of ground source heating technology is a hindrance to its uptake, whereas for other geo-resources their use may be better established.

After risk, the most frequent barriers identified across the stakeholder groups included:

- Expensive design/high capital costs
- Poor policy guidance
- Lack of expertise/knowledge

Policy was identified as a key driver for GSHP installations specifically in reference to climate action initiatives and reducing carbon emissions. Issues were also identified by several of the interviewees with regards to planning guidance. When asked about familiarity with sustainability policy, the client's representative said that "if I had to adhered to these then the GSHP project would not have happened. Much of the time these are just fluffy aspirations which usually fail" (Client, 2019). Furthermore, when asked about how often sub-surface resources are considered within planning applications, the local authority confirmed that there is no specific policy because ground source heating systems are only suitable in particular circumstances are the installation at Chestnut and Aspen Mews is a "relatively unique system" (Local Authority, 2019). The project consultant noted that planning policy was once an enabler but is now a barrier. After the recession there was a need to reduce the cost of building, meaning that the renewable energy initiative and ground source heating incentive was discontinued. In further discussion the consultant said that government policy was now focussing more towards renewable energy and ground source heating, and after 2021 (once the RHI scheme has been suspended) enforcement-based policy will take its place (Consultant, 2018). Before this happens however, "there is a lot of policy disconnect that we still need to plug the gaps in. Ground source heating has suffered from badly worded policy in the RHI and it was a big win in the last few years where GSHP specialists and experts are being listened to more in policy" (Consultant, 2018).

The infancy of ground source energy as an accessible renewable heating resource is demonstrated through the lack of support within planning or sustainability policy. Experienced specialists in the ground source industry are beginning to have greater input into proposed policy and regulation of ground source heating systems. At the moment, the lack of knowledge surrounding GSHT or the lack of specialist involvement in the initial design phase of a project may be a significant barrier to optimising installations.

More generally, unfavourable ground conditions (such as thermal breakthrough due to high groundwater flow; or poor thermal conditions), insufficient land space and competitively priced alternatives (such as solar, gas or oil) were mentioned in interviews as potential barriers to the implementation of GSHPs. For Chestnut and Aspen Mews, an interviewee disclosed that some tenants were resistant and unconvinced by the GSHP technology, although this view did change once the benefits were seen. All of these barriers will need addressing to see the widespread implementation of urban design which is more sustainable and resilient from the utilisation of ground heat.

5.4.1.4 Failures

Although not specific to the Chestnut and Aspen Mews installation, it was highlighted by the stakeholder interviewees that events can occur which may lead to the downfall of urban design infrastructure which utilises ground heat. Four ideas were suggested that could have this outcome. Two of these were also identified as barriers to GSHP implementation: insufficient above (or below) ground space and insufficient groundwater volumes (to support an open loop system). These failures are unlikely to occur in practice as an intrusive ground investigation and modelling would identify these risks in advance.

Financial problems prior to the completion of any project would also be a setback to implementation. This was identified as a potential reason for the failure of a ground source heating system, however, careful budgeting and financial management would reduce the risk of failure for this reason. Similarly, issues with land ownership was also raised as a potential reason that a GSHP project might fail. This would be resolved at the feasibility stage of a GSHP project and can be avoided by an expert accurately modelling the requirements of a GSHP system to determine if adequate land space is available.

5.4.2 Stakeholder Interviews Section Summary

It was clear from the interviews that financial viability and feasible costing were significant enablers and drivers for GSHP installations. Unfamiliarity with the technology generates caution with regards to spending, especially for large companies without a long term vested interest in project infrastructure. The consultant disclosed that when a main contractor is appointed for a project, they may steer other stakeholders away from GSHPs if they perceive ground source heating infrastructure as risky ventures. The general project manager suggested that a lack of knowledge or understanding of GSHP systems may justify this response.

Beyond these generalised views, the retrofit of the ground source heat pump network at Chestnut and Aspen Mews was undertaken due to the financial feasibility of the project from government grants and incentives, as well as the long-term vested interest of the buildings' owner. Monetary incentives and the prioritising of low cost infrastructure were raised in several of the interviews, which indicated that the other drivers (such as reduced maintenance costs, enhanced tenant wellbeing and reduced number of winter deaths) may be secondary benefits after the profit to be made from the installation, although these multiple benefits did contribute towards the decision to implement the scheme. The fate of the RHI after March 2021 is unclear, but ground source heating (amongst other renewable energy resources) may become scarcer if a subsidy scheme does not emerge.

The interviews also confirmed that there is scope to enhance the prominence of ground source heating within planning policy. Ways to establish this are yet to be confirmed however the consultant indicated that experts are having greater input with regards to how planning policy could better include ground source heat as an energy source. In a recent report, the Committee on Climate Change (CCC) (2016a) recognised that UK policies failed to increase the uptake of heat pumps, however they fully endorsed the use of heat pumps in the endeavour to be carbon neutral. The CCC also noted that optimising building design is part of expanding the uptake of ground source heat pumps across the country.

Sustainability was not a direct aim for the stakeholders at Chestnut and Aspen Mews, however it has been increased because of the GSHP network installed on site. The project highlights the impact that GSHPs can have in building urban resilience and sustainability.

5.5 Planning Policy, Urban Design Guidance and Sustainability Assessment Analysis

5.5.1 Introduction

Renewable energy was key in the context of carbon emission reduction when sustainability and resilience first surfaced as driving concepts for urban development. Yousefi et al. (2019, p.4) stated that "the global community's attention to issues such as energy security, energy equity and environmental sustainability, has changed the situation and the industry in bracing itself for a new growth period".

International organisations such as the Intergovernmental Panel on Climate Change (IPCC) aim to inform policymakers of current and future climate forecasts. Chapter 4 of the Renewable Energy Sources and Climate Change Mitigation Report by the IPCC discussed geothermal energy and its potential as a renewable energy source with a lower impact on climate change than other non-renewable resources such as fossil fuels. The chapter discussed the different levels of development that geothermal heat pump technologies have reached, for example enhanced geothermal systems are less technologically established than direct heating from ground source heat pumps (Goldstein et al., 2011). These innovations have enhanced the productivity of ground heat abstraction systems and reduced the cost of associated infrastructure.

In order to determine how ground heat can be utilised in urban design most effectively (and whether this has been effective in the retrofit at Aspen and Chestnut Mews, Burton on Trent), the planning policies, urban design guidance and sustainability and resilience agendas are explored across multiple scales. The key messages relevant to ground heat utilisation within these documents are presented in Table 5.5, as well as the cross-cutting themes which are discussed in greater detail below. These are:

- protecting the environment and reducing carbon emissions
- energy efficiency, conservation and reducing waste
- planning policy and urban design guidance
- financial incentives

- increasing the use of renewable resources
- decentralising resources

Case Study 2 – Ground Heat, Chestnut and Aspen Mews		
Level	**Document**	**Key Message/Impact Relevant to Case Study**
International	Sustainable Development Goals (SDGs)	Goal 7 - ensure access to affordable, reliable, sustainable and modern energy for all (United Nations, 2015a).
International	Rio Declaration on Environment and Development (1992)	**reduce consumption, increase efficiency, and restrict energy use** to **protect the atmosphere and environment**
International	United Nations Framework Convention on Climate Change (1992)	**prevent any further damage** from greenhouse gases to the Earth's climate
International	Kyoto Protocol (1998)	encourage sustainable development through avenues such as **policy** to **increase use of renewable energy** resources.
International	Paris Agreement (2015)	require **country authorities to build resilience** to **the effects of climate change**, whilst undertaking long-term actions to **reduce emissions**.
International	2030 Climate and Energy Framework (2013)	targeting **20% renewable energy** in gross final energy consumption by 2020
International	Roadmap 2050: a practical guide to a prosperous low carbon Europe (2010)	**reduce greenhouse gas emissions** to 80% below levels of 1990 by 2050
International	Directive 2009/28/EC	requires **national targets for amount of renewable energy sources**
International	Directive 2010/31/EU	**improve energy performance** of buildings
International	Directive 2012/27/EU	promote **energy efficiency** and meet the 20% energy efficiency target
International	Directive 2018/2001	Promotes the **use of renewable energy resources**

National	The Water Act (2003)	governs water abstraction in the UK and legislates water abstraction and discharge licensing
National	Environmental Good Practise Guide for Ground Source Heating and Cooling (2011)	provides detailed information on the technical aspects of GSHP systems as well as **good practise techniques**
National	National Planning Policy Framework (NPPF)	**supports low carbon** future and the **use of renewables resources**. expects **local authorities to set policies** for using **decentralised energy** supplies where possible
National	UK Renewable Energy Strategy (2009)	**guidance** which sets out the methods to meet the UK's **renewable energy use targets** for 2020, (one of which is to source 12% of the UK's heat demand from renewable sources)
National	National Renewable Energy Action Plan (2010)	provides an overview of policies in place to encourage the **utilisation of renewable energy** (focussing mainly on **financial incentives** and **regulatory policy**)
National	Non-domestic Renewable Heat Incentive (2011)	**financial scheme** based on renewable heat use and **system efficiency** (calculated and certified by an installer)
Regional	Regional Spatial Strategy for the West Midlands (2008)	Promotes **environmental protection, low carbon futures, conservation of energy**, **urban design** which **avoids energy wastage**, as well as use of **local** renewable heat sources
Regional	Staffordshire County-wide Renewable/ Low Carbon Energy Study (2010)	identifies the capability of utilising **decentralised heat resources** - not a significant focus on ground heat potential

Regional	Low Carbon Economy Programme (2013)	measures the progress to **address climate change** and implementing **low carbon solutions** using a benchmark assessment approach. Also states that **clear policies** should be developed for low carbon schemes.
District	East Staffordshire Local Plan (2015) 1. Policy SP7 2. Policy SP28 3. Policy DP2	1. **Include renewables** (including **decentralised**) where possible. 2. **renewable** energy resources and **reduced carbon emissions,** suggesting the **decentralisation** of energy sources where possible. 3. encourages the **design and delivery of low carbon buildings** by using **decentralised resources,** and will permit energy improvements to existing buildings
District	Climate Change Strategy and Implementation Plan (2010)	**reduce carbon emissions** whilst simultaneously addressing the fuel poverty issues and **bettering air quality**
District	East Staffordshire Sustainability Appraisal (2014)	recognises that **planning system should contribute** towards sustainable development
Local	Stapenhill Neighbourhood Development Plan (2016)	provides guidance for new developments but does not mention retrofitting or renovating existing infrastructure. that new developments should be **energy efficient** and **reduce carbon emissions**

National	Code for Sustainable Homes (CSH)	By time of case study, CSH was defunct and was only applicable to new builds not retrofit projects
National	Building Research Establishment Environmental Assessment Method (BREEAM)	Not applicable to case study, but does credit **reduction of energy use and carbon emissions** through **low and zero carbon technologies**
Grey = protect the environment and reducing carbon emissions, Blue= energy efficiency, conservation and reducing waste, Green = planning policy and urban design guidance, Red = financial incentives , Yellow = use of renewable resources, Pink = decentralisation		

Table 5.5 – Key planning policy, urban design guidance and sustainability and assessment documents impacting the Chestnut and Aspen Mews GSHP retrofit with their content related to ground heat summarised and categorised into themes.

5.5.2 Protecting the environment and reducing carbon emissions

Environmental protection was observed within documents on multiple scales in connection with ground heat and/or renewable energy resources.

In an international setting, ground heat utilisation is often considered within the broad context of renewable energy resources as observed in climate change agendas. Reducing the use of non-renewables is often at the forefront, for example, Agenda 21 of the Rio Declaration discussed restricting energy use to protect the atmosphere and environment (Rio Declaration on Environment and Development, 1992). In a congruous manner, under the United Nations Framework Convention on Climate Change (1992) countries decided to "promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases…in all relevant sectors, including the energy…sectors" (United Nations, 1992, p.10). The Paris Agreement (2015) (adopted by 195 countries to address global climate change) contained a section on the effects of climate change, and long-term actions that should be pursued to reduce emissions. Ground heat is one possibility for meeting these targets as a low-carbon option for replacing fossil-fuel-based heating systems in the long term in the UK (Committee on Climate Change, 2016b).

In a similar light but with a lengthier end date, the international 'Roadmap 2050: a practical guide to a prosperous low carbon Europe' set a target of reducing greenhouse gas emissions to 80% below those levels of 1990 by the year 2050 (European Climate Foundation, 2010) in order to protect the environment. Renewable energy use must continue to grow if there is a chance of reaching this goal, and ground heat utilisation can make a notable contribution towards this.

Many national scale documents recognised international agendas and considered global recommendations within UK policy. In the context of protecting the environment, the National Planning Policy Framework (NPPF) defined one of its core principles as supporting "the transition to a low carbon future in a changing climate…[to] encourage the reuse of existing resources…and encourage the use of renewable resources" (Department for Communities and Local Government, 2012, p.5). This included ground heat and GSHP technology as renewable resources.

In 2015 when the retrofit of GSHPs at Chestnut and Aspen Mews was undertaken, regional level planning policy had been abolished from UK law, and therefore district level planning policy had the closest level of influence to regional planning below national. The Regional Spatial Strategy for the West Midlands (2008) contained energy policies which focused on addressing climate change from a regional perspective and set its own targets for renewable energy generation. Ground source heat was not discussed as a prospective renewable energy resource (unlike solar and wind power) (Department for Communities and Local Government, 2008) although could be included in the general discussion of renewable energy supplies.

Also undertaken regionally was the Low Carbon Economy Programme (2013) which measured the progress that East Staffordshire was making to address climate change and how it was implementing low carbon solutions. The report presented a benchmark assessment approach for the regions performance and indicated that East Staffordshire was underachieving in all categories; climate change mitigation, adaptation and creating a low carbon economy. There is no specific mention of ground source heat within this document, however ground heat utilisation can contribute towards low-carbon urban design schemes, and therefore could be used to better East Staffordshire's carbon assessment.

At district level, ground source heat is considered under renewables and is addressed in the context of low carbon energy options. Policy SP28 of the East Staffordshire Local Plan (2015) described the role of renewable resources in the Borough and their association with low carbon energy. It set out the expectation of low carbon solutions to be implemented and the corresponding benefits (which include aspects of environmental protection and wellbeing). In addition, Policy DP2 (which provides detailed explanations for designing in sustainable construction) stated that developers will use renewable resource to reduce carbon emissions where possible, or where this is not feasible, will contribute “towards an off-site renewable energy or carbon reduction scheme” (East Staffordshire Borough Council, 2015, p.169).

The Climate Change Strategy and Implementation Plan (2010) was another district level document which meant to reduce carbon emissions in the Borough whilst simultaneously addressing the fuel poverty issues and bettering air quality (East Staffordshire Borough Council, 2010). However, this document did not include ground heat (or GSHPs) as a potential solution for tackling the wider issues.

Chestnut and Aspen Mews are within the parish of Stapenhill which published a Neighbourhood Development Plan in 2016. Although the retrofitting of GSHPs at the two blocks of flats slightly pre-date this local plan, its principles were in development at the time of implementation and are therefore extremely relevant to the site. The document focused on providing guidance for new developments but did not mention retrofitting or renovating existing infrastructure. Policy SH3 focused on high quality design and references the East Staffordshire Design SPD (East Staffordshire Borough Council, 2008) as a guiding document that should be adhered to for any new development schemes. This policy stated that new developments should be “demonstrating how they would deliver development which is energy efficient and aims to reduce carbon emissions” (Stapenhill Parish Council and Neighbourhood Plan Steering Group, 2016, p.23). GSHPs (or the utilisation of ground heat) would be appropriate under this policy however there was no direct guidance for the utilisation of renewable resources in any context.

As Chestnut and Aspen Mews is a residential building that was constructed prior to the establishment of BREEAM, BREEAM would not have been used in its original construction, nor when the GSHP network was retrofitted in 2015. Therefore, it would be irrelevant to assess the inclusion of ground heat or GSHPs within BREEAM for this particular case study. However, considering that this study explores the potential drivers and obstacles for the utilisation of ground heat in an all-inclusive perspective, and with the aspiration to augment future ground heat initiatives, the significance of ground heat within the most recent BREEAM manual has been included.

The BREEAM technical manual defined the contributory elements to BREEAM assessments. Energy is one such element, and Ene01 'Reduction of energy use and carbon emissions' (BRE Global Ltd, 2018) is the only section to directly reference ground source heat pumps where it is defined under "low and zero carbon (LZC) technologies" (p.138). The overall rating was based on the heating/cooling requirements of the building, the energy consumption and the emissions. Ground heat utilisation has the potential to influence the latter if ground heat technologies are implemented appropriately. Beyond this scope, ground heat does not impact the BREEAM assessment. The BREEAM Domestic Refurbishment assessment was for comprehensive retrofit projects and included renewable technologies however it cannot be used exclusively for this.

There was an established connection between the use of renewable energy resources (such as ground source heat) and the corresponding reduction in carbon emissions for climate change mitigation (which has been summarised under environmental protection). This was observed in commentary from international through to local levels of documentation, although the potential significance of ground heat in this field was not always discussed and almost always in insufficient detail.

5.5.3 Energy efficiency, conservation and reducing waste

Energy efficiency and conservation are associated with ground heat from international to local scales of documentation. For example, general commentary was made in Agenda 21 of the Rio Declaration which discussed changing consumption patterns to increase efficiency (Rio Declaration on Environment and Development, 1992), but there were also European Union (EU) Directives which related energy efficiency to shallow geothermal use. Pérez (2019) summarised the important EU policies for shallow geothermal use, several of which focus on energy efficiency. These included:

- Directive 2010/31/EU - to promote "the improvement of the energy performance of buildings within the Union" ('European Union Directive 2010/31/EU', 2010, p.17), and
- Directive 2012/27/EU - to promote energy efficiency and meet the 20% energy efficiency target ('European Union Directive 2012/27/EU', 2012)

At a national level, one of the most significant schemes which promotes energy efficiency by ground source heat utilisation is the Renewable Heat Incentive (RHI). The RHI is a scheme by the UK Government which aims to increase the uptake of renewable heat technologies in both domestic and industrial settings through grants. The non-domestic RHI started in 2011, and the domestic RHI followed in 2014. Ofgem administers the scheme and the Department for Business, Energy and Industrial Strategy (BEIS) governs it. The Chestnut and Aspen Mews retrofit project was eligible for the non-domestic scheme due to its set up as a district heating network. The economic significance of the RHI scheme for ground heat utilisation is presented in section 5.5.5.

Energy conservation and efficiency were also observed in regional documentation. Energy from renewable sources was highlighted in the Regional Spatial Strategy for the West Midlands (2008) prior to its abolition by the UK government in 2010. Policy QE3 emphasised the importance of a sustainable build environments and identified efficient energy supplies and renewables as options to be considered although ground heat utilisation was not directly mentioned.

General commentary on energy efficiency was also noted in local documents such as the previously mentioned Stapenhill Neighbourhood Development Plan (2016) which declared the importance of energy efficiency in mitigating climate change. However, energy efficiency and ground source heat were not directly associated within this local documentation.

Energy efficiency and conservation are closely linked to environmental protection as they work in unison towards sustainable development. Therefore, they often appear together and communicate ground source heat and GSHPs in similar ways, making the observations from these two sections much the same. There is a lack of clarity distinguishing ground heat as a potential source of renewable and efficient energy, and there is potential to promote ground heat utilisation through the existing avenues that highlight the importance of energy efficiency and conservation.

5.5.4 Planning policy and urban design guidance

The role of planning policy and urban design guidance for ground heat utilisation was most obvious at higher levels of governance, where documents poineted towards setting clear policies for the use of renewables and providing corresponding guidance.

In 1998 the Kyoto Protocol declared that participating countries shall "to promote sustainable development…implement and/or further elaborate policies and measures… [to enable] development and increased use of new and renewable forms of energy" (United Nations, 1998, p.2). Ground heat is one such renewable energy that when utilised effectively contributes towards this criterion. The Paris Agreement (2015) also required participating countries to charge their governing authorities with building resilience to lessen climate change (although no specific mention is made to renewable energy or ground heat).

As previously mentioned, there was a lack of explicit references to ground heat utilisation within documentation, and therefore this was also observed at the different levels of planning policy and guidance for the UK. Policy for ground heat utilisation has been considered under the broad heading of renewable energy resources.

Planning permission is not required for the installation of Ground Source Heat Pumps (GSHPs) in England, and as such no official record is kept regarding the installation. Ground heat as a resource is not regulated by any law within the UK. Since 2008, planning permission is not required to install GSHP systems (South Staffordshire Council, 2008). Policies surrounding ground heat only exist where it is an environmental pollutant (Abesser et al., 2018). There are however some regulations around open-loop ground source heat pumps which abstract groundwater. The EU Water Framework Directive set the legislation for this, which was implemented by the Environment Agency (EA) in the UK. The Water Act (2003) governs water abstraction in the UK and legislates licensing. In England, the law states that to abstract more than 20 cubic metres of water a day from any water resource requires a permit from the Environment Agency. In addition, a discharge permit may also be required. There are exceptions to these rules particularly where system requirements are for small volumes of water and returning water temperatures are not significantly different from the water abstraction source (Department for Environment, Food and Rural Affairs, 2016). Furthermore, the Environmental Good Practice Guide for Ground Source Heating and Cooling provided detailed information on the technical aspects of GSHP systems as well as good practise techniques. It also confirmed that "closed loop ground source heating and cooling systems do not currently require any form of permission" from the EA (Environment Agency, 2011, p.13).

There are also national level documents in the UK which highlight the role of authorities in setting policies for sustainable development. The NPPF stated that local authorities should set policies that expect the utilisation of decentralised energy supplies unless it is proven to be unfeasible to do so. The NPPF generally set standards for local authorities to promote and support the use of renewable resources in the aim to reduce societal dependence on carbon-intensive energy resources (Department for Communities and Local Government, 2012).

Besides this, most national guidance involving ground heat was incorporated into renewable energy planning and policy. For instance, the UK Renewable Energy Strategy (Department of Energy and Climate Change, 2009) set out the methods to meet the UK's renewable energy use targets for 2020, (one of which is to source 12% of the UK's heat demand from renewable sources). This document readily acknowledged that in order to meet this target, further use of heat pumps will be required. Following this document's release, the National Renewable Energy Action Plan for the United Kingdom (Department of Energy and Climate Change, 2010) provided an overview of policies in place to encourage the utilisation of renewable energy. There were many approaches highlighted in this plan which were mainly financial incentives, but also some governing approaches. The regulatory documents included planning policy statements and building regulations.

More locally, the Regional Spatial Strategy for the West Midlands (2008) stated that for the conservation of energy, urban design can avoid energy wastage as well as utilise local heat from renewable sources and minimise energy requirements by optimising building design to exploit the effect of natural heating. This universal advice implied that urban design guidance should be available to steer development stakeholders towards alternatives to traditional building design and energy supplies, which could be suitable for information dissemination on GSHT.

In addition, the Low Carbon Economy Programme stated that "clear policies and site-specific targets should be developed where possible for design standards and different low carbon technologies, linked to regional and national targets. Supplementary guidance with low carbon design assistance should be provided more systematically by Council teams" (Sustainability West Midlands, 2013, p.5). Furthermore, the report suggested that the region does have some good practise measures in the areas of policy outputs, for example the region aimed to have an annual 2% reduction in domestic carbon emissions per capita (Sustainability West Midlands, 2013). These objectives could be partially tackled by the utilisation of ground heat.

The East Staffordshire Sustainability Appraisal (2014) was a separate publication produced in alignment with the Staffordshire Local Plan but specifically for assessing the inclusion of sustainability measures. The appraisal recognised that one "purpose of the planning system is to contribute to the achievement of sustainable development" (East Staffordshire Borough Council, 2014, p.2). The baseline report of the appraisal acknowledged that there was a general lack of policy requirements for energy efficient design (East Staffordshire Borough

Council, 2014). The appraisal developed standard sustainability objectives to address this. The objectives were established from a stepwise process of identifying relevant documentation, collecting information on current environmental, social and economic conditions in East Staffordshire and identifying the main environmental issues. Two objectives were relevant to ground heat utilisation, one objective on climate change, energy and air quality to “reduce the causes and impacts of climate change, improve air quality, promote energy efficiency and encourage the use of renewable energy” (East Staffordshire Borough Council, 2014, p.3). The second objective was on natural resources; “to ensure the prudent use of natural resources and the sustainable management of existing resources” (ibid). The report suggested that the policies within the local plan supported the Sustainability Appraisal objectives. Furthermore, renewable energy resources are part of building sustainability for the region.

5.5.5 Financial Incentives

In the UK, the best-known financial motivator for utilising ground heat is the RHI scheme. There are separate eligibility requirements and rewards for the domestic and non-domestic streams depending on which is appropriate on a case by case basis. The strategic differences are summarised below (Table 5.6).

	Domestic RHI	**Non-Domestic RHI**
Coverage	Individual domestic properties	Residential district (2 or more properties)
Includes retrofit	Yes	Yes
Includes new build	No	Yes
Tariff payment	7 years	20 years
Tariff rates	Modest – requires combination with fuel cost saving to produce payback	Attractive – GSHP rates recently doubled

Table 5.6 – Strategic differences between the domestic and non-domestic RHI streams (amended from Kensa Heat Pumps, 2016).

The design at Chestnut and Aspen Mews met the requirements of district heating as set by the Department of Business, Energy and Industrial Strategy (BEIS). As previously mentioned, the installation comprises individual heat pumps in properties linked to a shared ground array, which at the time of installation qualified for the non-domestic RHI plan (Kensa Heat Pumps, 2015b). Crucially, district heating was eligible for the non-domestic renewable heat incentive (RHI) which delivers regular payments for 20 years after the installation of the GSHP network. Domestic RHI payments are based on the renewable heat systems annual heat use and the system efficiency (calculated and certified by the installer) (Department for Business, Energy and Industrial Strategy, 2020). The non-domestic RHI has a more complicated payment scheme that has been through several iterations. OFGEM (2020) state that “a tariff rate will be assigned to your installation based on its technology (e.g. biomass, heat pump, solar) and size. Payments are made based on the actual heat output of the installation.” These schemes incentivise GSHT for proprietors of both new and old buildings. The non-domestic scheme has a clear monetary advantage offering 20 years of payments instead of the seven years of payments from the domestic program.

The Department of Energy and Climate Change (2014) released an interim report which evaluated the impact of the non-domestic scheme (which is implemented at Chestnut and Aspen Mews). One observation was that over half of claimants for the scheme had issues with the application process, and many of these were for GSHPs. The main problem involved inaccurate or missing information about installations, which could be fixed by simplifying and clarifying the requirements of the scheme (Department of Energy and Climate Change, 2014). Another finding highlighted the disparity of awareness between renewable heat technologies (RHT) and the RHI scheme, in which 90% of non-domestic representatives were aware of RHTs but 79% were unaware of the RHI. Further inquiry into these statistics uncovered common misconceptions associated with the RHI scheme, particularly eligibility criteria (Department of Energy and Climate Change, 2014). This indicates that improved communication of the RHI scheme may increase the use of renewable energy, including GSHPs. The CCC found that the RHI did not incentivise GSHP utilisation as well as anticipated, and that the rate of uptake plateaued. This was attributed in part to the financial returns being less than expected, and restrictions from investment policies (Committee on Climate Change, 2016a).

Significant leverage lies in climate change initiatives for ground heat technology uptake. In 2016, the CCC published the ‘Next steps for UK heat policy’ which recognised that action was necessary to impact the UKs carbon footprint. The CCC stated that policies require “significant strengthening now to increase the implementation of low-carbon measures in the next decade” (Committee on Climate Change, 2016a, p.7). The report suggested that the uptake of heat pumps was not as successful in the UK as in other countries due to the policies in place, although utilisers of GSHP technologies were reportedly highly satisfied with insulation and heating efficiency where installations were successful (Committee on Climate Change, 2016a).

There are longstanding issues in legislative policy, its dissemination and its understanding with respect to ground heat utilisation in the form of GSHPs as well as other GSHTs. Misconceptions, fractured communication and unclear obligations by different stakeholders were evident in the review of current policies by several organisations. Despite the relative infancy of ground heat as an exploitable local geo-resource when compared to other geo-resources, significant effort is required to resolve national policy for the utilisation of ground heat across the UK. Chestnut and Aspen Mews navigated national policy and the available government incentives to implement an effective GSHP retrofit project which could set a standard to encourage similar systems in the future.

5.5.6 Increasing the use of renewable resources

The use of renewable resources was strongly encouraged in international documents particularly considering the agenda for environmental protection through anthropogenic action (such as reducing carbon emissions and implementing low carbon construction methods).

The European Union sought to increase the use of renewable energy sources to reduce greenhouse gas emissions and meet targets set under the Paris Agreement and the 2030 Climate and Energy Framework. The 2030 Climate and Energy Framework was set by the European Commission and included the ambitious target of 20% renewable energy in gross final energy consumption by 2020. In 2005, the portion of renewable energy was 8.5%, which had increased to 12.7% by 2010 (European Commission, 2013).

In 2009, the European Parliament issued Directive 2009/28/EC (the Renewable Energy Directive) which required nations to set “mandatory national targets for the overall share of energy from renewable sources” (‘European Union Directive 2009/28/EC’, 2009, p.27). Directive 2009/28/EC was an impactful policy, setting a target of 15% renewable energy sources for the UK, and imposing the publication of the UK strategy (National Renewable Energy Action Plan) for how this will be achieved.

By 2018, the European Parliament increased the target for renewable energy contributions from 27% to 32% by 2030 under the EU Directive 2018/2001 ('European Union Directive 2018/2001', 2018). Part of this decision was due to the declining costs for renewable energy technologies ('European Union Directive 2018/2001', 2018). EU Directive 2018/2001 further acknowledged that "small-scale installations can be of great benefit to increase public acceptance and to ensure the rollout of renewable energy projects, in particular at local level" ('European Union Directive 2018/2001', 2018, p.84).

As previously discussed, at a national scale, the UK encouraged the use of renewables via documents such as the NPPF, the National Renewable Energy Action Plan and UK Renewable Energy Strategy, which were interpreted at lower levels of governance, such as the East Staffordshire Local Plan which contained policies addressing the integration of renewable resources in practice (policies SP7, SP28 and DP2). As ground heat is incorporated under the heading of renewable energy or renewable resources, the limited amount of detail observed across the different scales of documentation is as expected. Fuller information would strengthen the role of ground heat within urban sustainability and resilience agendas.

5.5.7 Decentralised resources

The importance of decentralised resources was often shown in documents that focus on urban resilience, because diversifying the number of energy sources for a dependent site is an approach for increasing resilience. Decentralised resources were discussed in local documentation but also within national policies.

The NPPF referred to employing decentralised energy where feasible through local implementation. The use of local renewables was also briefly cited in the Regional Spatial Strategy for the West Midlands (2008) and the Staffordshire County-wide Renewable/ Low Carbon Energy Study (2010) (even with the lack of specific information on ground heat utilisation). Despite the loss of regional planning, the authorities of Cannock Chase, East Staffordshire, Lichfield, Newcastle-under-Lyme, South Staffordshire, Stafford, Staffordshire Moorlands, Tamworth and Staffordshire County Council commissioned the Staffordshire County-wide Renewable and Low Carbon Energy Study in 2010, constituting a regional-level study. Part of this study identified the capability of utilising decentralised heat resources in the region. Although this document had an excellent assessment of renewable energy resource potential from sources such as wind energy, hydro energy and biomass, there was not a significant focus on ground heat potential and GSHPs. This may have been partly due to the perception that GSHT is a specialist industry, only suitable in certain circumstances, and is a high risk venture (as discussed in the interview inquiry in Section 5.4.1.3).

Furthermore, as previously mentioned, policies SP7, SP28 and DP2 of the district level Staffordshire Local Plan (2015) touched upon the use of renewables and decentralised resources. Policy SP28 particularly suggested the decentralisation of energy sources where possible for developments in the region, and stated its general support for renewable energy technologies (East Staffordshire Borough Council, 2015). In addition, Policies SP7 and DP2 which focused on sustainable construction emphasised the importance of considering the use of decentralised resources wherever possible.

5.5.8 Document Examination Section Summary

The GSHP installations at Chestnut and Aspen Mews demonstrate the wider benefits that utilising ground heat can offer in a domestic setting. When compared to the utilisation of other geo-resources (such as groundwater or geo-materials) the use of ground heat is recent in small-scale residential projects. Its use on this scale is generally unregulated besides the obligation to meet the MCS standard in the UK and its wider role to meet climate change initiatives. The RHI has some impact on the uptake of this technology and was a key driver for the implementation of the GSHP system at Chestnut and Aspen Mews.

Ground heat as a resource was predominantly considered within district level policy for its renewability and potential to enhance energy efficiency. It was normally only referred to within the context of renewable energy, the sustainable management of natural resources, or in relation to climate change guidance. More explicit information on how to utilise ground heat (such as GSHPs) may increase awareness of ground heat, and of its potential value as an energy resource.

Incorporating ground heat exploration into planning policy would increase the uptake of GSHT, and therefore brings the UK closer to its carbon emissions targets. Furthermore, diversifying the types of energy sources enhances urban resilience within the UK. Harnessing this de-centralised and renewable resource may make urban centres less vulnerable to the threats associated with ongoing urban expansion.

In addition, although inclusive in many ways of ground heat utilisation, policies and urban guidance's were context specific and implied that a key driver to the uptake of GSHPs was climate change mitigation. A wealth of international documentation around climate change is relevant to the UK's impact in this area, however not all of these documents are clear enough to influence and impact the uptake of ground heat technology in the UK.

This document examination showed that there is significant opportunity for GSHPs and renewable heat technology to be better incorporated into planning policy. A lack of governance around ground heat utilisation is a significant hindrance to the uptake of GSHT. As GSHPs are not subject to national planning policy, there is currently no rationale for planners to consider aspects of ground heat within regional or local policy or urban plans. GSHPs are specialist systems and would become more commonplace if a mechanism to engage stakeholders was introduced to planning policy. The only record of GSHT is for open loop designs which may require a licence for water abstraction, or for vertical systems that are deeper than 15m (as a record of the borehole will be held with the BGS). Besides this there is no national record keeping accurate details of GSHP installations for the UK.

5.6 Chestnut and Aspen Mews Case Study Conclusion

The Chestnut and Aspen Mews low rise flats were retrofitted with micro ground source heat networks in 2015, built primarily to: address fuel poverty, improve tenant wellbeing, and to secure long term government funding. In addition, this project aligned with several general national, regional and local guidelines in place to enhance the sustainability and resilience of the site and surrounding area.

The ground heat potential mapping tool classified the site as poor potential for ground heat utilisation. However, this only accounted for the geological conditions and not for the increased feasibility of utilising ground heat which comes from financial incentives (such as the RHI) (which made the business case plausible for the retrofit at Chestnut and Aspen Mews). The UDG matrix demonstrated how GSHT could be considered to meet relevant planning policy and urban design guidance for Chestnut and Aspen Mews. The matrix displayed the same results across different GSHTs due to the lack of differentiation within most planning policy documents, however GSHTs can satisfy many sustainability and resilience agendas from national to local level (Appendix I). If this tool is utilised in the feasibility or early design phases of a construction project, it could steer stakeholders towards enhanced urban sustainability and resilience from the utilisation of ground heat.

As the installation at Chestnut and Aspen Mews is the second phase for the stakeholders, the interviewees were able to offer positive commentary on the outcomes of the project, and it was considered successful with regards to meeting the schemes expectations. There was not a follow up report produced to analyse the success of the installation, and therefore it is difficult to comment on the long-term functionality of the system. An assessment of the impacts and effects of the network will require information to be gathered on the systems performance, however, tenant savings were predicted to be between £350 and £750 per year in the blueprint report produced in 2016.

The interviews suggested that the incentives for the scheme were numerous: tenant wellbeing, infrastructure improvement and financial gain to name but a few. As Chestnut and Aspen Mews was a phase two project, familiarity with the approach and an established network of stakeholders enabled the project to go ahead. With a secure long-term financial guarantee, it was possible to bypass several potential difficulties (such as the high capital costs and competitive alternative heat sources). The high-risk perception of GSHPs was identified as a key barrier to its wider implementation, however this can only be addressed by practise to reduce the risks associated with GSHT in the future.

The examination of planning policy, urban design guidance and sustainability assessments confirmed that policy across all scales was often broadly expressed with regards to renewable energy resources, and could have a greater impact if more direct policy were in place for utilising ground heat in the context of urban sustainability. Furthermore, GSHT is developing faster than the policy that governs urban planning. Planning policies therefore need to set clear guidance in the energy sector (particularly in setting expectations for the level of efficiency expected from schemes) to increase the use of renewable and decentralised resources where possible, reduce carbon emissions and increase resilience in urban settings. The benefits of installing the system at Chestnut and Aspen Mews appeared coincidentally beneficial to sustainability and resilience discourses, instead of being a driver for the scheme. Disseminating information through the planning system will start to level the knowledge gap between development stakeholder groups.

The next chapter investigates the perception and use of underground space in creating sustainable urban design. A comparison of the case study findings is presented in Chapter 7 which evaluates geo-resource use for enhancing urban sustainability and resilience.

6 - Investigating Subsurface Space and Urban Design at Canary Wharf Crossrail Station

The use of subsurface space has become increasingly possible as technological advancements through time have allowed humankind to excavate to greater and greater depths below the surface. The ground is a complex heterogeneous resource that, if designed correctly, can be used to construct subsurface space which promotes the sustainable and resilient expansion of urban areas. In an urbanising world it is evident that stakeholders and governing authorities should be challenging the way that the subsurface is used to maximise its potential to accommodate the future development and growth of cities. Successful utilisation of the underground has been achieved worldwide, albeit to a limited extent, as shown by the examples discussed in chapter 2. However, these schemes are often discrete, and although are championed as innovative builds, sometimes do not work in sync with long-term broad-scope sustainability agendas. For example, in the future as cities densify, new subsurface developments may be impeded by existing subsurface uses which have been constructed on an ad-hoc 'first-come-first-served' basis.

A novel approach, for urban underground development, is required to identify solutions that harmonise the intersecting areas of urban governance, such as city planning, civil engineering, architecture and land development. The following chapter describes the mixed-methods analysis used to explore this exemplar case study.

The potential use of subsurface space was assessed by an innovate mapping technique applied across the case study site. In order to explore the challenges and incentives faced by development stakeholders, a series of interviews was undertaken with representatives of stakeholder groups for the case study site. Finally, the planning policy, urban design guidance and sustainability assessment methods relevant to the case study was evaluated to identify where any gaps exist in policy. This site-specific investigation can be used to infer how subsurface space may enhance urban sustainability and resilience, as well as an approach for measuring it on a local scale.

The Canary Wharf Crossrail Station (London, UK) was selected as the development for this case study as it offered a window into the most up-to-date approaches for utilising subsurface space, and the challenges that can be faced in aspiring to build a sustainable underground facility in the UK's largest city. Lessons from this project inform future schemes looking to maximise sustainability and resilience through the utilisation of subsurface space.

This project is a large-scale example demonstrating the augmentation of key components of resilience (discussed in Chapter 2). For example, creating new transport corridors diversifies the ways in which people can travel, improving the resilience of the transport network overall. Furthermore, it adds capacity to the existing railway system, providing more response opportunities should an event occur which necessitates a reaction.

Although this case study only assesses one type of subsurface use, it's complexity, size and ongoing status provides a characteristic example of the opportunities and issues that utilising subterranean space in a sustainable way can bring in an urban setting.

6.1 Introduction

Subsurface space is a valuable commodity that has tremendous potential, particularly in regions where land space is limited by existing infrastructure (Volchko et al., 2020). Canary Wharf Crossrail Station is an example of this, as the Isle of Dogs in the Tower Hamlets Borough of London is an established built up area. The development is approximately 0.92 hectares in size and is constructed within the West India North Dock. The Canary Wharf area is a business district but also contains other land uses such as mixed retail space. The Canary Wharf Crossrail Station is part of the new Elizabeth Line, and is currently expected to open in 2021 (Crossrail Ltd, 2020a). The oversite development contains mixed use leisure space including retail outlets and a publicly accessible open space. Crossrail as a publicly funded new transport link in London represents an ongoing well-documented project which will be tackling the typical issues that may be encountered when utilising subsurface space. Therefore, it provides useful evidence to evaluate issues associated with underground space use, which are explored in the following sections.

Canary Wharf Station (previously known as the Isle of Dogs station) was the first station to be constructed on the Elizabeth Line that had a stakeholder external to Crossrail taking on the design and construction as part of a contractual funding agreement (Crossrail Ltd, 2009a). The use of subsurface space was unique due to the added complexity of constructing a station 18 metres below the water table in the West India North Dock (and 28 metres below ground level overall) (Crossrail Ltd, 2020b). Figure 6.1 shows an architectural section through the completed Canary Wharf Crossrail Station. The structure is 272m long and 27m wide (Greater London Authority, 2008). Excavation of the subsurface produced approximately 200,000 cubic metres of material to relocate and re-use (Crossrail Ltd, 2012a).

Figure 6.1 – Cross-sectional architects impression of Canary Wharf Crossrail Station (Crossrail Ltd, no date).

The station building (also known as the 'station box') comprises seven levels with the railway platform on the lowest level. The overlying floors contain the ticket hall and retail space with the landscaped park area (roof garden) on the highest level. The over-station development is collectively known as Crossrail Place, and opened to the public in 2015. Flexibility of the retail space was a requirement of the over-station design from the beginning, to allow easy adaptation for changes of use in the future (Worsfold et al., 2018). Within the design approach, Worsford (2018) also mentioned reasonable project costs as a necessity, for example keeping costs competitive with the roof durability and other construction factors. Furthermore, Worsfold (2018, p.79) presented details on the construction materials, such as the retailing walls, pilers and reinforced concrete, stating that "the station structure is a mixture of in situ reinforced concrete and precast concrete". The timeline for the completion of Canary Wharf Crossrail Station was revised several times since construction started in 2009. To manage groundwater effectively and construct below the water table, a temporary cofferdam was constructed within the North Dock to allow the site to be dewatered. The water was pumped from the site area into the North Dock (High, 2010). After dewatering, the station box was built by a top down approach. During construction, Crossrail confirmed that "approximately 300,000 tonnes of material was excavated from beneath the dock bed and almost 375,000 tonnes of concrete poured" (Crossrail Ltd, 2015). 99.7% of excavated material across the Crossrail development was re-purposed, contributing to the responsible consumption and production approach of materials from the project (Crossrail Ltd, 2018a). This includes over five million tonnes of material transported for re-use at an RSPB reserve at Wallasea Island and other landscaping schemes (CrossrailLtd, 2020c).

The successful construction of the station required collaboration by many stakeholder groups which all had to consider the project requirements, local context, policy guidance and the environmental setting. These aspects are explored in the following sections.

6.2 Site Characteristics

6.2.1 Geological Setting and Hazards

The geological setting of the site is of great significance when considering the potential use of subsurface space for accommodating urban expansion. The characteristics of the ground dictate how easily underground space can be created and managed, how existing environmental conditions can be maintained and what resources might be available for use. For example, the stability and strength of the subsurface dictate the ease of excavation and whether shoring may be required. Similarly, the ability of stratum to hold water dictates the need for dewatering activities or whether any new subsurface space may require groundwater management. Records held by the British Geological Survey (2016a) indicate that the site is underlain by made ground over superficial deposits (alluvium). This reportedly overlies the London Clay bedrock formation across the eastern half and the Lambeth Group strata (clay, silt and sand) in the western half.

An on-site borehole recorded 1.8m of sandy gravel overlying silty clay to a depth of 9.9m (TQ38SE3107). This is overlying further gravel to 11.9m depth with sand beneath to the borehole completion depth of 21.5m below ground level. Another borehole approximately 50m to the south west was drilled to a greater depth and confirmed the presence of chalk bedrock from 28.8m below ground level (TQ38SE3108).

In summary, the site is underlain by interbedded clays, silts, sands and gravels of alluvium to a depth between 8 – 12m below ground level. This is underlain by thick deposits of sand (part of the Lambeth Group) in the western half of the site, and London Clay in the east. The Chalk Group is present from approximately 29m below ground level. This will be impacted by construction of the new Canary Wharf Crossrail station as its base slab resides nearly 30m below ground level.

Information available from the BGS confirmed that the site may be vulnerable to: ground stability problems, compressible ground, uneven settlement, running sands and shrink-swell due to the presence of medium plasticity materials (British Geological Survey, 2018).

6.2.2 Hydrogeological and hydrological setting

The hydrogeological and hydrological setting for the development provides important information on the environmental suitability for the exploitation of subsurface space in particular the permeability of the ground and the presence of groundwater.

As previously mentioned, part of the North Dock was dewatered in order to construct the subsurface aspects of the Canary Wharf Crossrail Station. The North Dock is hydraulically connected to the River Thames due to its location on the Isle of Dogs peninsula. The site falls on the River Thames tidal floodplain, and is therefore under the Thames Estuary management plan. This plan (TE2100 Plan, p.116) stated that the Isle of Dogs area is required "to take further action to reduce flood risk beyond that required to keep pace with climate change". Furthermore, the London Borough of Tower Hamlets Flood Plan (2017) confirmed that the site location is within a Flood Zone 3, meaning that the area has "a greater than one in 100 annual probability (chance) of river flooding (>1%); or greater than one in 200 annual probability (chance) of sea flooding (>0.5%)" (Environment Agency and Tower Hamlets Borough Resilience Forum, 2017, p.7). This confirmed that the flood risk was high for the Canary Wharf Crossrail development. The site is not within a Groundwater Source Protection Zone (SPZ).

Information available from modelling by the BGS identified groundwater levels at 2m below ground level, coincident with the Alluvium (British Geological Survey, 2015a). However, this dataset does not record groundwater levels that are shallower than 2m below ground level, and therefore groundwater levels within the Alluvium may be less than 2m below the surface on site.

The ES for Crossrail (Environmental Resources Management, 2005) confirmed that the upper chalk formations are in hydraulic continuity with the lower Lambeth Group strata.

The superficial deposit (Alluvium) recorded on site is classified as a secondary undifferentiated aquifer. The Environmental Agency use this category where variation within the deposits mean that is cannot be easily grouped into a secondary A or B category. The deposits are likely to contain layers of mixed high and low permeability on a local level. The underlying London Clay Formation across the eastern half of the site and the Lambeth Group in the western half are classified as unproductive and secondary A aquifers respectively. The Environment Agency confirmed that unproductive stratum has low permeability, and that secondary A aquifers have permeable layers capable of supporting water supplies at local scales (Environment Agency, 2017a). The Chalk aquifer at depth is classified as a principle aquifer, meaning it can store water and act as a source for water supply (Environment Agency, 2017a). The Chalk Group, as a principle aquifer, supports significant groundwater abstraction. However, following a decline in abstraction of groundwater from the Chalk across London a gradual rise of groundwater levels has been observed. "The station box design accounted for uplift forces arising from this possible return of the groundwater to its natural artesian level" (Travers and Yeow, 2014, p.171). The dewatering undertaken for the construction site displaced the dock water (in hydraulic continuity with the alluvium) and the underlying chalk aquifer (Environmental Resources Management, 2005).

6.3 Subsurface Space Potential Mapping Tool

In order to retrospectively assess the potential of utilising subsurface space at Canary Wharf Crossrail Station, a mapping tool was devised from a geological perspective which provides a rating (from excellent to very poor) across the site area. This rating gives an indication of the geological suitability of utilising subsurface space on site.

The methodology undertaken to create the mapping tool was described in chapter 3. The map produced comprised five components which represent some of the principle properties that affect subsurface space utilisation (Table 6.1).Table 6.2 summarises these datasets, their original purpose, and the reworking required for use within this study.

Factor	Dataset	Justification
Is my site suitable for foundations?	(Civils) Foundations	Indicates the expected suitability of the ground for constructing foundations, and therefore a proxy for the suitability for subsurface construction.

Is the ground easy to excavate?	(Civils) Excavatability	Indicates the anticipated equipment required to excavate the ground and therefore what techniques may be required to achieve necessary depth for utilising subsurface space.
Is there shallow groundwater that may impact construction?	Groundwater Levels	Indicates the anticipated maximum depth to the water table. May impact the construction method, dewatering requirements, and design parameters for subsurface structures.
Can excavation materials on site be reused?	(Civils) Fill	Indicates the potential reuse of subsurface materials to offset some costs of subsurface space development (by re-using elsewhere on site or selling on).
Is made ground absent from the site?	Artificial Geology	Indicates the presence and type of made ground in the area which may impact construction techniques or potential contamination pathways.

Table 6.1 - Key factors affecting subsurface space utilisation potential, the related datasets and justification for its use.

Dataset Name	**Background**	**Reworking**
(Civils) Foundations	Aims to "provide general guidance on the foundation conditions of rocks and soils present within geological units"*	The foundations dataset was not reworked.
(Civils) Fill	Aims to "provide general guidance on the use of geological units, as defined … by their lithostratigraphic description"**	The fill dataset was not reworked.
Ability to excavate the ground – 'Excavatability'	British Geological Survey dataset based on geotechnical property information.	A new column was created due to cases when data was 'na' for typical strength or typical density excavation type. The new

		column 'typ_ex' presents data from the filled column to maximise map coverage.
Groundwater Levels	"A raster grid, with 50 x 50 metre pixels holding values that represent the probable maximum depth, in metres, to the water table" ***	Converted into vector data and grouped into ranged classifications (e.g. 0 – 2m, 2 – 5m, etc).
Artificial Geology	An extract of the BGS Geology map, providing a visualisation of known artificial deposits.	Areas within the site boundaries were created where no artificial ground was recorded.

Table 6.2 - Utilised datasets for the subsurface space potential mapping tool, background information and reworking undertaken for use in the tool.
* Entwisle et al., 2016
**Entwisle et al., 2012
***McKenzie, 2014

The subsurface space potential map (Figure 6.2) showed that the site has a 'moderate' potential for subsurface space utilisation due to the following features:

- Made ground is recorded across the southern two-thirds of the site.
    - 30% of the site area is reportedly underlain by infilled ground.
    - 44% of the site area is reportedly underlain by worked ground.
    - 26% of the site area is reportedly underlain by no artificial ground.
- Shallow groundwater levels are recorded across the whole site (equal to or less than 2m below ground level).
- It is anticipated that materials can be excavated by hand tools across the site.
- There is some potential to re-use materials that have been excavated on site as they comprise fine ('wet') soil.
- The site is underlain by ground conditions 'generally unsuitable for most foundation types'.

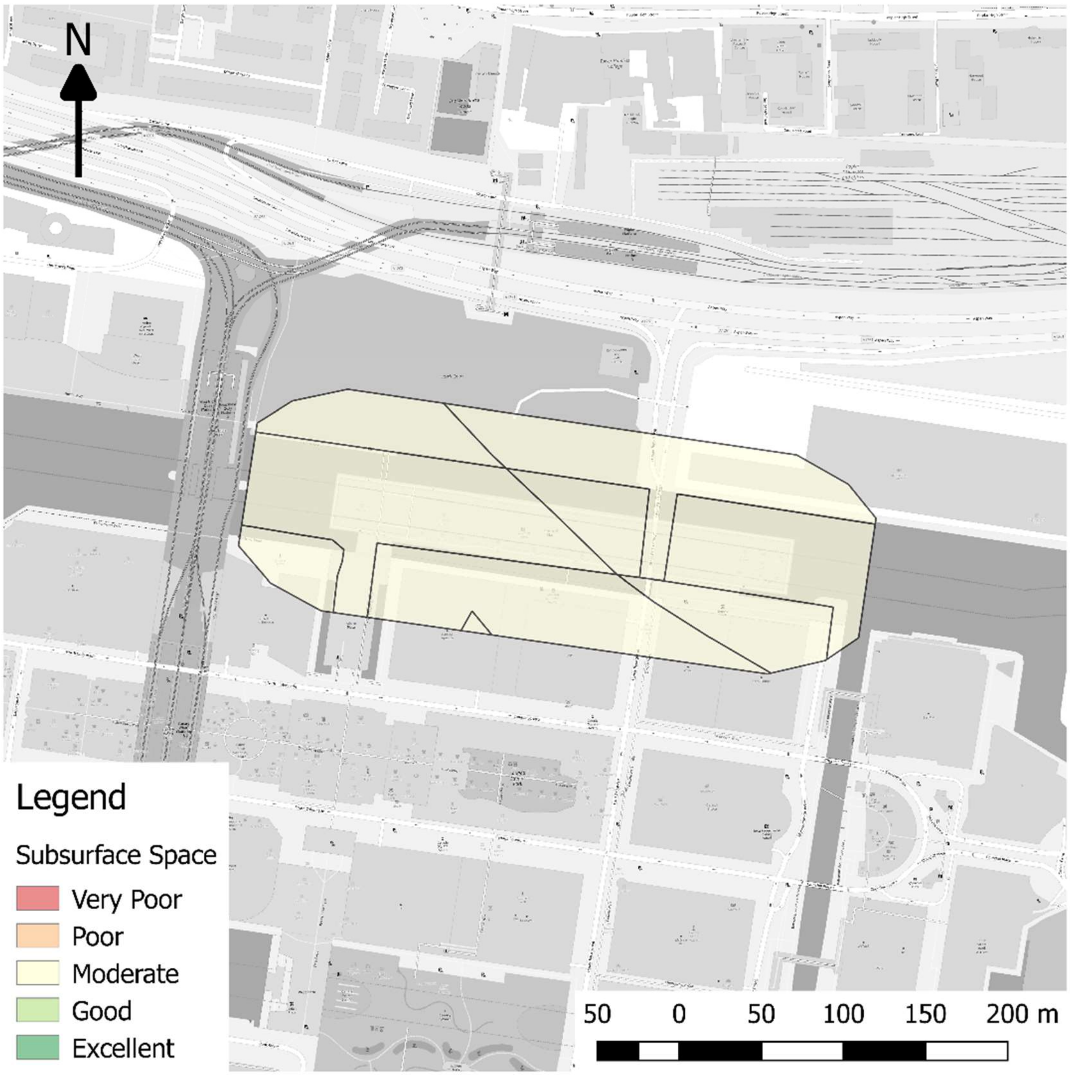


Figure 6.2 – Subsurface space potential map for Canary Wharf Crossrail Station.

6.3.1 Map Validation

The data behind the geo-resource classifications was assessed against factors contributing towards the 'moderate' rating for potential subsurface space use. Table 6.3 compiles the factors contributing towards the map rating, and the findings of the external reports and records.

Ref No.	Mapping result	Subsurface space potential contributing factor	External information/data source	External information/data comment	Age of data
1	Moderate	Infilled ground across the southern boundary of the site.	Old Maps – OS Plan – London 1850	West India Import Dock observed since at least 1850. The dockyard was constructed prior to this in 1800-1802.	Map extract from 1850
		Worked ground across the centre of the site (in the location of water within the dock).	Survey of London: Volumes 43 and 44, Poplar, Blackwall and Isle of Dogs (Hobhouse, 1994).	The West India Import Dock was excavated during 1800 and 1801. Arisings were used to build up the surrounding ground level. Furthermore, fill was deposited against the southern dock banana wall in 1986-87 (Hobhouse, 1994).	1994
			Yeow et al. (2012)	The underwater area of the site "typically comprises a downward geological sequence of dock sediment [and] made ground…" (Yeow et al., 2012). This indicates interbedded layers of	2012

				naturally deposited sediment and man-made deposits.	
		No artificial ground across the northern area of the site.	Survey of London: Volumes 43 and 44, Poplar, Blackwall and Isle of Dogs (Hobhouse, 1994).	Alterations were made to the north quay of the West India Import Dock in 1894-95 (Hobhouse, 1994).	1994
			Boreholes across the northern boundary of the import dock – TQ38SE539, TQ38SE540, TQ38SE541	Made ground reported between 4.5m and 5.4m below existing ground level (begl).	1911
2	Moderate	Shallow groundwater levels are recorded across the whole site (equal to or less than 2m below ground level).	Boreholes across the northern edge of import dock – TQ38SE539, TQ38SE540, TQ38SE541	Groundwater reported between 3m and 3.9m begl.	1911
			Off site borehole circa 125 north of site – TQ38/139	Groundwater reported at 2.5m begl.	1895
			Off site borehole circa 450m east-northeast of site – TQ38SE3178	Groundwater reported at 3.8m begl.	1984

3	Moderate	Anticipated that materials can be excavated by hand tools across the site.	Off Site borehole log – circa 40m south of the site – TQ38SE BJ 3108	Medium dense sand from 0 – 1.7m begl. Stiff clay from 1.7m to 3.7m begl. Very stiff clay from 3.7m to 9.7m begl. Very dense gravel from 9.7m to 11.5m begl.	November, 1987
4	Moderate	Site is underlain by ground conditions 'generally unsuitable for most foundation types'. Additional information: Hazard description states "likely highly compressible ground. Possible large and differential settlement and aggressive acidic conditions. Excavations might to be unstable" (Entwisle et al., 2016).	Off Site borehole log – circa 80m north west of the site – TQ38SE BJ 3106	Medium dense gravel from 0 – 0.5m begl. Medium dense becoming very loose gravel from 0.5m to 2.2m begl. Firm to stiff clay from 2.2m to 4.8m begl. Stiff to very stiff clay from 4.8m to 7.3m begl. Very stiff clay from 7.3m to 9.6m begl. Very dense gravel from 9.6m to 10.6m begl.	November, 1987
5	Moderate	Potential to re-use materials that have been excavated on site.	BGS Lexicon of Named Rock Units - Alluvium	Site is underlain by: Alluvial deposits - unconsolidated clay, silt, sand and gravel.	2019

			BGS Lexicon of Named Rock Units – London Clay	London clay to the east and north – usually silty clay to clayey silt	2019
			BGS Lexicon of Named Rock Units – Lambeth Group	Lambeth Group to the west and south – mainly clay with some silt and sand.	2019

Table 6.3 – Validation information for factors used in subsurface space potential map.

The information shown in Table 6.3 to validate the map results suggests that the artificial geology data used within the mapping tool is misrepresentative or incomplete in places, as reports of made ground are recorded in the northern area of the site. Information from local intrusive ground works could be used to improve this dataset (although this process would be labour intensive and may only be feasible on a site-by-site basis).

Also, it is well reported that groundwater levels in London have been rising since groundwater abstraction decreased in the late 20th century (Travers and Yeow, 2014), and therefore the accuracy of the data presented in Table 6.3 is relative to its age. The boreholes vary in age from 1895 – 1984, and therefore these boreholes are taken as an indication of groundwater levels, but cannot accurately validate the groundwater levels dataset despite their proximity to the site area.

The groundwater levels dataset defined the shallow water table in the Alluvium deposits and not the groundwater levels in the chalk aquifer at depth. A report produced to assess the impact of Crossrail on regional groundwater levels suggests that the Canary Wharf Crossrail Station has groundwater levels within the chalk aquifer at 90m above tunnel datum (Wilson and Jensen, 2005). This depth relative to tunnel datum ("which is 100m below ordnance datum" [Lawrence et al., 2018, p.31]) equates to a groundwater level of 10m below ordnance datum. This is approximately 9.3m lower than the recorded groundwater level from a local borehole in 1984, suggesting a drop in groundwater levels over time in the region. This may be explained by the GARDIT scheme, instigated to control the rising groundwater in London which predicted a decrease in water levels for the region of up to 6m below the groundwater levels recorded in 1990 (Wilson and Jensen, 2005).

There is a deep complexity to groundwater levels for the Canary Wharf Crossrail Station, which in part are exasperated by the limitations of the groundwater levels dataset. "The dataset has not used observations of groundwater level in wells or boreholes directly, but they have been used to validate its performance" (McKenzie, 2014, p.iii). Furthermore, "it assumes that groundwater and surface water are in hydraulic continuity, so that groundwater is unlikely ever to be below a surface interpolated between surface water bodies" (McKenzie, 2014, p.4). This describes the situation of the Canary Wharf Crossrail site, as the site is on an archipelago surrounded on three sides by the River Thames. Therefore, the groundwater levels dataset offers the worst-case scenario for the groundwater levels that will be encountered on site and is therefore a suitable representation to demonstrate the presence of shallow groundwater across the site area.

The ‘moderate’ rating for potential subsurface space use was further characterised by the anticipated suitability of hand tools to excavate the site. Local exploratory logs support this interpretation. Material to a depth of 1.7m to 2.2m may be suitable for excavation by hand tools although deposits deeper than this are likely to require power tools to excavate (which has not been represented in the map (discussed in section 3.3.7.1)).

According to the foundation conditions dataset utilised for the map, the ground conditions are ‘generally unsuitable for most foundation types across the site’ (British Geological Survey, 2016b), contributing towards a moderate potential for subsurface space utilisation on site. However, the standards on which the foundations dataset user guide is based considers the typical scenario in which foundation types are used. This dataset considers the ground conditions and is not specific to any foundation type. Detailed information on the foundation design for Canary Wharf Crossrail Station is not available, and given the necessity for the station development, it was highly unlikely that the ground conditions would have been completely unsuitable to support foundations for the Canary Wharf Crossrail Station. This dataset may be inappropriate for use for the Canary Wharf Crossrail Station due to the size and complexity of the structure and its subsurface use, however it would provide valued information for smaller developments which utilise subsurface space.

Finally, the ‘moderate’ rating for potential subsurface space use was determined by the potential to re-use the materials that have been excavated on site. The geological units encountered on site are predominantly very fine materials, as confirmed by the formation rock descriptions and the exploratory logs in proximity to the site. The fill was reportedly ‘fine and wet soil’ which combined with the information confirming the presence of shallow groundwater across the site, validates the data utilised from the Civils Fill dataset.

Table 6.3 reveals information and data which conflicts with some of the findings from the subsurface space utilisation potential map. However, some of the external information and data may be inappropriate to verify the map due to its age. From this process, the subsurface space potential map can be considered a logical interpretation of site conditions, however, there are some limitations that must be considered during its use. The map provides an indication for where subsurface space utilisation might be investigated and is not a final model to be used for the installation of any infrastructure.

6.3.2 Translation into Urban Design Criteria

The Canary Wharf Crossrail Station was designed in accordance with planning guidance documents and policies from a national to a local scale. The key relevant policies and guidelines were translated into an urban design geo-resource (UDG) matrix for the Canary Wharf Crossrail Station site (Appendix I). The matrix connected the subsurface space potential map with the urban design agenda for sustainability and resilience (and/or subsurface space utilisation) specific to the case study setting. It demonstrated how subsurface space can be utilised to meet different urban agendas and allowed users to target specific urban criteria. The following documents were included in the UDG matrix:

- UK Government Design Guide,
- Planning Policy Statement 1: Delivering Sustainable Development,
- Planning Policy Statement 13: Transportation and Land Use,
- Planning Policy Statement 7: Sustainable Development in Rural Areas,
- Planning Policy Guidance 2: Greenbelts,
- Planning Policy Guidance 25: Development and Flood Risk,
- Planning Policy Statement 10: Planning for Sustainable Waste Management,
- Planning Policy Statement 23: Planning and Pollution Control,
- Planning Policy Guidance 24: Planning and Noise,
- Planning Policy Statement 6: Planning for Town Centres,
- London Plan (2004),
- Sustainable Design and Construction SPG (2014),
- Sustainable Development Framework for London (2002),
- BREEAM Bespoke 2008,
- CEEQUAL 2010.

These documents influenced the design of the Crossrail scheme as a whole (and are discussed in detail in subsequent sections). The utilisation of subsurface space must meet urban design criteria and planning policy in order to contribute towards sustainable urban growth in practice. Therefore, the relationship between these issues are presented in the UDG matrix (Appendix I).

As explained in the methodology (section 3.6.6), the UDG matrix (Appendix I) presents elements of sustainable urban infrastructure utilising subsurface space across the horizontal axis, and sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Figure 6.3 demonstrates two approaches to using the UDG matrix. Firstly, by reading horizontally, the user can prioritise urban criteria (relevant to the Canary Wharf Crossrail Site) and see which approaches of subsurface space use may fulfil particular criteria. Alternatively, by reading vertically, if pursuing a specific method of subsurface space use, the user can see how implementing it may fulfil certain criteria. A selection from the UDG matrix is presented in Figure 6.3.

Given the results of the subsurface space potential map, and disregarding the use of subsurface space for the Canary Wharf Crossrail Station, the following assessment was determined from considering the UDG matrix:

As the whole site is rated as having a 'moderate' potential for the use of subsurface space, utilising subsurface space may contribute towards the urban resilience and sustainability of the development and surrounding area, however, there may be some geological issues which present difficulties (such as the presence of made ground or shallow groundwater levels).

However, it can be drawn from the UDG matrix that the utilisation of subsurface space for transport infrastructure satisfies specific urban criteria relevant to the Canary Wharf Crossrail Station (Appendix I). For example, Planning Policy Statement 1, to build "carefully planned, high quality buildings and spaces that support the efficient use of resources"(Office of the Deputy Prime Minister, 2005, p.14), or the Sustainable Design and Construction SPG (2014), for example that "developments and lighting schemes should be designed to minimise light pollution"(Greater London Authority, 2014, p.20).

As this assessment has been completed retrospectively for the Canary Wharf Crossrail Station, these results can provide verification of the approach taken on site. In this case, given the intended use of the site and the need to connect the station with the remainder of the Crossrail network, subsurface space and construction was a necessity. The inclusion of subsurface space was a must for the Canary Wharf Crossrail Station, and despite the

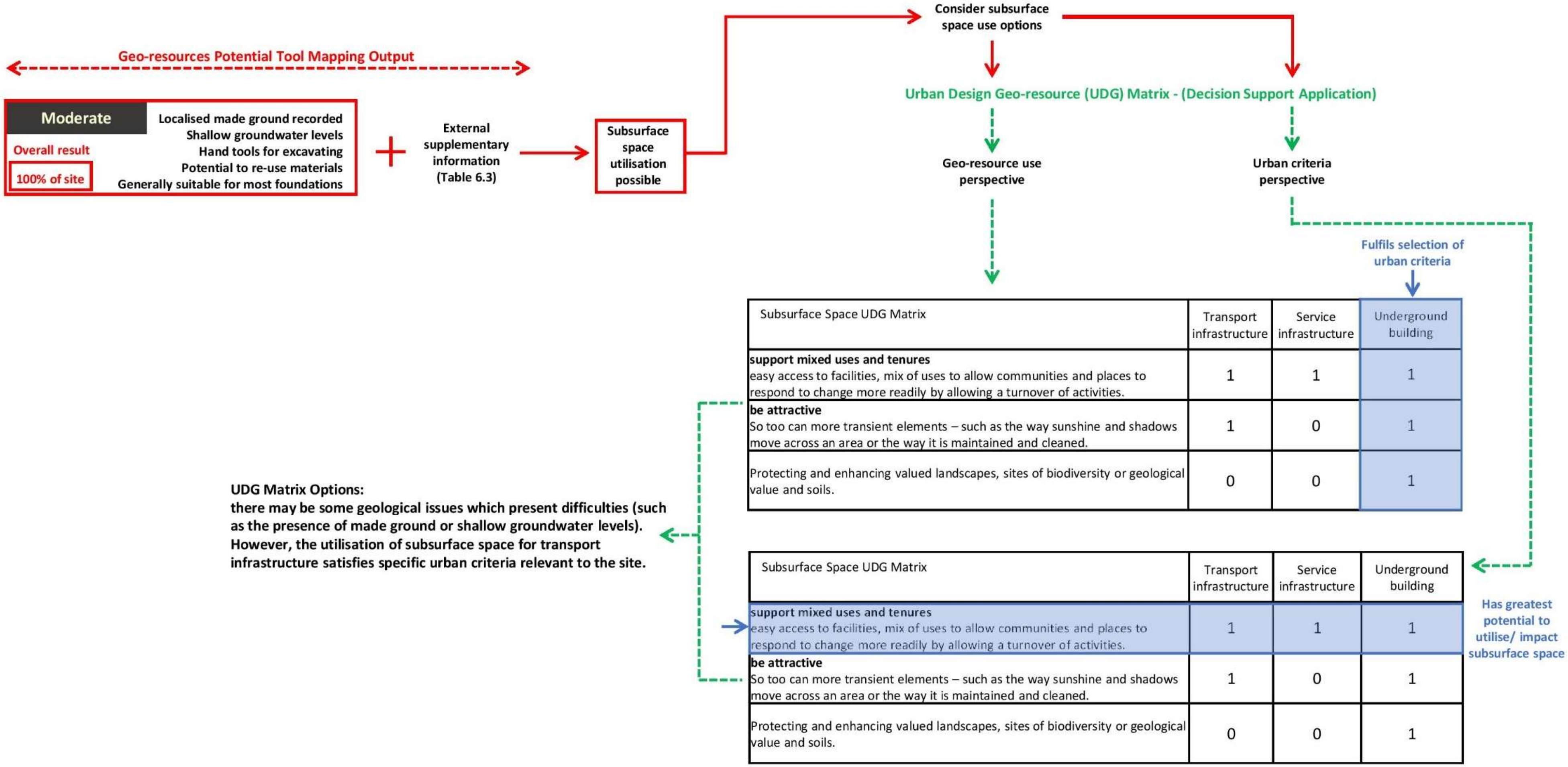


Figure 6.3 – Flow diagram summarising the method of applying the subsurface space potential map output to the Urban Design Geo-resource (UDG) matrix.

potential difficulties that may have been encountered (as highlighted by the mapping result), the success of the scheme is evidence that even with a 'moderate' potential for subsurface space utilisation, geological uncertainties can be addressed to enhance wider urban sustainability and resilience

6.3.3 Subsurface Space Potential Mapping Tool Limitations

As previously noted, a key issue with measuring the potential use of subsurface space is representing groundwater levels accurately (particularly in London which has been subjected to groundwater fluctuations over time). The level of groundwater is important for determining factors around foundation design, anticipated ground stability and the potential need for de-watering during construction. External factors such as abstraction licensing must also be considered, and for the Crossrail Development particularly, the future of the GARDIT (General Aquifer Research Development and Investigation Team) strategy (which has become successful in controlling the rising groundwater levels in central London via a series of targeted abstraction boreholes) should be considered.

Furthermore, some of the data used to validate the subsurface space potential map may be considered too old for authenticating the map result (such as the boreholes from 1895 – 1984 or the survey of London in 1994). The most recent information and data should be used wherever possible.

In addition, as discussed in Chapter 3, the score rating was based on the national range of scores that can be achieved from the subsurface space potential mapping tool. Any results from the subsurface space potential map may need to be refined by more granular information should the use of subsurface space be pursued. Furthermore, other factors (such as economic and environmental) must be considered as it is more than just the geological factors which determine the viability of subsurface space utilisation.

Further limitations of the general geo-resources mapping tools are discussed in the methodology chapter of this study (chapter 3).

6.3.4 Subsurface Space Potential Mapping Tool Section Summary

The Canary Wharf Crossrail Station was designed knowing that subsurface space was a prerequisite for the development (in order to connect with the remainder of the Elizabeth Line). The depth of the station was carefully considered in recognition of the effect that the development may have on the surrounding buildings. The base slab for the development is 18m below the dock bed (which itself is 9m below water level) with the over station development creating a flexible space subsurface space which can be adapted to suit future needs (Worsfold et al., 2018). Although the station has not been officially opened yet, the over station development contains “97,000 sq.ft of retail space in 17 new units alongside a new public garden on the four storeys above the station” (Lindsay, 2018).

The subsurface space potential mapping tool indicates a ‘moderate’ potential for subsurface space utilisation at the Canary Wharf Crossrail Station. The site-specific urban design criteria within the UDG matrix indicates that the utilisation of subsurface space for the Canary Wharf Crossrail Station meets many planning policy measures and is contributing to urban sustainability locally but also regionally due to its accessibility to the public, and its estimated number of users. Furthermore, the use of previously unoccupied subterranean space has improved connectivity around London and will increase the sustainability and resilience of the transport infrastructure (and its users) once fully operational.

6.4 Case Study Stakeholder Interviews

To investigate the main drivers, enablers and challenges for subsurface space utilisation at Canary Wharf Crossrail Station, a series of interviews were undertaken with stakeholder representatives of the site.

Crossrail Ltd and the Canary Wharf Group Plc both contributed financially to the development of Canary Wharf Crossrail Station and established shared responsibility for completion of the project. Interviews with representatives from both companies were undertaken for this research, with their views considered from the perspective of proprietor/developer for the site. Architectural views were provided from interviews with representatives from two companies involved with designing Canary Wharf Crossrail Station (or a component of the Crossrail network). A representative of the consultant company for the development (ARUP) also participated in an interview. Transport for London were contacted to participate however they did not consider the questions relevant to the Canary Wharf Crossrail Station and therefore did not comment. As previously discussed, guidance for subsurface space management is not provided by any level of governance in London, and therefore an interview with the local authority was not pursued. Furthermore, as a major project of national interest, Crossrail was not approved through the customary planning system but was orchestrated and authorised by the *Crossrail Act* 2008, and therefore the perception and role of authorities was considered through the document examination section of this case study.

Following full transcription of interviews, the interview documents were coded to correlate findings across stakeholder groups. In the following section, the main enablers, drivers and barriers of the scheme are the focus of discussion.

6.4.1 Interview Response

6.4.1.1 Enablers

Once coded into themes, seven enablers were identified across the stakeholder groups. One enabler was commonly identified by multiple stakeholder representatives – the economic returns over the project life cycle/ cost-effective design solutions. This factor was most frequently mentioned by representatives of the architectural stakeholders associated with Crossrail. This may reflect the restrictions associated with the project funding requirements (i.e. funding for Crossrail is only granted by government if the financial and economic business case is proven). Several interviewees drew upon the business case for subsurface projects, for instance one architect said that "the business case is… based on economic viability rather than the physical subsurface" (Architect, 2019a). Furthermore, "building below ground is very expensive so in order to justify it you need a high level of use. In order to achieve a high level of use you need to build a business case to justify it" (Architect, 2019a). The cost of underground construction is impacted by the geological conditions. For example, a more competent bedrock may not require as expensive structural support than weak/poor bedrock conditions. Another interviewee who agreed that cost-effective design was an important enabler also suggested that "sustainability shouldn't cost more, it's about intelligent design" (Architect, 2019b). This argument was particularly valid when considering disused underground space, such as the Lowline project which is planning to utilise the abandoned Williamsburg Bridge Trolley Terminal in Manhattan (New York). The subsurface space already exists, and therefore high construction costs are not associated with its re-use potential. Canary Wharf Crossrail Station was a new site that had to be excavated for subsurface space use, with the added complication of dewatering the site. However, the high value scope of the Crossrail project meant that the construction was economically viable. Furthermore, in the case of Canary Wharf Crossrail Station, the representative of an architectural stakeholder made a general comment that "for railway lines underground in cities, adding a second line more than doubles the value of the existing line because of the additional functionality" (Architect, 2019a), demonstrating the further financial benefits to be gained from the additional line (and station).

Other enablers identified by stakeholders included having:

- A safeguarded route
- No conflicting uses for the space
- Achieving multiple benefits (economic and environmental)
- Good understanding of subsurface potential
- Data available from ground investigations and consultation with other subsurface users

The complete safeguarded route for Crossrail was secured under the Town Country Planning Order (1995) from January 2008. The article stated that any development proposal for "building, engineering or other operation deeper than 3 metres below ground level" within the route would have required consultation with the local authorities (Secretary of State for Transport, 2008). The safeguarded alignment was an important enabler for protecting subsurface space from other development, without which construction activities would likely have occurred given the high value of space in London. Although safeguarding the route reserved its use for Crossrail, it was carefully considered so that the surrounding area would benefit from its positioning. A representative of the CWG stated that "high rise buildings are fundamental to the success of the new business district of Canary Wharf, so any un-developed land in the area is valuable and likely to also be built-up to a considerable height. Therefore, the location of Canary Wharf Crossrail station was chosen to avoid potential clashes with the foundations of existing and probable future large buildings" (CWG, 2019).

The lack of conflicting uses of subsurface space was another enabler for the Canary Wharf Crossrail Station. This enabler is linked to safeguarding of the route as subsurface space utilisation was controlled under legislation. This enabler could be globally applied if a central authority were designated to manage subsurface space holistically. For example, the city of Helsinki's underground master plan has been enforced since 2011 and is strictly regulated by city administration (City of Helsinki, 2020).

Achieving multiple benefits via subsurface space utilisation is probable in many circumstances as the surface environment can be managed as a separate entity to the subsurface use. In the case of Canary Wharf Crossrail Station, a representative of the consultancy firm said that with regards to the final design it "was cheaper to build within the dock accepting that water needs to be kept. Some marine works would be required but it would be better environmentally. It was win-win where the economics also favoured a more sustainable solution" (Consultant, 2019). However, this enabler could be considered more of a by-product of subsurface space use, as several of the interviewees commented that subsurface construction was characteristically more expensive than building above ground. An architect said that “people will tend to drive a line on ‘why don’t we do more underground stuff? Is it because we don’t like it?’ when in fact more often than not it’s done out of necessity more than desire” (Architect, 2019a). This impression was given from several interviewees, and suggested that where underground construction was necessary, demonstrating multiple benefits may be beneficial to the business case for the development.

The final frequent enabler identified by interviewees was having a good understanding of subsurface potential, but also having data available on the subsurface environment. Understanding ground conditions is important for above and below ground construction projects, and therefore having access to information is essential to the accurate prediction of construction conditions. This was relayed by the representative of the consultancy, who said that “you must look at the geology, risks and environmental factors with what you’re doing underground because constraints occur which don’t exist above ground” (Consultant, 2019). The importance of data gathering and data sharing was emphasized by the interviewee representing Crossrail. They said that “you would talk to utility companies as to where their utilities are. You can do searches of records in terms of building plans. But you can also consult with those who have buildings along the route and obtain plans. You can conduct your own surveys as well, for example trial boreholes and ground investigations. However, you have to remember that the Crossrail project has been in gestation for the best part of 25 years, and during that time a lot of data was gathered and continues to be gathered at a greater granular level. You have data gathering for deep tunnels, for specific sites, for utilities, it’s a mixture of desktop work and physical investigation. You can also talk to others who may have information on the subsurface already such as other rail providers” (Crossrail Ltd, 2019). International subsurface space specialists shared the view that collaboration is key to successful subsurface management. Vähäaho (2018, p.4) stated that “the close cooperation that the City of Helsinki has established with the numerous ‘partners’ involved in the planning, financing and designing as well as the actual construction and maintenance of tunnels and underground spaces has perhaps been the crucial factor in sustainable underground property development”. Crossrail as a large-scale infrastructure project has countless companies working towards its completion. The sheer number of stakeholders this includes encourages firms to share relevant information between parties and across disciplines due to the widespread vested interest in the successful implementation of the project. This may differ for smaller developments utilising subsurface space which have a limited number of engaged stakeholders. Subsurface information they require may be difficult to obtain if it already exists, and oppositely any information they acquire may be kept private due to the financial investment made to obtain the data. Breaking down the barriers between stakeholder groups is a recognised approach to building resilience. Building connections between sectors and implementing holistic plans increases the ability of urban systems to respond and adapt to shocks and stresses.

Identifying the main enablers for subsurface space utilisation can be used to infer the actions needed to see subsurface space used more widely. The interviews confirmed that the central enablers are safeguarding subsurface space, delivering multiple benefits and understanding subsurface potential across stakeholder groups. These enablers are all lacking in the UK, with the Crossrail project being an exception to the general trend. Designating a central authority for subsurface space management and obligating local authorities to assign and legislate subsurface construction would be a start to increasing sustainable urban growth through the utilisation of the underground.

6.4.1.2 Drivers

Eleven codes were identified across the stakeholder interviews denoting drivers for implementation of the Canary Wharf Crossrail Station. The most common drivers across the stakeholder interviews were:

- Meeting government targets (carbon reduction)
- Future-proofing infrastructure
- Avoiding dense urban fabric at surface/avoiding existing infrastructure
- Alleviating stress on transport system, adding capacity/meeting end user requirements

Several interviewees noted that the alignment of government proposals with Crossrail's development plan supported the implementation of Crossrail. The representative of Crossrail noted that they were "reflective of the Mayors sustainability strategy, his plan for London, and the government's policy at the time", but also that "Crossrail is part of the bigger transport plan" for London and the wider area. Furthermore, "some drivers come from the local UDP's [Unitary Development Plans] and that's pressures from the local authorities as you're developing the scheme. You have to consider what they want as well". It was described as a "a multitude of strategic pressures" although these needs were reportedly addressed by modelling processes and growth forecast provided by the London Plan (Crossrail Ltd, 2019). An architect for the Crossrail project commented that “in the last few years there has been a tipping point because of the decarbonisation of the UK grid”. In addition, “the driver is regulation, you must consider it… however, we need the government to do a timeline for sustainable carbon. We’re still tinkering around the edges but to meet a target we need the government to mandate carbon now” (Architect, 2019b). There is currently a target for the UK to be at almost zero carbon emission by 2050 (National Infrastructure Commission, 2017). However, it is also recognised by the UK government that “there is a gap between existing Government policies and achieving the UK’s emission targets. Policies have not been implemented to enable a lowest cost transition. Despite the stability of having a long-term goal, policies have often been subject to sudden change, creating a challenging environment for private investors” (ibid, p.16). The Architect (2019a) justified Crossrail’s carbon footprint saying that “Crossrail spent huge amounts of concrete and produced masses of carbon in construction, but it is a public transport facility reducing long term carbon outputs”. The construction of Crossrail contributes to the mitigation of carbon emissions over time by reducing the use of private vehicles in central London (a key priority identified in the National Infrastructure Assessment) (National Infrastructure Commission, 2017).

Multiple stakeholder groups recognised the need to incorporate subsurface space into urban design to meet sustainability agendas set by the UK government. However, inexplicit commentary on how to achieve sustainable design is not enough to incite a significant impact. Government policy and targets are recognised as an important driver for sustainable urban design, however more detail is required about how to meet government targets, as well as more information on how to employ subsurface space most effectively.

Connected with this is the concept of futureproofing, particularly under future climate scenarios which was identified as a driver for subsurface space use by multiple stakeholders. One interviewee said that “there’s a lot of buildings out there that may not get any insurance in the future because they are not prepared” and in anticipation of this, “we model all of our buildings in future climate settings and make them adaptive”. Moreover, “the financial model is changing, and smart money investors are now looking at building better designs to mitigate and adapt for the future” (Architect, 2019b). This shift in perspective may see the development industry start to utilise underground space more in response to climate change forecasts (for example by providing additional capacity for flood waters during extreme weather events [Ko et al., 2018]).

In line with the theme of future-proofing, the representative of Crossrail deemed the implementation of the development to be a contribution to sustainability, stating that “it will be around for a very long time and needs to be able to accommodate a lot of people and growth” (Crossrail Ltd, 2019). It also contributes to sustainability by facilitating cross-town journeys to complement the existing radial transport system in London (Architect, 2019a). In addition, the use of underground space to join the existing transport network boosts sustainability by adding capacity to the system and relieving congestion (Architect, 2019a).

Another key driver for utilising subsurface space was in avoidance of the dense urban fabric on the ground surface. This is particularly relevant in established urban centres which lack land space to accommodate urban expansion. One interviewee suggested that “in other cities [outside of London], the dynamic of how high you can go, to how deep you can go is evident” (Architect, 2019a) implying that the places where it was economically feasible to build higher infrastructure was where it was also feasible to develop underground. The location of subsurface structures as well as the location of portals to the surface were identified by the representative of Crossrail as drivers for the route positioning (and as constraints for the route alignment) (Crossrail Ltd, 2019). This concurred with the earlier comment that [the location of] underground construction was “done out of necessity more than desire” (Architect, 2019a). It was not coincidental that subsurface space utilisation occurs most frequently in urban areas. Most stakeholders attributed this trend to the higher perceived value of subsurface space in highly populated areas where there is a better financial return on investment. As urban centres grow, this driver will become more important and the use of subsurface space will become more competitive. Without a centralised system of governance to manage the underground, the subsurface will become chaotic and work against the principles of building sustainable cities. The concept of being ‘driven’ underground by existing surface infrastructure needs to be acknowledged by governing authorities so that the use of subsurface space can be optimised.

6.4.1.3 Barriers

Twenty-four themes were identified as potential barriers for the utilisation of subsurface space in building sustainable and resilient urban design.

The hindrance identified most often across the stakeholder interviews was high capital costs associated with subsurface construction, and the prioritisation of cost minimalisation for development projects. The representative of Crossrail confirmed that “setbacks tend to be of political and funding nature” (Crossrail Ltd, 2019). Most stakeholders agreed that subsurface construction is more expensive than surface construction. The representative for the consultant stated that “underground construction is quite a lot more expensive” and “cost came first” (Consultant, 2019). Furthermore, “it was cheaper to build within the dock accepting that you have water that needs to be kept” than it would have been to infill the area and create an artificial subsurface setting (which was one proposal during the early design phase of the Canary Wharf Crossrail Station, although this would have been opposed by Policy 4C.32 ‘Docks’ of the London Plan (Greater London Authority, 2004)). One interviewee observed that “for London, it is most economic to build underground within zone one” (Architect, 2019a) and given the financial stature of the Canary Wharf area, it was an economically viable location to invest in subsurface development. Economic viability will always be the dominant factor controlling the feasibility of development, however the role of sustainability is evolving and is becoming increasingly important for new construction. As this continues, and sustainability persists as a substantial factor in planning policy and urban guidance, this barrier will become less of a problem as stakeholders will become more incentivised and/or pressurised to engage in sustainable building techniques (such as the use of subsurface space).

After cost, the most frequently identified barriers discussed during stakeholder interviews were:

- Subsurface obstacles/ competitive space use
- Lack of communication
- Perceived geo-hazards/geo-technical risks
- Maintaining artificial environments

As discussed earlier, safeguarding the route for Crossrail reserved the subsurface space so that no other infrastructure could be constructed along its route (where the depth of construction would exceed 3m below ground level). The safeguarded route was depicted as a constraint by one stakeholder, who noted that “there were a couple of buildings that managed to get into the safeguarded alignment, and some piles that had to be dealt with. There were some unexpected underground obstructions” (Crossrail Ltd, 2019). The interviewee also confirmed that “the local authorities had to remember for a long time about the safeguarded zone, and sometimes mistakes are made and sometimes people put down piles deeper than they needed to” (Crossrail Ltd, 2019). The architect (2019a) agreed that “a constraint is the amount of infrastructure below ground in the first place. A congested subsurface makes it difficult to implement subsurface projects" (Architect, 2019a). Despite these issues, safeguarding of subsurface space for specific functions was successfully practised in other densifying metropolises, for example, the city of Helsinki has had an underground space plan since the 1980's (Vähäaho, 2018), which allowed the central authority to manage the resource to adapt to the cities future needs.

The lack of communication across and between stakeholder groups was also identified as a barrier to the utilisation of subsurface space. This issue was underpinned by the knowledge gap which was identified during stakeholder interviews; "knowledge is contained in separate reports and it's all about liability with people not talking to each other" (Architect, 2019b). The Architect (2019b) also thought that "engineers may not be trained enough in passive building physics and building physicists are not aware enough of construction, so there is a definite breakdown there, and they need to understand one another". Mielby et al., (2017, p.13) concurred that there was a "communication gap between subsurface experts on the one hand, and urban planners and decision makers on the other". In order to address the issue both groups must select the essential information that is required to instigate effective design and manage the subsurface. Mielby et al., (2017, p.18) accurately stated that "mutual agreements about the content, common terminology, language, timing and…basic information for all needed themes will facilitate communication between the demand side (planner) and the provider (geoscientist)". During an interview, it was also mentioned that sceptics of underground construction for sustainable urban growth could make it difficult for stakeholders to gain support for subsurface development. Architect (2019b) said that "if there's a team of naysayers then the effect is big...if parties are neutral then you can work with them and build a plan, but if the engineer is not on board then this cascades down". Uncertainty in subsurface construction may be associated with the risks that can be associated with underground construction. During the interviews, another common concern that arose was the geological hazards and geotechnical risks associated with subsurface construction. The consultant confirmed that "you must look at the geology, risks and environmental factors with what you're doing underground because constraints occur which don't exist above ground" (Consultant, 2019). These issues can be minimalised by attaining accurate granular data of the subsurface (particularly in areas of high concern), however this data may not exist. Admiraal and Cornaro (2018, p. 117) state that "the biggest challenge we face when it comes to the subsurface as a liability is that data is often not available to assess whether a threat exists or not". Ground investigations to attain new data or data modelling are currently the best methods for addressing this problem.

The Crossrail representative revealed that the presence of a geological fault detected during tunnelling caused some difficulties, and that another location experienced an issue with groundwater ingress, however both of these complications were resolved by good design following geotechnical guidance.

In addition, by constructing underground spaces intended for human occupation, there was a requirement to create appropriate environmental conditions in a subsurface setting. “Technical designs such as creating an environment below ground with the correct light, air and inhabitable environments must be factored in. Retail can be achieved underground as it is an artificial controlled environment and is a high value environment” (Architect, 2019a). This was a barrier that could be overcome with appropriate equipment to provide lighting, heating/cooling and air circulation underground. In addition, in the UK there are fire and safety regulations and guidance documents that support the Consultants (2019) statement that “the deeper you go, the harder it is to achieve safe egress to the surface in case of a fire or an incident”. Crossrail as a major infrastructure project with 200 million expected passengers every year (Crossrail Ltd, 2018b) must satisfy these elements of concern on a large scale.

6.4.1.4 Failures

It was highlighted by the stakeholder interviewees that events can occur which may lead to the failure of subsurface space utilisation, and although these were not specific to the Canary Wharf Crossrail Station project. Two examples were discussed, both of which are the worst-case scenario for barriers already discussed:

- “The land was too expensive and so because they hadn’t resolved the land ownership problem the project couldn’t go ahead” (Consultant, 2019).
- “Acts of Parliament in the UK do work, but if you can’t get the land or legal rights you can’t do the project” (Consultant, 2019).

These issues are unlikely to arise for more common subsurface space use (such as basement development which occurs in some areas of London), though high capital costs are virtually guaranteed for any subsurface development project in the UK. However, this is a pre-commencement issue which should be addressed at project feasibility stages. Accurate budgeting and financial management should prevent the initiation of a project that has a chance of failure due to financial restrictions. Issues with land ownership was identified as another potential reason for project collapse. Similarly, these issues should be resolved at the feasibility stage of any project and can be prevented with accurate modelling to determine if adequate space is available.

The representative for Crossrail confirmed that there were no factors which caused the programme of works to completely stop. However, in the wider Crossrail development there were some localised delays for example where difficult ground conditions were encountered and where infrastructure had unintentionally impinged on the safe-guarded zone. These were previously discussed as barriers to subsurface space utilisation.

6.4.2 Stakeholder Interviews Section Summary

Interviews indicated that safeguarded space and a good understanding of the subsurface are significant enablers for subsurface development projects. Furthermore, knowledge of underground conditions and ample site-specific data supports optimal use of subterranean space. Government targets (particularly in regard to reducing carbon emissions) and the aim to create 'future-proof' new infrastructure are two key drivers for utilising subsurface space. A congested surface setting is also justification for underground development, particularly in high-value locations which already have a dense urban fabric above ground. These drivers set in motion a positive feedback loop, where increased guidance and legislation from governing authorities increase the need for urban underground experts to contribute towards urban development projects (which furthers knowledge and the data available for subsurface use).

The key barriers identified during the interviews, such as the high capital cost associated with subsurface construction, subsurface obstacles, geological conditions and the mechanism for creating and supporting an artificial environment may deter development stakeholders from considering the underground as a resource for subsurface space. However, with the aid of appropriate domain experts and specialists, the challenges associated with these issues can start to be addressed.

The interviews confirmed that there are benefits to be gained from the management of subsurface space by a central authority. However, as yet there is no central organisation with a mandate for this. In a related study, von der Tann et al. (2018, p.34) found that "the current governance of subsurface space in England is largely sectoral and project centred rather than based on the premise to control all activities in a given volume". Addressing this issue holistically will contribute towards the government's aspiration for sustainable urban expansion. Whether this will be recognised soon enough to influence the increasingly chaotic subsurface environment remains to be seen.

6.5 Planning Policy, Urban Design Guidance and Sustainability Assessment Analysis

6.5.1 Introduction

As previously discussed, the subsurface offers many functions and services to accommodate urban expansion. Volchko et al. (2020) discussed the lack of available information on subsurface use in international policy and legislation, which highlights the novelty of subsurface space management as an extensive opportunity. On a national scale, use of the subsurface has been poorly managed in the UK and followed the 'first come first served' rule in most circumstances.

Planning policy and urban design guidance must be satisfied to proceed with most developments in the UK. This system can therefore act as a pathway to delivering knowledge of subsurface space as a resource and dictate actions that should be taken in order to maximise urban sustainability from it and use it in a sustainable way. Planning policy and legislation regulates some subsurface uses, however management of underground space is a complex issue, particularly in the context of planning permission. Planning consent is only required where proposed works fall under the definition of development. Under the Town and Country Planning Act (1990) the definition of development included the "carrying out of building, engineering, mining or other operations in, on, over or under land". The inclusion of 'under land' acknowledged the subsurface for construction space, and indicated that subsurface construction should be regulated by local planning laws.

As Canary Wharf Crossrail Station fulfils a larger transport function (to ease increasing pressure on the London Underground network), its creation was subjected to compliance with many planning policies and guidance documents across multiple scales. This driver is not present for more routine underground development such as basements.

Canary Wharf Crossrail Station is in the City of London, the Borough of Tower Hamlets, and the Canary Wharf ward. Policies and guidelines prepared across these scales were adhered to when the Canary Wharf Crossrail Station was initially planned. A planning policy assessment compiled in 2005 addressed the route wide planning considerations as well as the Tower Hamlets route section for compliance with local and wider agendas (Crossrail Ltd, 2005a). In the following section, this assessment as well as national policies, guidance documents and wider sustainability and resilience strategies were examined for themes surrounding subsurface space utilisation and its management, as well as any established connections with urban sustainability and resilience agendas. The key messages relevant to subsurface space within these documents are presented in Table 6.4, as well as the cross-cutting matters which are discussed in greater detail below. These are:

- Omission of Subsurface Space
- Efficiency of Use
- Governance and Planning
- Sustainable Management or Mismanagement

Case Study 3 – Canary Wharf Crossrail Station		
Level	**Document**	**Key Message/Impact Relevant to Case Study**
International	Sustainable Development Goals (SDGs)	Goal 12 to "ensure sustainable consumption and production patterns….by 2030, [and] achieve the **sustainable management** and **efficient use of natural resources**" (United Nations, 2015a). - **no direct discussion** of subsurface space.
International	Rio Declaration on Environment and Development (1992)	Agenda 21 – **sustainable consumption and efficient use** of natural resources – **no direct mention** of subsurface space
National	National Planning Policy Framework (NPPF)	Subsurface uses discussed under oil, gas and coal exploration and extraction – **no discussion of subsurface space.**
National	New Roads and Street Works Act 1991 (Section 79) and the Streets Works (Records) (England) Regulations 2002	Recording presence of subsurface assets is mandatory – implies **first come first served basis** to subsurface use.
National	The Route Wide Planning Policy Assessment (Crossrail Ltd, 2005b)	**No direct mention of managing subsurface use**, but implied in some circumstances relevant to the identified planning policies.

National	Town and Country Planning General Development Order 1988	**Safeguarded subsurface routes reserved through planning** for future expansion
Regional	London East-West Study	Alignment issues where existing structures obstruct intended route - implies subsurface space **mismanagement**
Regional	Crossrail's Sustainability Strategy (CSS) (2009)	Promotes the **prudent use of natural resources** and protecting the environment as well as general sustainability principles. - **no direct discussion** of subsurface space.
Regional	Crossrail Annual Sustainability Reports (and summary) (2012 – 2018)	Mentions **avoiding existing subsurface infrastructure** in Crossrail project, and creating **bespoke sustainability assessment for Crossrail. Developed specialist training programme** which incorporates geology.
Regional	The London Plan (2004)	Subsurface space **not discussed** from resource perspective.
Local	Tower Hamlets Route Section Assessment (2005)	Station design **minimises amount of space used** within docks.
Local	Tower Hamlets Environmental Strategy (2005)	Subsurface space relates to **use of allocated underground parking** due to surface congestion - **no general discussion** of resource
National	BREEAM (Bespoke)	Customised for Crossrail stations - **no mention of subsurface space management**, only underground water storage measures.
National	CEEQUAL	Customised for Crossrail tunnels, ports and shafts - **no mention** of subsurface space as a resource or management
Grey = omission of subsurface space, **Blue=efficiency of use**, **Green = governance and planning**, **Pink = sustainable management/ mismanagement**		

Table 6.4 – Key planning policy, urban design guidance and sustainability and assessment documents impacting the Canary Wharf Crossrail Station retrofit with their content related to ground heat summarised and categorised into themes.

6.5.2 Omission of Subsurface Space

Throughout the document examination, the most pervasive finding within urban guidance and policy was that at all scales relevant to the Canary Wharf Crossrail Station there was a general lack of discussion of subsurface space as a resource.

Even from an international perspective, Von der Tann et al. (2018) explored the presence of subsurface space utilisation across international policies and found that there were no specific guidelines for subsurface construction. On the international agenda the subsurface was mainly included within environmental European Union (EU) Directives, such as global strategies relevant to the protection of water, wastewater treatment or the disposal of excavated materials. There was a distinct lack of international guidance for subsurface space construction and management, possibly due to the knowledge gap between urban stakeholders, and their understanding of the range of functions that the subsurface can fulfil. In addition, urban planning systems are different across the world, and policies are based on the individual needs on a place by place basis.

The subsurface was not generally referred to in international urban sustainable development documents unless it was considered under the heading of natural resources. For example, the Sustainable Development Goals (SDGs) made reference to natural resources and their conservation under goals 1, 5 and 12. The most applicable to subsurface development space was goal 12 to “ensure sustainable consumption and production patterns….[and] by 2030, achieve the sustainable management and efficient use of natural resources” (United Nations, 2015a, p.24). However, Figure 2.3 (section 2.4) suggests that subsurface space could contribute to more SDG’s than they propose. In fact, seven of the 17 SDG’s may benefit from subsurface space utilisation if considered more thoroughly (Admiraal and Cornaro 2016). This is significantly more than the three goals that currently include natural resources for global sustainability.

Von der Tann et al. (2018) highlighted national level planning policies that are relevant to subsurface space utilisation, such as guidance on: environmental impact assessments, waste disposal and flood risk. These documents are transferred into wider regulations in force across England, and subsurface space utilisation can often get absorbed as a minor factor to consider in a wider scheme. Alternatively, the underground may only be referenced where it is applicable to the context (for example basement development planning is only enforced in London in the UK) and therefore is not considered within the different aspects of subsurface space utilisation holistically.

Furthermore, as the governments updated national guidance for planning policy, the 2019 National Planning Policy Framework (NPPF) should contain the advice required to control subsurface development and planning policy where it arises. However, the primary mention of subterranean utilisation is under 'oil, gas and coal exploration and extraction', where minerals planning authorities encourage underground gas and carbon storage where possible whilst maintaining safety precautions for underground storage facilities (Ministry of Housing, Communities and Local Government, 2019). In this the subsurface is only referred to where directly relevant to planning issues. However, from an urban design perspective, there are numerous criteria identified within the NPPF that subsurface space utilisation could contribute towards. For example, utilising subsurface space would "optimise the potential of the site to accommodate and sustain an appropriate amount and mix of development" (ibid, p.38). Furthermore, the NPPF looks favourably upon the remediation of contaminated land and the reduction of flood risk, both of which could be supported by subsurface space utilisation. Recognition could be given to subsurface space potential to address these criteria.

The route-wide planning policy assessment (Crossrail Ltd, 2005b) illustrated the planning policy framework influencing the Crossrail development plan. Below the national planning policy guidance's and planning policy statements, the report identified the structure of planning at regional and local levels within London, as reproduced in Figure 6.4.

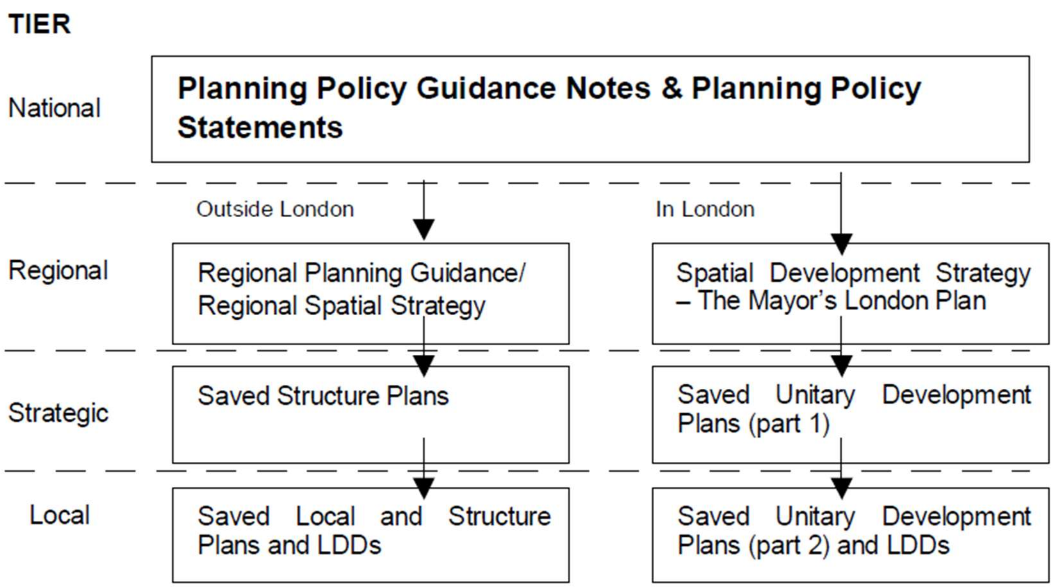


Figure 6.4 – Planning system for London during Crossrail's route-wide planning policy assessment (Crossrail Ltd, 2005, p.2.)

Prior to the NPPF, the Route Wide Planning Policy Assessment (Crossrail Ltd, 2005b) stated that Planning Policy Guidance notes (PPG's) and Planning Policy Statements (PPS's) must be considered in regional and local level planning documents. The report focused on identifying where the Crossrail project aligned with or juxtaposed national planning policy. As previously stated, there is no national planning policy for the development of subsurface space, and therefore this article was assessed on the inclusion of subsurface space within relevant planning policies for Crossrail. The report summarised all PPS's and PPG's viewed as relevant to Crossrail at the time of its design which included the following policies with descending relevance to Crossrail (according to Crossrail Ltd, 2005b) : PPS1 (Delivering Sustainable Development), PPG13 (Transport), PPG15 (Historic Environment), PPS7 (Sustainable Development in Rural Areas), PPG2 (Greenbelts), PPG17 (Other Protected Open Space), PPG25 (Development and Flood Risk), PPG9 (Biodiversity and Geological Conservation), PPG16 (Archaeology), PPG10 (Waste Management), PPS23 (Pollution Control), PPG24 (Noise) and PPG6 (Town Centres). The Planning Policy Assessment (Crossrail Ltd, 2005b) did not include the utilisation of underground space within any of these PPS's or PPG's for enhanced sustainability or resilience for the Crossrail project, though the importance of the subsurface is implicit for many of these.

At the time of the policy appraisal for the Crossrail development, regional planning was in place in the UK, however the 2004 London Plan (Greater London Authority, 2004) provided the regional planning guidance at the time of Crossrail's policy assessment. Given the generalised context of Crossrail within the 2004 London Plan there were no specifics for underground space use, although it was noted under Policy 4C.9 that rising groundwater levels were causing issues for some of London's underground transport network, services and building foundations (Greater London Authority, 2004). The reference to subsurface assets and the threat of rising groundwater demonstrated the established connection between tackling geo-hazards and urban sustainability via planning guidance. The 2004 London Plan did not discuss subsurface space as a geo-resource outside of the context of improving the Underground network.

In addition, at a local level the Tower Hamlets route section report (as part of the planning policy assessment) confirmed that the "statutory development plan comprises the saved Tower Hamlets Unitary Development Plan [UDP] (adopted December 1998) and the London Plan (adopted February 2004)" (Crossrail Ltd, 2005a, p.3) were key documents used in aligning the Crossrail Development with district level policy. The route section report further confirmed that despite knowledge of a future version, the saved UDP had greater influence on Borough-level planning policies than the draft version of the UDP that was available at the time of Crossrail's policy review. The UDP was unavailable at the time however considering the lack of subsurface space commentary within similar documents, it was reasonable to assume that the UDP did not include any significant guidance on the utilisation of subsurface space.

At a site-specific level, there was no policy or guidance that influenced the utilisation of subsurface space for the Canary Wharf Crossrail Station, however the Canary Wharf Group (CWG) (which are independent to Crossrail but are a partner in the project), had its own sustainability report which promoted the sustainability features of Crossrail Place but overlooked its underground aspect. Although this may in part have been due to the delay in the opening of the line, it further demonstrates that subsurface space is forgotten as a valuable commodity which otherwise could contribute to the sustainability and resilience of the Canary Wharf area to a wider degree. Furthermore, the Canary Wharf Crossrail Station could have theoretically utilised underground space to a greater extent via several avenues. For example, the inclusion of underground parking or underground passages to connect subsurface spaces, or the use of the underground as flood water storage space.

However, it is arguable that at this scale, developing policy or guidance for subsurface space utilisation may have limited influence on its uptake due to the developed status of the Tower Hamlets area already. However, demonstration of subsurface space utilisation (such as the Canary Wharf Crossrail Station) would showcase the potential benefits that replication of the design may bring.

6.5.2.1 Building Research Establishment Environmental Assessment Method (Bespoke)

Crossrail uses two environmental sustainability assessments to evaluate the sustainability performance of Crossrail's infrastructure; these are the Civil Engineering Environmental Quality (CEEQUAL) and the Building Research Establishment Environmental Assessment Methodology (BREEAM).

BREEAM is an environmental certification scheme that is conducted on non-residential structures and is being undertaken for the majority of the Crossrail stations in central London. It requires sustainable urban design to be implemented (across different environmental aspects) in order to achieve set standards for certification. Crossrail is unique in design and therefore the BREEAM assessment was customised (using BREEAM Bespoke

2008 and specifically chosen BREEAM assessment criteria) to assess Crossrail's underground stations (Silva, 2018).

Due to the complexities between stakeholders of the Canary Wharf Crossrail Station development, it was decided that the custom-built BREEAM assessment would not be conducted for the station. However, a tailored criteria report (Building Research Establishment Ltd, 2009) detailing the BREEAM assessment criteria for the underground Crossrail stations confirmed that the assessment was originally intended for the station (referred to as the Isle of Dogs station). Furthermore, given the underground nature of other Crossrail stations it is important to discuss the inclusion of subsurface space within the bespoke BREEAM package.

The BREEAM Bespoke 2008 manual (Building Research Establishment Ltd, 2008) did not include any specific mention of the management of subsurface space to achieve credits. The only mention of subsurface use occurred in relation to underground storage for surface water run-off and irrigation systems, not in relation to subsurface space construction or management. This was also the case for the BREEAM Technical Manual (Building Research Establishment Ltd, 2014).

The tailored criteria report addressed issues under: management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology and pollution which were specifically relevant to the underground stations for Crossrail. In many cases, the criteria stated that there was no adaptation from the BREEAM Bespoke 2008 scheme for assessing underground space utilisation although there were isolated exceptions to this (Building Research Establishment Ltd, 2008).

6.5.2.2 Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL)

CEEQUAL is used to measure the sustainability performance of civil engineering projects. For Crossrail this included tunnels, portals and shafts (Silva and Paris, 2015) but not stations. However, considering that this study explores the potential utilisation of subsurface space in an inclusive perspective, the presence of subsurface space within the CEEQUAL manual (which was used for two other central London Crossrail stations) was explored. Version 4 of CEEQUAL was used to assess Whitechapel and Liverpool Street station tunnels during their construction, and in 2017 the project was awarded an 'Excellent' (92.5%) rating in line with CEEQUALs certification criteria (Building Research Establishment Ltd, 2020).

There were two categories that may at first glance be associated with the use of subsurface space (land use or material use) (CEEQUAL Ltd, 2010), however upon inspection, neither contained indicators which regard subsurface space as a resource to be managed.

Across all scales of governance and through urban design guidance, planning policy and sustainability assessment procedures, there is a general lack of inclusion of subsurface space utilisation within documentation. This is limiting the potential value that subsurface space development can bring to urban sustainability and resilience agendas.

6.5.3 Efficiency of Use

Subsurface construction makes good use of a finite resource, and if this resource was considered under the broad heading of natural resources, it could be argued that it was present in international agendas. For example, Agenda 21 of the Rio Declaration on Environment and Development (1992) (a sustainable development plan actioned by the United Nations) frequently mentioned the use of natural resources in relation to creating sustainable growth. With the aim of changing unsustainable consumption, it stated that "special attention should be paid to the demand for natural resources generated by unsustainable consumption and to the efficient use of those resources consistent with the goal of minimizing depletion…" (Rio Declaration on Environment and Development, 1992, p.18). However, considering subsurface space to be included under natural resources is risky as it is unlikely to include any precise guidance on how to achieve the most effective utilisation of subsurface space, or why it is a valuable commodity.

More directly relevant to the case study, Crossrail's Sustainability Strategy (CSS) (2013) set out the site wide objectives for achieving sustainability. The strategy stated that one of the three components of sustainability is "using natural resources prudently, whilst protecting and if possible enhancing the environment" (Crossrail Ltd, 2013, p.4). There was no specific reference to the use of subsurface space within the document, however it presented a summary diagram of crosscutting sustainability themes from relevant sustainability documents (see Figure 6.5).

Figure 6.5 demonstrates the breadth of influence that subsurface space utilisation could have when considered in a multitude of contexts. These high-level guidance documents set the overarching aims and general context to sustainable development for London and refer to the environment (or natural resources) as key components for building sustainable urban infrastructure.

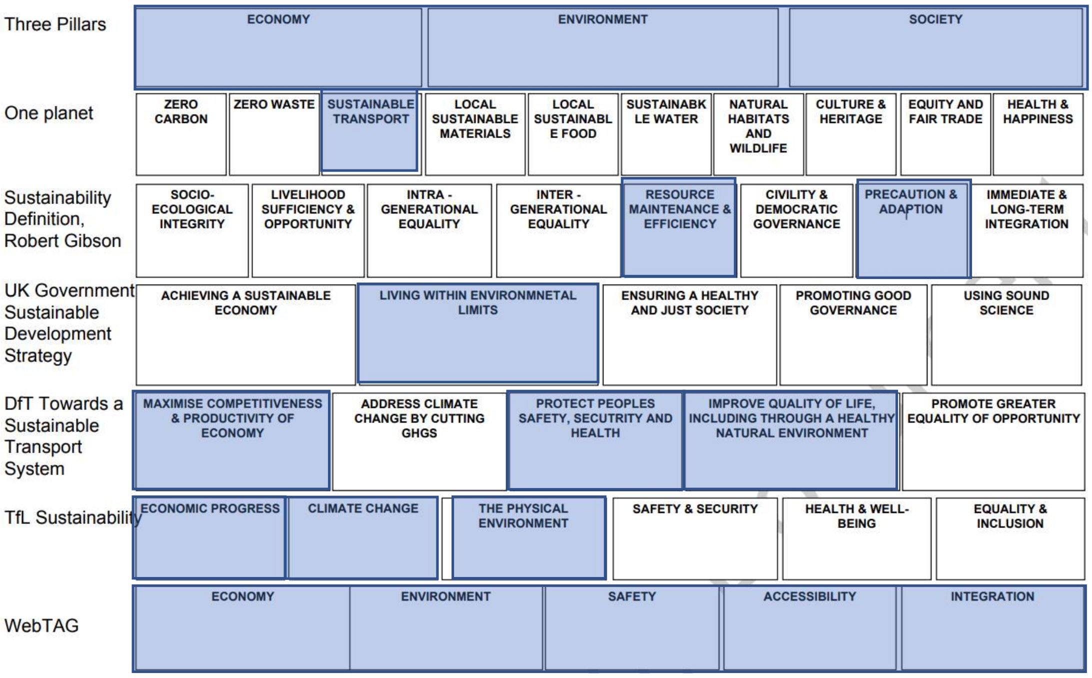


Figure 6.5 – Summary of various divisions of sustainability. Subsurface space utilisation may impact categories highlighted in blue (Amended from Crossrail Ltd, 2013, p.5).

Although the efficient use of subsurface space is an underlying objective where subsurface development is undertaken, it is not often clearly stated beyond broader statements which encourage the prudent use of natural resources.

6.5.4 Governance and Planning

For the other geo-resources explored in this study (groundwater and ground heat), many international discourses relating to geo-resource use for sustainability demonstrated broad applications and adoption into national and local policy. For the Canary Wharf Crossrail Station case study this was not evident, and the lack of international guidance for subsurface space utilisation may in part be due to the contextual nature of subsurface development. Although guides or agreed methods of assessment might be useful for broad direction without enforcement, policies and guidance documents are often designed for specific conditions and therefore it is challenging for international groups to impose regulations that are applicable to many circumstances. Furthermore, any policies would be based on the existing amount of subsurface utilisation and type of management strategies in place globally (which is wholly inconsistent).

In the UK, one of the earliest considerations of subsurface space (as a resource) was that it was a by-product of the extraction of materials and minerals in underground mining (Price et al., 2011). Some of these mines may have been repurposed but many have also been backfilled or flooded due to the end of dewatering activities which allowed mining processes to occur below the water table. Despite long term use of the subsurface in the UK, there is no national guidance or policy in place to manage it. There are exceptions to this in some circumstances, for example there are regulations that require companies to record and report the positions of underground assets. The New Roads and Street Works Act 1991 (Section 79) and the Streets Works (Records) (England) Regulations 2002 are two such regulations that do this (Future Cities Catapult et al., 2017b).

Large infrastructure schemes such as Crossrail manage aspects of subsurface development through specific Acts of Parliament (*Crossrail Act*, 2008) and its comprising Bill documents. Canary Wharf Crossrail Station was incorporated into the *Crossrail Act* 2008 holistically. Subsurface space use was not specifically discussed from a resources perspective although the overall venture including its subsurface aspects were managed through this policy.

Although some attention was paid to governing the use of subsurface space for Canary Wharf Crossrail Station on a broad scale, there was scope to better include subsurface space from a governance and planning perspective.

6.5.5 Sustainable Management or Mismanagement

On a national scale, despite regulations such as the New Roads and Street Works Act 1991 (Section 79) and the Streets Works (Records) (England) Regulations 2002, the lack of a central mapping scheme means that work is required to locate and evaluate existing subsurface structures in order to coordinate and manage buried assets and infrastructure for the future. The UK government recognised this and designed a national underground asset register to record the location of all subsurface pipes and cables, starting with London (Greater London Authority, 2020) and the North East of England. Projects such as 'Mapping the Underworld' and 'Assessing the Underworld' also worked towards developing detectors that can accurately record information on subsurface assets without physically breaking ground (UK Research and Innovation, 2019). This demonstrates some action towards the management of subsurface space.

Furthermore, there are organisations and research groups that have formed with the aim of bridging the general knowledge gap between the subsurface space, its utilisation and urban stakeholder groups. UK-based groups include ThinkDeepUK and Project Iceberg, which comprise multiple research organisations and urban stakeholder representatives collaborating for the optimisation of subsurface space use and its management.

In central London, subsurface space was a crucial element of Crossrail's development and was recognised as such in the London East-West Study (Shadow Strategic Rail Authority, 2000). This report disclosed possible alignment issues which may have occurred due to existing underground infrastructure (such as building foundations and other tunnels). However, the report confirmed safeguarded routes which offered a solution for Crossrail to navigate London's congested subsurface (Shadow Strategic Rail Authority, 2000). These safeguarded routes were secured in 1990 under articles 14(1) and 18(3) of the Town and Country Planning General Development Order 1988 (Department for Transport, 2008), which demonstrates an awareness of subsurface congestion that is not frequently addressed in policy. However, the existence of safeguarded routes is evidence of some subsurface planning in the UK, despite the need for more detailed guidance for a real contribution to urban sustainability.

The Borough of Tower Hamlets did not have specific guidance for subsurface space development, however its Environmental Strategy did mention the use of allocated underground parking to reduce the effect that private vehicles are having on the environment (Tower Hamlets Council, 2007). Unfortunately, the Environmental Strategy Action Plan (2007-2010) was not consistent with this as it did not include any reference to underground car parking facilities or subsurface space utilisation.

Specific to the development, sustainability was integral to many aspects of Crossrail since its inception, although the understanding and application of sustainability has evolved over time. The sustainability strategy reviewed in 2013 demonstrated an awareness of the three pillars of sustainability: social justice, stable economic development and environmental and resource protection (and enhancement) (Crossrail Ltd, 2013). The sustainability objectives of Crossrail were determined by fourteen 'critical success factors' which were: clarity of vision, identification of all activity, performance management, alignment, prioritisation of sustainability activity, awareness and engagement, working in effective strategic partnerships, stakeholders, clarity of organisation, budget, integrated portfolio approach, timely decision making, integration with programme processes and innovation (Crossrail Ltd, 2013).

Crossrail produced annual sustainability reports between 2012 and 2017 and a sustainability summary in 2018. The first report highlighted the challenges of subsurface construction, particularly the need to avoid existing underground infrastructure to depths up to 40m below ground level (Crossrail Ltd, 2012b). This went some way towards acknowledging the need to manage subsurface space. Furthermore, the report acknowledged the absence of performance criteria for underground stations in environmental assessments and confirmed that Crossrail addressed this issue by developing the previously discussed bespoke environmental assessment with the Building Research Establishment (BRE). In addition to this, and in recognition of the growing use of subsurface space in London, the Tunnelling and Underground Construction Academy (TUCA) (which delivers specialist training in underground construction) was developed in line with Crossrail's sustainability agenda. One aspect of their curriculum included an introduction to geology and ground risks, which acknowledged the role that geo-science plays in times of increasing subsurface space utilisation. These themes continue through the annual reports, highlighting the design characteristics utilised in underground spaces to create "accessible, safe and comfortable spaces" (Crossrail Ltd, 2018b, p.15).

In addition, the previously mentioned Tower Hamlets route section assessment (Crossrail Ltd, 2005a) which formed part of the wider route appraisal, discussed the impact of the Canary Wharf station (referred to as the Isle of Dogs Station Worksite) specifically in the context of the Borough. The subsurface-space aspect of the station was designed to minimise the amount of space removed from the docks whilst meeting other design criteria for the station (Crossrail Ltd, 2005a). This demonstrates an aspect of subsurface space management as a side-effect of controlling the impact that the development had on the Docks. Besides this comment, the report did not deeply examine subsurface use of the new station other than the impact that it would have on the pre-existing underground transport network. Indirectly the implication is that by utilising subsurface space at the Canary Wharf Crossrail site, the existing subsurface transport network will have greater resilience and sustainability for the future due to the increased capacity absorbed by the Elizabeth Line.

6.5.6 Document Examination Section Summary

The Canary Wharf Crossrail Station is a unique project for utilisation of subsurface space due to its size, location and regional significance. However, even for a development of this magnitude there is a distinct lack of guidance and policy governing the use of subsurface space. From international guidance, through planning policy and sustainability assessment procedures, the omission of subsurface space and its management has been exhibited by this case study. This issue exasperates the problems that already exist for subsurface space use, such as the hazards associated with unknown pre-existing structures, and the conflicts that can occur when the subsurface may need to be used for the utilisation of another geo-resource. Governing subsurface space utilisation through planning policy at multiple scales would facilitate improved utilisation for urban sustainably and resilience. It is imperative that subsurface space is urgently addressed within urban documentation to lessen the problems that may arise when urban expansion is inevitably forced underground.

Furthermore, the impact of inefficiently using subsurface space is not widely considered, and unless action is taken to showcase the value of subsurface space use (and management of it), effective use may be more isolated and bespoke than widespread and holistic.

There has been some management of subsurface space, although more as a reactive response than with a proactive agenda. Safeguarding subsurface space for a transport network was a starting point for optimising its use as a geo-resource. Furthermore, the initiatives observed to retrospectively record underground assets are improving the opportunities for subsurface space use in the future. The greater the investment is in managing subsurface space now, the greater the impact will be for maximising sustainability and resilience in new and expanding urban settings.

6.6 Canary Wharf Crossrail Station Case Study Conclusion

Despite the delay in the opening of the underground Crossrail station at Canary Wharf, it is evident from Crossrail's sustainability reporting that the utilisation of subsurface space was successful for the development. Once fully functional, the increased capacity of the transport network provided by the Elizabeth Line will result in improved resilience of London's transport network regionally, and increased sustainability for the city.

The subsurface space potential mapping tool classified the site as 'moderate' for subsurface space utilisation. The map demonstrated that geologically speaking, the subsurface at Canary Wharf may be suitable for utilisation, although some of the ground conditions may present challenges for the use of subsurface space. There was some discrepancy with the information used to validate the map, however this was found to be outdated and unsuitable for assessing the accuracy of the map. The corresponding UDG matrix demonstrated that some of the goals from planning policy and urban design guidance (such as supporting the efficient use of resources) can be met by the effective use of subsurface space, or vice versa (as different types of subsurface use can achieve different urban agendas).

The interviews suggested that the economic returns over the project life cycle and achieving cost-effective design solutions were the primary enablers for the development. The drivers for the development were to alleviate the stress on the existing transport system for London whilst providing future-proof infrastructure and meeting government targets (such as carbon reduction). Furthermore, underground development was considered a necessity to avoid existing infrastructure and the dense urban fabric at ground level. Ultimately the high capital costs were identified as the greatest barrier to subsurface space utilisation, as well as subsurface obstacles and lack of communication between groups. Ultimately, the benefits gained from the Canary Wharf Crossrail Station outweigh the difficulties of utilising subsurface space. This is in part due to the high end-use value that the Elizabeth Line will bring to London's transport network.

The management of subsurface space as a resource was not considered within policy beyond the initial safeguarding of the route. The main purpose behind the subsurface space utilisation was one of necessity - the station platform needed to attain a certain depth to align with the connecting tunnels on the Elizabeth Line. The space overlying the platform (termed the over station development) was optimised to create flexible retail and service space which can adapt to accommodate the future needs of Canary Wharf Station.

Despite the successful use of the subsurface space for the development, the document examination showed that there is significant opportunity for the subsurface to be managed by policy (both locally and regionally) in order to maximise its potential for future use, and harmonise it with the urban design features of the surrounding region. This would bring the benefit of increasing the awareness of subsurface assets for future investors, and provide information about the opportunities and potential risks that may occur on a granular scale. Furthermore, optimising the use of subsurface space would make urban centres less vulnerable to the threats associated with ongoing urban expansion.

The next chapter compares the geo-resource case studies presented in Chapters 4, 5 and 6, and evaluates the findings and implications of geo-resource use for enhancing urban sustainability.

7 - Case Study Comparisons and Implications

Three case studies with urban design aspects that utilise geo-resources were closely examined in chapters 4, 5 and 6 to explore their role in building urban sustainability and resilience. The case studies were assessed using a mixed methods approach, by applying a two-part geo-resources potential mapping tool, conducting stakeholder interviews and examining urban guidance, planning policy and sustainability and resilience assessment documents. This chapter comparatively analyses the case study findings and considers potential areas of further work.

7.1 Evaluation of Geo-Resource Potential Mapping Tools

The prototype geo-resource potential mapping tool was implemented on all three case studies as a proof of concept model. The two distinct components of the tool: a geospatial map assessment and the Urban Design Geo-resource (UDG) matrix are evaluated in turn.

The map output provides early stage advice on the suitability of geo-resource use based on the sites ground conditions. The process considers whether geospatial data sources are sufficient to provide evidence in support of geo-resource use.

Across the three case studies, the geo-resources potential maps were validated by isolating each factor that contributes to the mapping result (for example, for Chestnut and Aspen Mews in chapter 5, made ground in the north eastern corner of the site contributed towards the poor utilisation potential for the area) and finding external information to verify the accuracy of each factor. In most cases, the external information was found to support the data behind the geo-resource potential use, and where information contradicted the result, the limitations of the data, tool and/or external information was found accountable. For example, the map suggested excellent groundwater potential at NW Cambridge with the data suggesting a potentially productive (>6l/s) principal aquifer present at outcrop. However, with added geological information the chalk aquifer was found to have a limited extent and thickness that was not sufficient to support large groundwater supplies. The validation process for the map outputs was undertaken for all data incorporated into the maps and was consistently performed across each case study.

As previously discussed (and chosen for its simplicity), heat maps depicted the potential suitability of geo-resource use on site from excellent (green) to very poor (red). The associated text in the respective chapters then described the factors that contributed to the mapping result. Based on the results from the maps, the associated commentary could be interpreted as advisory notes for the conditions impacting geo-resource utilisation on site. The map can also be used in conjunction with desk-study site assessments, to provide a visual representation of geo-resource potential alongside more detailed information that aligns with some map commentary. For example, at Canary Wharf Crossrail Station, made ground was recorded across two thirds of the site, there were shallow groundwater levels anticipated, the ground was generally unsuitable for most foundations, there was some potential to re-use materials, and excavations could be undertaken using hand tools. This simple presentation of information is suitable for all urban stakeholder parties and could be used to facilitate cross-sectorial discussions of geo-resource utilisation at the involved project site.

The Deep City Method (an alternative subsurface resources model discussed in Chapter 2) shares a similar approach of sourcing and compiling data into a geographical information system, and evaluating sub-surface geo-resources by calculating resource potentials that can be presented spatially. However, the geo-resource potential mapping tool produced as part of this research furthers this shared approach by integrating urban design guidance via the UDG matrix (Appendix I).

The UDG matrix connects the geo-resource potential result with site-specific planning policy and urban design guidance (Figure 7.1). It allows users to create urban designs that fulfil a desired policy or demonstrates which policies can be fulfilled from urban designs utilising geo-resources (Figure 7.2). The simple matrix design allows the user to clearly understand the relationship between geo-resource use and planning policy/urban design criteria.

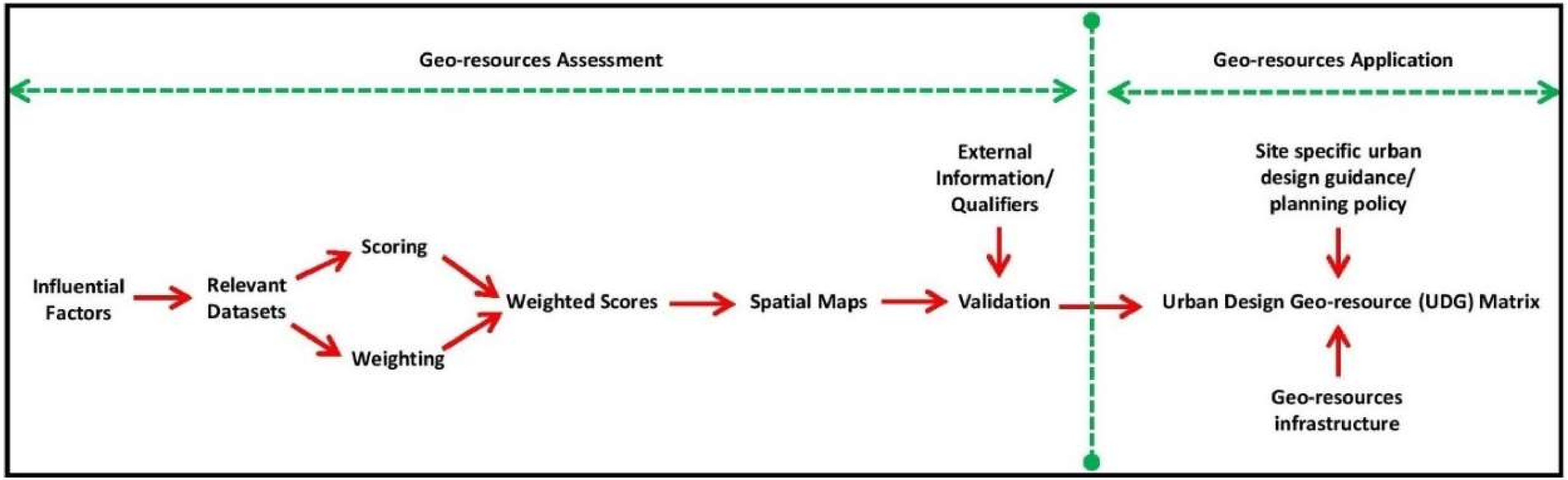


Figure 7.1 – Flow diagram summarising the method of creating the geo-resource potential mapping tool – producing the maps and applying to the Urban Design Geo-resource (UDG) matrix.

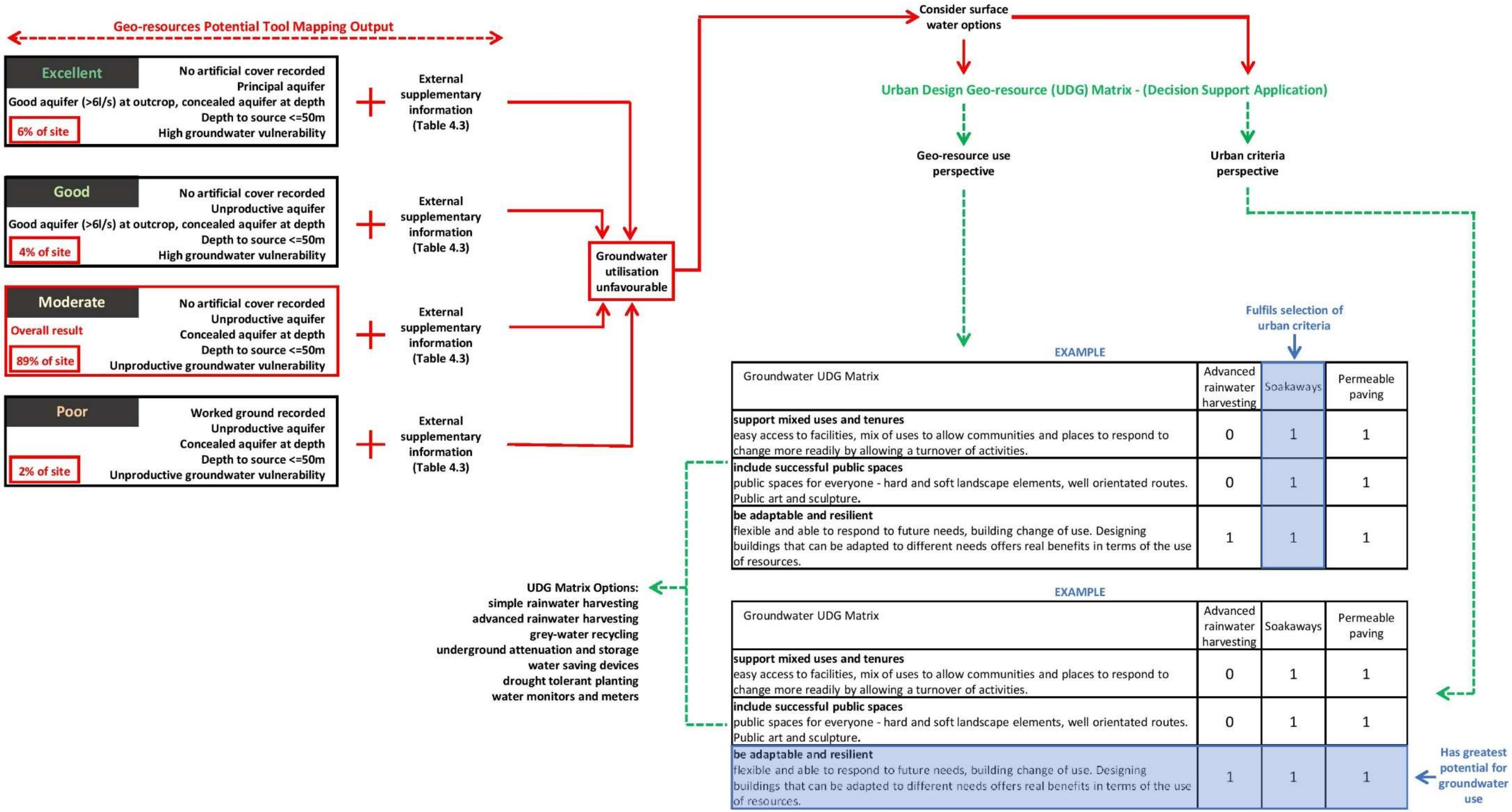


Figure 7.2 – Flow diagram summarising the method of applying the geo-resource map output to the Urban Design Geo-resource (UDG) matrix using an extract of the UDG matrix for groundwater as an example.

7.1.1 Application

This technique has been developed as a starting point to engage urban stakeholders with the ground as a resource. The tools offer early-stage site-specific information on geo-resources in locations where urban stakeholders have a pre-existing interest. Furthermore, the tool is a mechanism for delivering information on geo-resources to planners, developers and engineers, breaking down the barriers between sectorial siloes.

This tool was designed for use prior to intrusive ground investigations, and ideally prior to the project design phase. Therefore, it was useful to place the tool within the context of an overall design process such as described in the Royal Institute of British Architects (RIBA) which is a recognised management scheme across the development industry. This scheme divides any building project into distinct phases and allows different urban stakeholders to define the extent of their role in the overall scope of a project (Figure 7.3). In the latest RIBA Plan of Work (2020) the mapping tool outputs would be produced at Stage 1 (Preparation and Briefing) alongside the feasibility studies and site information reporting. The outputs can then be considered in Stage 2 (Concept Design) (which addresses the outline specification and cost plan), as well as the later stages of the project to aid in decision making regarding sustainable urban design opportunities.

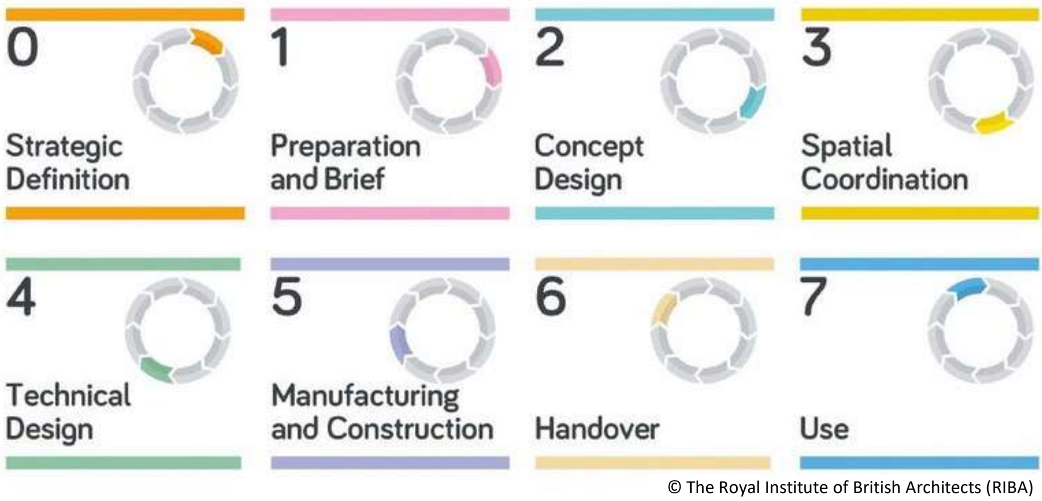


Figure 7.3 – Stages of RIBA Plan of Work 2020 (RIBA, no date, cited in Sinclair, 2019).

Collaboration between urban development stakeholders (for example architects, engineers, environmental consultants, planners, etc) whilst reviewing the outputs of this tool would enhance its usefulness.

Having developed the geo-resources potential tool prior to conducting stakeholder interviews and the document examination, a retrospective critique of the geo-resources potential tool was undertaken based on the knowledge gained from the latter techniques.

During stakeholder interviews, participants were asked to consider the value of a tool which assesses the usability of sites from a geo-resources perspective. The discussions that followed considered the usability of the tool, drivers for using it, functionality, as well as target audience (Table 7.1).

Stakeholder Expertise	Commentary
Developer	*"**On larger sites where you have opportunities with groundwater or levelling or ground conditions, it may be useful** but on smaller sites you sort of know the opportunities anyway within the confines of what we normally do."*
Engineer	*"A lot of the time **people focus on constraints**, and come up with a constraint map, but they **don't really convert that into opportunities** or do an opportunities map to go alongside that. Or sometimes wrongly call things constraints when they could be opportunities. Sometimes **it's about changing people's mindsets to think about opportunities** particularly things like geo-resources."*
Hydrogeology	*"Yes, but it depends how it would be deployed. **It would have to be usable and available to a client and not just rehashed by a consultant**. It's easy for a consultant with that knowledge base already there to whip through it and give a result. But it would **have to be available for a client-level person to understand**. Maybe I'm just wary of just having it available to a consultant because they could restrict a knowledge transfer through their fees. It could be **available to a developer as a screening tool**. I think it would be good because you could pull together quite a lot of sources to get a start to finish assessment. Geological records for the UK are excellent, and it's all largely public domain or cheap to access. I think **the big thing is who you would make it available too**. It's so easy for consultants to add fees on for running a tool and writing a report on what it says."*

Hydrogeology	*"It certainly would be useful but I don't know as there are a number of tools that do this not in a great way. For example what sort of SuDs are appropriate.* ***<u>These tools can never quantify thew financial metric</u>*** *and that's a driver that if you can establish would make the tool far more powerful to people. At the moment UK SuDs tools work by saying 'oh wouldn't this be lovely' without considering how much it is going to cost. A tool like this would be useful if we can get it done and developed right. But again, everything needs to come with a health warning,* ***<u>there is no one size fits all for these things</u>****…* *My nervousness would be you don't want it to be another online tool or spreadsheet that doesn't go far enough.* ***<u>The financial aspect of a tool would be key."</u>***
Hydrogeology	*"Yes, I think it's something that could help people understand what resources are available to them. I think the only caveat is that in some patch's* ***<u>groundwater resources are stressed and are not available for consumption, so that sort of thing would need to be part of it</u>****. Also,* ***<u>it could encourage things like air or ground source heat pumps</u>*** *if buildings were suitable for that."*
Planning	*"It* ***<u>depends who would use the tool</u>****. To be perfectly honest, the thing that motivates most developers is the bottom line, so* ***<u>if that tool is going to show developers that they can get more money out of the site then they will listen</u>****. But if it is something that is to be used by the development management team, and it will put* ***<u>more burden on developers then they will try and get around it</u>****.* *You also must* ***<u>make sure that development management teams are aware of it</u>****, to encourage developers, which means* ***<u>educating the decision makers</u>*** *at senior and junior level. You need to* ***<u>find champions of it</u>****, you must make it interesting.* *A tool I had experience with previously, developed by a tutor was so numeric and difficult to comprehend in that the creativity had gone from it, and I'm not sure how successful it will be. You have to* ***<u>think about the audience</u>*** *to make it interesting and easy to use. If a landowner can see that they can get more money out of their site for it, they will be all ears."*

Sustainability	*"Yes broadly, but ideally **it would be more valuable if it was part of planning conditions**. Water is a common resource, so if such as tool was available for the authorities it would be much more powerful so that **developers could be assessed on their impact or contribution**. **It is isn't enforced people won't care**, but if it was a planning condition people would have to think."*
Water	*"Yes this would be hugely beneficial. **The problems that we have now wouldn't have come together in the first place if we had a system like that** in the first place…[For example an] aquifer. If we had not of built an industry which produces contaminants on top, then the aquifer could have been a resources for thousands of people, but as it is, it is not, because nobody joined the dots. Some resources however can be utilised together by luck…"*
Water and Environmental	*"…most developers are asking how they can maximise profit. **How can I comply with the planning constraints** imposed here? How can I reduce the community infrastructure charges and other charges applied to my development? Flagship developers who want to do everything might go to it, and all of the others might ask '**is it going to save me money**? Can I use this resource to offset costs and charges?'… 'why should I do that if it's going to cost me money, how can I maximise my profits?'.*

Table 7.1 – Verbatim interview commentary when participants were asked about the value of a tool which assesses the usability of sites from a geo-resources' perspective. Key findings bolded and underlined.

As noted in Table 7.1, some specialist interviewees were enthusiastic about the geo-resource potential tool, affirming that it would be beneficial to the industry. Some suggested that it would be particularly useful on large sites, and that such a tool would offer an insight into geo-resource opportunities over the duration of a project. It could also work as an educational tool, to inform urban stakeholders of geo-resource prospects and demonstrate that there is no ubiquitous approach to harnessing geo-resource potential.

However, other stakeholders instead considered geo-resources potential tools more cautiously. One stakeholder representative said that a geo-resource potential tool would only be useful on larger sites (as smaller sites have limited geo-resources which are usually known about from the outset of a project). Others thought that a tool would only be useful if it incorporated financial aspects of geo-resource utilisation. Concerns were aired that without a financial standpoint, it would be another online tool that cannot provide a full idea of geo-resource utilisation because costs are omitted. Economic implications are difficult to estimate accurately due to the restricted interpretation of site conditions during the very early phases of development , and therefore it would be of limited value to develop an economic aspect as part of the geo-resources potential tool.

However, the analysis of governing (and guiding) documentation revealed key themes surrounding geo-resource use in urban development, and indicated improvements that could be made for the design and content of the geo-resources potential tool.

Firstly, protecting geo-resources from over-exploitation and multiple aspects of environmental protection are apparent from the case studies. Within each tool there is scope to assess the vulnerability of geo-resource use by including additional information. For example, for CS1, the abstraction licencing strategy (which reports the availability of groundwater in the region) could be incorporated into the UDG matrix, or for CS2, renewable energy targets that are directly impacted by ground source heat use could be integrated in the UDG matrix.

Secondly, the lack of clarity within planning policy on actions for geo-resource utilisation was identified across the case studies. Instead of options of geo-resource use, direct instructions on practical solutions (with supporting information) could be incorporated into the UDG matrix to improve both the understanding of geo-resources and how their use can meet planning guidance and requirements.

Many interviewees also put onus on defining the intended user of the tool as this would greatly impact its usage. Given the niche position of geo-resources in development proposals, presenting the tool to environmental or geotechnical consultants who have the geological expertise to interpret the raw map outputs may be the most effective way of ensuring that the details and purpose of the tool are not lost. However, as determined by some interviews, this approach promotes specialist use of the tool when it is intended for use by any stakeholder group. This could encourage reselling or rebranding of the tool by consultants which may hinder its uptake.

Some interviewees further suggested that developers would have limited interest in a tool unless it was mandated or financially incentivised. If pursuing the compulsory approach, a route into planning practice must first be established. The leading method is via the planning system as a standalone document that should be included within national or/and regional sustainability guidance. As shown in the case study planning policy assessments (Chapters 5,6 and 7), introducing new a policy (or tool) at a national level would filter down into regional and local guidance. This would strengthen the knowledge that planning authorities would have of the role that geo-resources can play in an urban context. It would also encourage stakeholders (including developers, proprietors, and consultants) to broaden their knowledge and bridge the gap between stakeholders and their knowledge of geo-resource potential. Of the discussions undertaken, there was a consensus that this route would be the most effective in distributing a geo-resource potential tool, however as Hakkinen and Belloni (2011, p.250) have previously noted, “although technological solutions have been developed and improved for years, much is still to be done before a wide range of actors have really adopted these technologies”.

However, proposed changes to planning approaches in the UK (in the recently released Planning for the Future White Paper) are looking to make planning simpler and more flexible, and may potentially make it easier to incorporate such methods into the practices of developers. Recent government initiatives deem the existing planning system overcomplicated and flexible instead of simple and exacting (Ministry of Housing, Communities and Local Government, 2020). Part of the proposed solution is to introduce “a single statutory ‘sustainable development’ test to ensure plans strike the right balance between environmental, social and economic objectives” at local levels of governance (ibid, p.28). With the aim of stream-lining the planning system, incorporating a geo-resources component into the proposed sustainable development test may be sufficient to secure the role of geo-resources within sustainable and resilient urban development.

Furthermore, there is an ongoing effort to digitise the planning system for it to offer “real-time information, high-quality virtual simulation [and] straightforward end-to-end processes. It should be based on data, not documents [and] inclusive for all members of society” (ibid, p.18). The geo-resources tool (as a computerised approach) aligns with this agenda, and in part contributes towards the digitisation of planning documents through the UDG matrix.

7.1.2 Evaluation of the Urban Geo-Resource (UDG) Matrix

Table 7.2 summarises the potential impact that utilising geo-resources could have on the respective levels of planning policy based on the UDG matrices. Where the value of C is closer to 1, geo-resource utilisation can make a greater contribution towards the planning policies included in the respective UDG matrix. Where the value of C is closer to 0, geo-resource utilisation makes less of a contribution towards the planning policies included within the respective UDG matrix[1].

	National			Regional			Local			**Averages**		
	G	P	C	G	P	C	G	P	C	**G**	**P**	**C**
Ground Heat	16	28	0.57	3	7	0.75	16	24	0.67	**11.67**	**18.67**	**0.66**
Groundwater	15.14	35	0.43	1.86	8	0.23	7	11	0.64	**8**	**18**	**0.43**
Subsurface Space	27	32	0.84	42	61	0.69	N/A	N/A	N/A	**40**	**56**	**0.72**
Averages	**19.38**	**31.67**	**0.61**	**15.62**	**25.33**	**0.56**	**11.50**	**17.50**	**0.66**			

G = Number of applicable geo-resource uses,
P = Number of policies in UDG matrix,
C = Contribution of geo-resources to documents listed in UDG matrix

Table 7.2 – The average potential contribution that geo-resources could make to policies and design criteria included within the relevant UDG matrices.

Table 7.2 shows that when comparing the UDG matrices for each case study, there is a lot of variation in the level of contribution that each geo-resource (groundwater, ground heat and subsurface space) can make to the relevant planning policies, guidance documents and sustainability assessment measures for their respective sites. However, across the different levels of documentation (national, regional and local) the average contributions are similar with just over half of the included sustainability and geo-resources policies influenceable by geo-resource utilisation. Furthermore, Table 7.2 suggests that when averaged the utilisation of subsurface space at Canary Wharf Crossrail Station contributes to planning policy and urban guidance to a greater extent than when compared to the other case study sites. However, it must be considered that local policy is absent from the UDG matrix for subsurface space due to the lack of relevant guidance at borough level.

The withdrawal of regional planning is evident from the number of policies included in the UDG matrices for ground heat and groundwater. The number of regional planning policies for the sub-surface space UDG matrix is significantly higher as the study was based in London which is classified as a region (and an exception to the national trend).

[1] The contribution of geo-resources to planning policies in UDG matrix (C) is calculated from the number of applicable geo-resource uses (G) divided by the number of policies in the UDG matrix (P).

As previously stated, the three geo-resources maps are not comparable against one another as the geo-resource potential scales are independently formulated. Of the two smaller case study sites (ground heat and subsurface space), the mapping outputs show that 100% of the Chestnut and Aspen Mews site is poor and 100% of the Canary Wharf Crossrail Station site is moderate. Whereas at NW Cambridge 6% of the site is excellent, 4% is good, 2% is poor and the remainder (89%) of the site is moderate. It can be surmised that due to the coarseness of the data, the geo-resource potential maps may offer more insight into geo-resource potential when undertaken across larger sites or at the city scale. This may be because sites are more likely to encounter variable ground conditions if they are on a larger scale. In practice, at NW Cambridge this may direct stakeholders towards the areas of the site most worthy of investigating potential geo-resource utilisation. If performed across wider urban areas, different sites across a region can be compared for potential geo-resource suitability.

The geo-resource potential mapping tool does not assess the potential of utilising multiple geo-resources on a site, or the potential conflicts and trade-offs that exist from harnessing one geo-resource. As stated by von der Tann et al. (2016, p.361), "if the subsurface is divided into layers by depth, it has to be acknowledged that deeper layers cannot be accessed without drilling or digging through shallower layers", inferring that shallow use must therefore be sacrificed. Due to the number of variable factors, potential conflicts are case-specific and must be considered individually. Some of the main factors to consider when thinking about conflicts include competition for space, competition for the resource, environmental impacts, interference that affects performance of the use, conflicts during construction/installation versus conflicts in the long-term.

There are also potential compatibilities that can be achieved when utilising geo-resources. For example, at NW Cambridge, the use of a non-potable water network to alleviate groundwater stress in the region may operate alongside a closed loop GSHP system.

At Chestnut and Aspen Mews, the implementation of a vertical closed loop GSHP system could function alongside a water management scheme (similar to NW Cambridge) that could support groundwater resources. The limited space available may restrict the nature of collecting water for a non-potable water network but small-scale designs (such as simple rainwater harvesting and green roofs) may be feasible.

Finally, the Canary Wharf Crossrail Station could achieve some aspects of water management, for example by incorporating water-saving infrastructure into the roof garden at the highest level of the station box. However, a major opportunity was assumed when the materials extracted from the excavation works were reused. As discussed in Chapter 6, 300,000 tonnes of material was excavated from the Canary Wharf Crossrail Station site, and over five million tonnes was reused at a nearby site (Crossrail, 2020c). This is an excellent example of geo-resource compatibility contributing to sustainable development.

7.2 Comparative Analysis of Case Studies

Throughout the case study chapters, analogous themes have arisen in answer to the questions posed by this research. Table 7.3 compiles the factors identified by interview participants as enablers, drivers, barriers and failures across the three case study sites. Similarities that have emerged from the comparison of transcripts across the different case studies have been highlighted in Table 7.3.

Table 7.4 presents the themes identified from the document examinations undertaken for each case study site, with cross-cutting themes highlighted. A high-level summary describing the alignment of the findings from the document examinations is provided in Table 7.5.

		Geo-Resources		
		CS1	**CS2**	**CS3**
Cross-cutting Themes – Interview Series	**Enablers**	Effective partnerships	Government subsidy	Economic returns over project life cycle/cost effective solution
		Supported by policy	Economic feasibility	Safeguarded space
		Feasible/viable	Good stakeholder communication	Good understanding of potential
		Solution to multiple issues	Motivated stakeholders	Multiple benefits - economic + environmental
		Sustainability high on agenda	Unlikely for geological conditions to cause a setback	No conflicting uses
	Drivers	More efficient for water distribution	Planning requirements/policy	Government targets (carbon reduction)
		Sustainability high on agenda	Effective systems	Futureproofing
		Driven client	Reducing building problems/maintenance	Dense urban fabric at surface/avoiding existing infrastructure

		Accommodation scarcity in region	Government subsidence	Alleviates stress on transport system and adds capacity/end user requirements
		Water stress identified in policy	Previous success	Meeting spatial development strategy planning
	Barriers	Expensive/costs/money-focus	High risk perception	High capital costs
		Safety concerns/ risk/liability	Expensive design/high capital costs	Prioritising costs
		Weakened/loss of national policy for the built environment	Poor planning policy	Subsurface obstacles
		Scattered engagement across the country (some more resistant/ less interested)	Lack of expertise/knowledge	Lack of communication
		Sustainability is not as important as location or money	Cutting/unclear government subsidence	Geo-hazards/ geotechnical risks
	Failures	Breakdown in communication	Insufficient ground space available	Land cost
		Rebound effect - causing people to use more	Insufficient water for open loop system	Unsettled legal dispute
			Financial problems	
			Land ownership issues	

Red = costs and finance, Yellow = communication and knowledge, Green = planning policy, Blue = multiple benefits, Grey = risks and unknowns

Table 7.3 – Factors identified by interview participants as enablers, drivers, barriers and failures across the three case study sites grouped by themes.

	Geo-Resources		
	CS1	**CS2**	**CS3**
Cross-cutting	protection	protect the environment and reducing carbon emissions	omission of subsurface space

	efficiency of use	energy efficiency, conservation and reducing waste	efficiency of use
	governance and planning	planning policy and urban design guidance	governance and planning
	SuDs	financial incentives	sustainable management/ mismanagement
	water management	use of renewable resources	
		decentralisation	

Yellow = protection, Blue = efficiency, Green = planning policy and governance, Grey = Management strategies

Table 7.4 – Themes identified across the document examinations for each case study.

	Geo-Resources		
	CS1	**CS2**	**CS3**
International	High-level, generic guidance relayed through national policy.	Part of wider agenda for sustainable energy and tackling climate change. Some EU Directives relevant to ground heat.	No specific guidance for subsurface space management. Included within some EU Directives with other agendas.

National	Broad statements but some focussed guidance for specific aspects of groundwater management. No specific planning policies for non-potable or grey water management.	Planning permission not required for GSHPs but water abstraction required for open loop schemes (unless volumes are less than 20 cubic meters). Financial incentive (RHI scheme) sets eligibility requirements and certification under a recognised scheme.	No central management of subsurface space use but beginning to map underground assets. Subsurface space relevant to some policies are relayed into urban guidance and policy.
Regional	Some general commentary on optimising water management.	Discourages energy waste. A regional carbon assessment classified the region and made recommendations for policy. Sustainability appraisal gives general statements for energy efficiency and careful management of natural resources.	Subsurface space mentioned only in reference to geo-hazards. Crossrail sustainability approach gives no overall guidance to the use of subsurface space.
Local	Site specific guidance designed to align with wider sustainability objectives. Development plan gives details of groundwater efficiency infrastructure.	Energy efficiency encouraged at neighbourhood level but no direct guidance for how to harness renewables.	Amount of subsurface space utilised was considered within urban design. Local planning considers underground space to ease surface congestion.

Table 7.5 – High-level summary of the alignment of themes observed from the document examination.

The following section discusses the findings of this study through the lens of some of the key themes that have arisen from the multiple case study approach. These include:

- Costs and finance mechanisms
- Risks and unknowns
- Communication
- Provision of inconsistent and decentralised policy
- Multiple benefits

7.2.1 Costs and Finance Mechanisms

When comparing the enablers of geo-resource utilisation success for all three sites, the economic feasibility is a major facilitator for all schemes. Whether it be by government subsidy (CS2) or project-life-cycle returns (CS3) this factor was most frequently identified by stakeholders across the case studies. Although exact costings are not available, at NW Cambridge installing the non-potable network (and other water infrastructure) will have cost significantly more than having a conventional water supply scheme, but the priority for sustainability across the development outweighed the cost. Similarly, the nature of the GSHP network at Chestnut and Aspen Mews will have incurred high up-front capital costs, although this factor was counteracted by the long-term payments secured as part of the RHI scheme. For example, Liu et al. (2014) finds that in a domestic setting, 71% of study participants were saving money on their energy bills having had a GSHP installation. This may act as a long-term enabler for geo-resource utilisation.

The subsurface space excavation in the West India Docks at Canary Wharf also had significant costs associated with subsurface excavation. However, the wider regional importance of the station (and scheme) as well as the physical location constraints at Canary Wharf permitted the project from an economic perspective. Furthermore, although not confirmed for the Canary Wharf uprisings, the recycled excavated material may have provided some recompense from the excavation of subsurface space if sold.

Cost was also the most frequently identified barrier across the interview series; specifically high capital costs and expensive design, as well as concern over the longevity of government financial schemes. Only a few potential failures of geo-resource utilisation were identified by case study interviewees, however, land ownership issues, unsettled legal disputes as well as financial problems were all identified as factors which may contribute towards the failure of geo-resources schemes. The costs associated with sustainable building are frequently recorded as a barrier in other studies (Williams and Dair, 2007; Hakkinen and Belloni, 2011; Nelms et al., 2005). For example, Zhou and Lowe (2003, p.114) identified "the misperception of incurring higher capital costs and the lack of awareness of market value", concluding that stakeholders need to be re-informed on sustainability within the construction industry. This may be a particular issue if the investor is not the one who is deriving the benefits/value. For example, at Chestnut and Aspen Mews (CS2), the owner paid the initial construction costs but the residents got the savings on the energy bill (although in this case this is offset by government bursaries). Furthermore, government backed financial incentives (such as the RHI scheme) have been cut in some locations (Macauley, 2019) which has instilled concern for some stakeholders that other UK government schemes which aid sustainable development may follow.

The document examination found that planning policy does not focus on the economic implications of utilising geo-resources for enhancing urban sustainability, but it does acknowledge some of the sustainability measurement and incentive mechanisms in some policies (for example the BREEAM assessment). To incorporate geo-resources (and maximise their value) more readily in a development proposal, geo-resources could be included in the cost-benefit analysis of a project (Bricker et al., 2018). This would integrate geo-resources costs into the budget of a development and help to measure the returns.

As sustainable construction is encouraged by the UK government there is hope that any associated costs will become an acceptable norm, however until then financial incentives or building regulations may be the strongest advocates for sustainable design (as well as any tactics meant to enforce sustainability).

7.2.2 Risks and Unknowns

Risk is a common theme identified as a barrier in the interview series from the different perspectives, notably associated with the use of some geo-resources. For example, whether non-potable water is safe for use or whether GSHP systems cause the surrounding ground to freeze. The initial concern stems likely from the infrequent use of non-potable water systems and its unknown and unfamiliar results. In an early study, Higgins et al., (2002) found that providers and end users were worried about the quality of recycled water. This can be addressed by the wider uptake of grey water infrastructure (and non-potable water systems) over the long term, so that the perceived risks can be tackled by appropriate water treatment should issues arise. The latter concern associated with GSHP systems may have stemmed from EA guidance for ground source heating which stated that “you should identify the risks of a closed loop system freezing the ground if very close to a wetland site or river” (Environment Agency, 2011, p.7). However, as directed in the guidance this possibility should be assessed as part of the environmental risk assessment for the scheme. In fact, any concerns associated with potential environmental or geo-technical hazards (such as suitable construction conditions along the route alignment for CS3) are addressed during early investigative stages of a project proposal by a form of systematic risk management (Clayton, 2001).

Moreover, in cases where concerns are unproven, the risks can be tackled by improving the understanding of geo-resource utilisation across all stakeholder groups. This knowledge gap is partially addressed through the geo-resources potential tool developed from this study.

Ultimately, these findings indicate that without a comprehensive understanding of subsurface ground conditions projects may be liable to “overspending, project delays, and overly conservative design” (Bricker et al., 2015, p.1). It is important to minimise these risks to be beneficial for all development stakeholders. Without knowledge of the ground utilisation options may be very limited.

Other stakeholders associate risk with liability, particularly in designating responsibility for the system and its maintenance. In the context of SuDS, Oladunjoye et al., (2017, p.426) observed that “the lack of clarity in regard to the responsibility of the cost of maintenance… will need to be addressed before there becomes better acceptance of SuDS retrofit in the UK”. This issue is most readily resolved from experience but can be facilitated by the assignment of obligations early on in schemes and settling any ambiguity prior to the commencement of a geo-resources’ component.

7.2.3 Communication

Motivated stakeholders that convey effective communication and understand geo-resource potential make the utilisation of geo-resources possible. In the context of sustainable building, the role of communication and cooperation have been identified by Hakkinen and Belloni (2011, p.250) who argued that “fluent cooperation and networking are very important for SB [sustainable building] to gain momentum both in design teams as well as within the industry”. They go on to acknowledge that “knowledge sharing was also considered problematic because of strategic reasons. This requires the development of new ways for sharing strategic knowledge between actors.”

Effective communication was identified as an enabler by interviewees across all case studies. This is a well-established contributor to successful schemes, but particularly for projects with a unique element such as geo-resource utilisation. For example, Hwang and Tan (2012, p.346) suggested that within the context of green infrastructure, "a higher level of communication is required amongst the project team's members as compared with conventional building projects" due to the added complexity of their design. Furthermore, sharing the knowledge and increasing the awareness of geo-resources across development stakeholder groups is important in establishing their value to urban sustainability and resilience (Ascott and Kenny, 2019). This notion was common across the case studies in contemplating the utilisation of different geo-resource types. However, early engagement across the stakeholder groups is just as crucial in facilitating communication.

7.2.4 Provision of Inconsistent and Decentralised Policy

A frequently occurring driver for geo-resource use identified during stakeholder interviews was the requirement to address planning policy or a government target. For CS1 this was about policies driving a reduction in water consumption and installing water-saving urban design where possible. For CS2, this notion is based on the growing effort for sustainable energy consumption, and the ground heat utilisation guidance that higher levels of governance are starting to provide. For CS3, this was in the context of reducing carbon emissions (in line with national targets set by the government), and also the need to meet the requirements of spatial development strategies. Planning policy and governance also recurred as a theme across case studies from the document examinations (Table 7.4).

Developers look to planning policy and urban design guidance for direction to satisfy the targets for sustainable construction. Regions utilising more subsurface resources (e.g. London) may have more guidance for subsurface use simply because there is a demand for it, however for all geo-resource utilisations there is a call for guidance to be more precise and instructive. This follows other studies that also noted that "major cities lack a coherent planning strategy which integrates surface and subsurface assets" (Von der Tann, 2016, p. 356). The case studies demonstrated the decentralised nature of geo-resource management and the lack of core governance to determine issues such as ownership, long term adoption and maintenance responsibilities. This is in line with the extant literature which highlighted that "in many countries, much of the governance of natural resources is decentralised, often with lower levels of government taking responsibility together with resource users in collaborative arrangements" (Nunan, 2016, p.7). Furthermore, "in many cases, decentralisation has been imperfect; often it has not been supported by adequate power and resources, either due to central government holding onto these or to a lack of resources within the sector to sustain devolved processes" (ibid, p.7). In the case of geo-resources, even at the widest level, international guidance for urban planning is broad and generic in the context of geo-resources (Table 7.5). EU Directives contain references to geo-resources where applicable to the central topic however there is no guidance for specific geo-resource utilisation. For example, ground heat is considered within the context of renewable energy resources, and therefore targets to shift energy use to renewables (such as Directive 2009/28/EC) directly relate to the uptake of GSHT. However, as GSHT is only one possibility of many renewable technologies, no guidance for how or where to implement it is provided.

It has been acknowledged in other studies that subsurface resources are not dealt with as a global resource, but are considered on a country-by-country basis (Von der Tann et al., 2018), however the contribution of geo-resources to support global challenges (such as climate change) could be emphasised more at the highest level of urban sustainability. Volchko et al. (2020, p.6) concurred that "despite the obvious importance of the subject [subsurface planning], information on treatment of the subsurface in policy and legislation worldwide is scarce". Although indirectly inclusive in some aspects of geo-resource management, international guidance is conveyed through national policy, and therefore the inclusivity of geo-resources at national level provides a clearer picture on the current role of geo-resources for urban sustainability and resilience in the UK.

The inclusion of geo-resources within national level planning policy and urban guidance is wide-ranging. Water is recognised as a valuable commodity that requires careful management in the UK. SuDS are an established technique (widely covered in planning policy) that contribute towards sustainable water resource management and there are national documents which govern urban development stakeholders and increase their knowledge of how urban design can increase sustainability through the implementation of SuDS or more wide ranging WSUD schemes. In addition, from a hazards perspective the protection of groundwater is covered by policy in England, and the EA manage groundwater abstraction through licencing. However, there are no specific planning policies linking groundwater management and urban design to enhance sustainability. Similarly, planning permission is not required for most GSHPs but water abstraction licencing is required if the volume of water is greater than 20 cubic meters per day for an open loop system. National policy documents have strategic weaknesses that may be causing the under-use of ground heat for sustainable and resilient urban design. Policy could be strengthened according to the UK Climate Change Committee (CCC, 2016) by deploying:

- A long-term planned framework for change alongside an up-to-date standard for building performance (in terms of emissions).
- A cooperative approach to reduced emissions across urban infrastructure.
- A clear certification scheme and training programme to improve general understanding of low-emission initiatives.
- An opportunistic proposal to potential households (which may include incentives).
- Reliable cost estimates promoting the uptake of Renewable Heat Technologies (RHTs).

Applying these principles to all geo-resource types would strengthen the role of geo-resources in building urban sustainability, but ultimately a central authority to manage geo-resource utilisation would better support the impact that geo-resources could make on sustainable and resilient urban design.

As UK regional planning was abolished in 2010 its inclusion in this discussion is retroactive, however the commentary on geo-resources was common in encouraging efficient use of geo-resources and discouraging waste. For CS1, district and local planning levels provided the most detail connecting urban design with groundwater for sustainable development, including recommending water-based infrastructure. The district and local planning policy for CS2 and CS3 gave no clear guidance on harnessing the respective geo-resources through urban design for increasing sustainability and resilience. Local documents for CS3 do acknowledge that subsurface space was considered within the urban design of the project, but this was not explicitly linked to urban sustainability. Von der Tann et al., (2018, p.34) suggested that "the current governance of subsurface space in England is largely sectoral and project centred rather than based on the premise to control all activities in a given volume". The instability of geo-resource management within planning policy supports this statement, with no clear pathway to navigate when considering the utilisation of any geo-resource within the urban design aspects of a project. Generic policy relies on experts interpreting site specific solutions, although geo-resource use could become commonplace if detailed policies become more available and/or are enforced. As well as this, increased communication (particularly amongst these experts) is encouraged for focusing on opportunities and benefits during planning consultation, and not just on constraints and risks.

The GSHP retrofit scheme undertaken in CS2 highlights the lack of policy or guidance available for retrofit projects. Policy has a focus on new development and needs to consider the value of renovating existing infrastructure which has the potential to contribute towards a sustainable urban future. As Branson (2020, p.2) noted, “local planning authorities already have the ability to include specific policies in their local plans and could take action to promote reusing buildings. But producing a local plan takes time and, quite simply, the planet can’t wait. We need national planning policies to promote retrofit”. This notion applies to general retrofit projects but has particular weight for schemes that can advance sustainable development (such as those inclusive of geo-resource utilisation).

In addition, it is apparent that in some cases, (such as for ground heat) the technology to harness the geo-resource is developing faster than the guidance and policy which regulates it. Planning policy and urban guidance is always playing catch-up to the latest systems due to the numerous stages before new policy and guidance is released. This is unavoidable under existing regulations, however enacting some general guidance and expectations for the exploration of geo-resources would encourage the exploration of geo-resource utilisation in new developments.

Finally, where schemes are introduced to provide an economic incentive, there needs to be a mechanism to inform development stakeholders. For example, the RHI review explains that the start of the application process is when organisations become aware of the scheme (Department of Energy and Climate Change, 2014), however it does not describe how awareness is achieved. Planning policy or well-established urban design guidance could facilitate this as an avenue to promote geo-resource utilisation for urban sustainability and resilience.

From the document examinations and interview discussions there is an evident gap (in awareness and knowledge) between geo-resources and the global agenda of urban sustainability and resilience. Chapter 2 acknowledged that the distinction between resilience and sustainability is not well-defined or internationally agreed. The multiple case studies have highlighted this disparity between these concepts, although their inclusion in urban policy and guidance has neglected to demonstrate the discreet differences. For example, the geo-resources mapping tool output for CS1 demonstrated how implementing a dual water system has added capacity to a water network that is already under strain; building in resilience to the development by seeking to ensure a steady water supply, but also providing an opportunity for sustainability by introducing independence in water sources for the site. This use of water has demonstrated the definitions of resilience and sustainability when delivering these distinguishable outcomes. CS2 aligned with the global agenda for sustainability through its contribution as a renewable energy option for reducing carbon emissions – meeting the current needs of the people on site by utilising geo-resources without compromising the ability of future generations to meet their needs. As well as contributing to this wider agenda, the use of ground source heat brings flexibility and adaptability to the site, increasing its ability to act resiliently when required. Finally, the use of subsurface space at CS3 is part of the wider goal to create a city capable of supporting urban growth (i.e. sustainability) by creating additional capacity to the transport system (i.e. resilience) through a targeted site.

Although sometimes referred to in wider contextual settings of urban development, sustainability and resilience are seldom examined following actions at a site level. Many urban development projects refer to sustainability or resilience goals within broad strategies but fail to follow up on measurable outcomes or show the impact that their contributions make. For future research, key quantifiable outcomes need to be managed, centrally organised and holistically accessible for urban sustainability and resilience concepts and indicators to improve and evolve.

7.2.5 Multiple Benefits

Aspects of protection and protecting the environment (and reducing carbon emissions) were observed as cross cutting themes from the document examinations undertaken for CS1 and CS2. The efficient use of geo-resources was also observed in the document examinations for all three case studies. The presence of these factors in urban guidance documents proves that there are multiple benefits from employing multiple geo-resource types, and that utilising geo-resources locally can contribute towards wider agendas.

Multiple benefits from geo-resource uses have been observed across the case study sites. For example, CS1 had the aim to construct a holistic sustainable centre for the University of Cambridge that (from a water perspective) did not negatively impact the already stressed water regime for the region. The non-potable network also provides access to green space as a local amenity for the community using the development. Similarly, the multiple benefits from CS2 included reducing the number of excess winter deaths (by improving end user wellbeing) as well as easing fuel poverty. CS3 represents one node that is part of a regional transport network, and therefore the use of subsurface space at this site is beneficial to end users far beyond a local perspective. These multiple benefits may be overlooked or poorly recorded as urban policy and guidance will be steered from a particular angle. Therefore, these multiple benefits cannot be readily assessed but should be acknowledged.

7.3 Summary

Across the different geo-resources case studies, through the implementation of a geo-resources potential tool, stakeholder interviews and a documentation examination, it was determined that financial circumstances greatly influence the possibility of geo-resource utilisation. Whether capital is secondary to sustainability, or finance schemes incentivise a project, economic conditions can act as enablers or barriers to urban design utilising geo-resources. Besides this, clear planning policy and design guidance are key drivers for geo-resource utilisation in sustainable development. Conversely, the perceived risks and liabilities associated with geo-resources infrastructure are potential barriers to geo-resource use.

The discussion of key themes that have emerged from the multiple case study procedure highlights the different states of existence of geo-resources in planning but also the general perception of their exploitability amongst developers. It is apparent that a change of culture in industry, new guiding policy and further research into geo-resource utilisation are all required for geo-resources to be more valued in urban design for urban sustainability and resilience.

8 - Conclusion

Urban areas around the world are experiencing a range of challenges which threaten their advancement, expansion and existence. These threats are often being tackled through sustainability and resilience approaches by measuring and applying a range of techniques across multiple scales to bring together a holistic approach for urban settings. As part of this, it is imperative that the opportunities presented by geo-resources contribute towards this agenda, with many previously discussed examples demonstrating their potential value for long-term sustainable and resilient urban planning and design.

This research has furthered knowledge of geo-resource utilisation in the context of sustainable and resilient urban development by addressing three research questions:

1. How can a geo-resource potential tool aid urban design and planning criteria and enhance urban sustainability and resilience agendas?
2. What are the current uses and perceptions of geo-resources by development stakeholders?
3. To what extent are planning policy, sustainability and resilience assessments and urban design guidance documents inclusive of geo-resources?

These questions and the wider study have been situated within the global context of growing geo-resource utilisation, focussing on urban planning and design settings for three sites in the UK. Through this process, it was possible to develop site-specific geo-resource potential mapping tools which contain relevant urban design and planning agendas through a UDG matrix. The utility of these tools was demonstrated for three commonly used geo-resources (groundwater, ground heat and subsurface space) across case study sites. Furthermore, the way of implementing this tool (through exploring the enablers and barriers to geo-resource utilisation) has been investigated through interviews with case study urban stakeholders, as well as a detailed examination of the occurrence of geo-resources in urban design guidance and planning policy documents across multiple scales relevant for each case study site.

This concluding chapter summarises the contributions made to knowledge for each research question and highlights the wider implications for urban geology and geo-resource applications. Lastly, future work beyond the scope of the alpha concept of the tool and the findings of the interviews and document examination series are suggested.

8.1 The Potential of Geo-Resource Mapping Tools to Enhance Urban Sustainability and Resilience

The geo-resources mapping tool developed as part of this research provides early stage advice on what ground conditions may or may not be suitable for geo-resource utilisation. The site-specific geo-resource potential tools are presented as heat maps that indicate potential geo-resource suitability and a corresponding urban design geo-resource (UDG) matrix to link the map outputs to site-specific urban planning and design criteria. Importantly, this output was designed to distil geological information into a usable form and then connect it to urban design guidance and planning policies relevant to each case study site.

Trialling this tool across three sites utilising different geo-resources allowed the role of multiple geo-resources in the UK development industry and urban sector to be explored in situ and provide a proof of concept. While the map outputs from this alpha version require some revision to account for more data variables and finer data granularity, all three tools provided options for incorporating geo-resources in urban design to enhance urban sustainability and resilience. The process allows targeted investigations to occur where geo-resource potential varies across a site and indicates how utilising a specific geo-resource could meet site-specific urban guidance and planning policy. In summary, this tool, when further advanced would offer its user(s) the ability to see geo-resource potential within the context of urban guidance and planning, and the associated urban sustainability and resilience benefits it offers.

This study has found through the geo-resources potential tool that the utilisation of geo-resources is a complex issue, and it may not be possible to create a universal tool that can encompass all of the different components surrounding geo-resource use. However, to assess the geo-resources potential on a site, a map output depicting the geological suitability of an area is useful, but requires accompanying information (advisory notes) and a method to communicate the results between urban stakeholder groups. The addition of a cost-benefit aspect within the tool would also be advantageous, although was not attempted as part of this study. As previously stated, this may not be possible universally due to the range of circumstances that may occur at site level. Any future iterations of this tool (or geo-resources modelling) should consider the limitations from this study and incorporate feasible solutions as appropriate.

8.2 The Perception of Geo-Resources from Urban Development Stakeholders

Interviews undertaken with urban stakeholders across the case study sites revealed the exploration of the use and perception of geo-resources in applied circumstances. The interviews were designed to reveal cross-cutting themes with respect to enablers, drivers, barriers and failures specific to the case studies, and to geo-resource utilisation within the development industry in general. The key themes impacting the uptake of geo-resources included costs and finance, communication and knowledge, planning policy, multiple benefits and risks and unknowns.

It is however implied from the interview series that the use of geo-resources in a sustainability and resilience context is spatially isolated, mainly occurring in individual projects and bespoke builds. This focus upon localised approaches can be seen to be facilitating knowledge disparities across urban stakeholder groups and therefore obstructing the transfer of useful geo-resource information in the move towards urban sustainability and resilience at wider spatial scales. Establishing these factors through research allows their consequences to be addressed through further work.

8.3 The Inclusivity of Geo-resources In Planning Policy, Urban Design Guidance and Sustainability and Resilience Assessments

The examination of documents across multiple scales for each case study has revealed themes specific to each type of geo-resource but also matters which span all geo-resources. Cross-cutting themes included aspects of protection (environmental), the efficient use of geo-resources, and the role of planning and governance. Documents were also considered at their scale of influence (such as the international sustainable development goals, national sustainability frameworks and site-specific scorecard methods) and were often found to exclude specifics on valuable geological information, or fail to account for geo-resource prospects that may contribute towards wider sustainability and resilience goals.

In order to see the value of geo-resources translated into practice in the UK, increased recognition across all levels of governance is required, and appropriate translation into guiding documentation. The previously mentioned planning reforms presents an opportunity to inject information on the potential of geo-resources, so that consideration of their use is mandatory for the development industry in the UK. The proposed standalone sustainable development test may facilitate this outlook, and further the idea to holistically integrate geology into urban settings.

8.4 Implications for Urban Geology and Geo-Resource Applications

Urban geology spans two broad research fields and encompasses a diverse range of subjects. Therefore, for this research to comprehensively evaluate the impact and perception of geo-resources in an urban context required numerous analytical approaches. This thesis benefits urban geology by identifying the issues dividing sustainable (and resilient) urban design from geo-resources and presenting a unique mapping tool to better connect these neighbouring disciplines. Furthermore, technical geoscience and geological analysis are brought together with more interpretivist social science methods to better understand the barriers and facilitating factors in geo-resource utilisation.

The relationship between the built environment and natural resources is complicated with some areas overexploiting natural assets and many other areas overlooking them. The multiple case study analysis has explored geo-resource use in a UK setting and demonstrated viable approaches to optimising the relationship between urban sustainability and resilience and geo-resource utilisation. The geo-resources potential tool, if further developed and implemented widely has the potential to alter the outlook on urban design and encourage urban stakeholders to approach new development from the perspective of nature rather than from a finance standpoint.

Conducting individual interviews with a varied set of urban stakeholders allowed the decision makers of urban development to be questioned on their perceptions and experiences of geo-resources. The findings of the interview series emphasised the value of geo-resource information at the case study sites, and implied that a mapping tool to measure the existence of geo-resources linking with urban design and planning policy could moderately address the miscommunication contributing to the lack of geo-resource uptake in the UK. From a geo-resources perspective this work highlights that enhancing the knowledge of urban stakeholders can improve geo-resource use in urban settings (and give them protection from overexploitation) while promoting sustainable and resilient urban designs.

Furthermore, from an extensive examination of policy documents and urban design guidance it was possible to examine the inclusion of geo-resources across urban multiple scales and compare the findings of geo-resources in different scenarios across England. Previous studies have shown that the English planning system is sectorial in nature (von der Tann et al., 2017; Coaffee and Lee, 2016) while this research highlights the inconsistency of geo-resource inclusion across multiple scales of planning policy, and the challenges that need addressing within urban governance to establish a clear hierarchy of who is responsible for the different facets of sustainability and resilience (as well as what actions should be implemented for change).

8.5 Future Research

The limitations identified throughout this study have prompted ideas to further this research. Firstly, whilst the case studies were restricted to three sites in England, the mapping tool could be replicated across larger scales to demonstrate the wider potential of geo-resource utilisation across multiple sites in urban and rural areas. A wider geo-resources assessment could also explore whether there are any cities or regions which are significantly underutilising geo-resources that would otherwise benefit from implementing sustainable and resilient infrastructure from a geo-resources perspective. Furthermore, a wider geo-resources mapping tool could be used to consider greenfield sites, specifically to identify which sites may have the potential for geo-resource use prior to any predetermined development design.

Secondly, this thesis has shown that economics plays a significant role when considering geo-resource utilisation in urban planning and design. Therefore, in a revision of the mapping tool the output could be enhanced by providing an economic evaluation of the geo-resources on site. As discussed previously, it may not be possible to add this in as a layer to the map due to the site-specific conditions that need to be appraised to present a monetary evaluation. For example, to estimate of the value of arisings from the excavated material and the constructed space at CS3. However, Li et al., (2013) suggested that the "value of underground space is firstly linked to its surface economic context (land price, density, transport accessibility, livability, and affordability of users) and also is linked to its subsurface executability (construction costs, skilled builders and materials)", and therefore it may be possible to estimate the value of some geo-resources to supplement the site information.

Furthermore, a second iteration of the mapping tool could include more indicators for each geo-resource where possible. For instance, the inclusion of subsurface temperature data for the ground heat tool would enhance the accuracy of the geo-resource potential measure. Additionally, more granular versions of the datasets in use would increase the accuracy of the tool.

Thirdly, the factors facilitating and preventing the uptake of geo-resources that were disclosed in the interview series should be investigated to a greater extent by an extended round of interviews with a wider audience. Interviewees were selected from stakeholders associated with the case study sites which although is representative of a range of appropriate groups does not include the views and experiences that broader development stakeholders may have. A similar avenue should also be explored for planning policy examination. This study has investigated multiple scales of policy for geo-resource inclusion but only where relevant to the case study sites. Focusing primarily on the neighbourhood and local levels of governance would investigate how effectively national planning policy and urban guidance on geo-resources is devolved and enforced across the UK at the most granular level of urban management.

Having identified these potential extensions, future studies should be undertaken within this research area to further the understanding of geo-resources and their role in building urban resilience and sustainability.

8.6 Final Remarks

The contributions made from this research have furthered the understanding of geo-resources and the factors which influence geo-resource uptake in a UK setting. This study has trialled a tool which links geo-resource potential to site specific urban planning and design criteria across multiple scales of urban governance. Social science techniques have revealed the obstacles to geo-resource utilisation in the effort towards sustainable and resilient urban expansion.

There is a growing importance to incorporate geo-resources into pluralistic urban development decision making. Future research calls for reimagining planning policy and urban design from a geo-resource perspective, so that the benefits from geo-resource utilisation can be valued and obtained for sustainable and resilience urban development.

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Ground Heat - Horizontal closed

	Extremely More Important		Very Strongly More Important		Strongly More Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly More Important		Very Strongly More Important		Extremely More Important	
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater vulnerability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater levels
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater levels
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
groundwater levels	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater levels	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability

Appendix A1 - Pairwise comparison response form for characteristics of horizontal closed loop ground heat systems. Yellow = original response. Red = adjustments following step 4.4.

Ground Heat - Vertical closed

	Extremely More Important		Very Strongly More Important		Strongly More Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly More Important		Very Strongly More Important		Extremely More Important	
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater vulnerability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability

Appendix A2 (also Table 3.6) - Pairwise comparison response form for characteristics of vertical closed loop ground heat systems. Yellow = original response. Red = adjustments following step 4.4.

Ground Heat - Vertical open

	Extremely More Important		Very Strongly More Important		Strongly More Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly More Important		Very Strongly More Important		Extremely More Important	
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater vulnerability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
excavatability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential

Appendix A3 - Pairwise comparison response form for characteristics of vertical open loop ground heat systems. Yellow = original response. Red = adjustments following step 4.4.

Groundwater

	Extremely More Important		Very Strongly More Important		Strongly More Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly More Important		Very Strongly More Important		Extremely More Important	
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater vulnerability
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
aquifer designation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	depth to source
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater vulnerability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
depth to source	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	bedrock aquifer potential

Appendix A4 - Pairwise comparison response form for characteristics of groundwater utilisation. Yellow = original response. Red = adjustments following step 4.4.

Subsurface space

	Extremely More Important		Very Strongly More Important		Strongly More Important		Moderately More Important		Equal Importance		Moderately More Important		Strongly More Important		Very Strongly More Important		Extremely More Important	
suitability of foundations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	re-usability of fill
suitability of foundations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater levels
suitability of foundations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
suitability of foundations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
re-usability of fill	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	groundwater levels
re-usability of fill	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
re-usability of fill	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
groundwater levels	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	presence of made ground
groundwater levels	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability
presence of made ground	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	excavatability

Appendix A5 - Pairwise comparison response form for characteristics of subsurface space utilisation. Yellow = original response. Red = adjustments following step 4.4.

Original Scoring = 15% Inconsistency Index	Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability
	aquifer designation	1	1	1/6	1/5	1/7
	groundwater vulnerability	1	1	1/5	1/3	1/5
	groundwater levels	6	5	1	1	4
	presence of made ground	5	3	1	1	3
	excavatability	7	5	1/4	1/3	1
	TOTAL	20.00	15.00	2.62	2.87	8.34

Original Scoring = 37% Inconsistency Index	Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability
	aquifer designation	1	1	1/5	5	1/3
	groundwater vulnerability	1	1	1/5	3	5
	depth to source	5	5	1	3	3
	presence of made ground	1/5	1/3	1/3	1	1/5
	excavatability	3	1/5	1/3	5	1
	TOTAL	10.20	7.53	2.07	17.00	9.53

Original Scoring = 36% Inconsistency Index	Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential
	aquifer designation	1	7	1	8	7	1/8
	groundwater vulnerability	1/7	1	1/5	5	5	1/8
	depth to source	1	5	1	7	6	1
	presence of made ground	1/8	1/5	1/7	1	1/3	1/9
	excavatability	1/7	1/5	1/6	3	1	1/7
	bedrock aquifer potential	8	8	1	9	7	1
	TOTAL	10.41	21.40	3.51	33.00	26.33	2.50

Original Scoring = 37% Inconsistency Index	Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential
	aquifer designation	1	5	1/3	7	1/9
	groundwater vulnerability	1/5	1	1/5	5	1/7
	depth to source	3	5	1	5	1/5
	presence of made ground	1/7	1/5	1/5	1	1/7
	bedrock aquifer potential	9	7	5	7	1
	TOTAL	13.34	18.20	6.73	25.00	1.60

Original Scoring = 16% Inconsistency Index	Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability
	suitability of foundations	1	5	1/3	5	1/5
	re-usability of fill	1/5	1	1/5	1	1/4
	groundwater levels	3	5	1	4	1
	presence of made ground	1/5	1	1/4	1	1/4
	excavatability	5	4	1	4	1
	TOTAL	9.40	16.00	2.78	15.00	2.70

Appendix B - Original comparison matrices for all geo-resource tools with intolerant consistency indexes. (Table 3.7 highlighted in red text).

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	TOTAL
aquifer designation	0.05	0.07	0.06	0.06	0.02	0.26
groundwater vulnerability	0.05	0.07	0.08	0.12	0.03	0.35
groundwater levels	0.35	0.36	0.39	0.35	0.47	1.92
presence of made ground	0.30	0.21	0.39	0.35	0.36	1.61
excavatability	0.25	0.29	0.10	0.12	0.12	0.87
TOTAL	1.00	1.00	1.00	1.00	1.00	

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	TOTAL
aquifer designation	0.12	0.10	0.15	0.22	0.06	0.66
groundwater vulnerability	0.24	0.20	0.15	0.28	0.38	1.25
depth to source	0.36	0.60	0.45	0.28	0.38	2.07
presence of made ground	0.03	0.04	0.09	0.06	0.04	0.26
excavatability	0.24	0.07	0.15	0.17	0.13	0.75
TOTAL	1.00	1.00	1.00	1.00	1.00	

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	TOTAL
aquifer designation	0.15	0.34	0.28	0.27	0.26	0.09	1.40
groundwater vulnerability	0.03	0.07	0.09	0.09	0.11	0.07	0.47
depth to source	0.15	0.20	0.28	0.27	0.23	0.37	1.51
presence of made ground	0.02	0.02	0.03	0.03	0.02	0.04	0.16
excavatability	0.02	0.02	0.05	0.06	0.04	0.04	0.23
bedrock aquifer potential	0.62	0.34	0.28	0.27	0.34	0.37	2.22
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	TOTAL
aquifer designation	0.12	0.32	0.10	0.22	0.11	0.86
groundwater vulnerability	0.03	0.08	0.10	0.13	0.11	0.45
depth to source	0.24	0.16	0.19	0.22	0.18	0.99
presence of made ground	0.02	0.03	0.04	0.04	0.06	0.19
bedrock aquifer potential	0.59	0.41	0.58	0.39	0.54	2.51
TOTAL	1.00	1.00	1.00	1.00	1.00	

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability	TOTAL
suitability of foundations	0.12	0.28	0.17	0.25	0.08	0.89
re-usability of fill	0.02	0.06	0.07	0.06	0.07	0.28
groundwater levels	0.24	0.28	0.34	0.25	0.39	1.50
presence of made ground	0.03	0.06	0.08	0.06	0.07	0.30
excavatability	0.59	0.33	0.34	0.38	0.39	2.03
TOTAL	1.00	1.00	1.00	1.00	1.00	

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	TOTAL
aquifer designation	0.05	0.07	0.06	0.07	0.02	0.27
groundwater vulnerability	0.05	0.07	0.08	0.12	0.02	0.33
groundwater levels	0.30	0.33	0.38	0.35	0.48	1.84
presence of made ground	0.25	0.20	0.38	0.35	0.36	1.54
excavatability	0.35	0.33	0.10	0.12	0.12	1.02
TOTAL	1.00	1.00	1.00	1.00	1.00	

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	TOTAL
aquifer designation	0.10	0.13	0.10	0.29	0.03	0.66
groundwater vulnerability	0.10	0.13	0.10	0.18	0.52	1.03
depth to source	0.49	0.66	0.48	0.18	0.31	2.13
presence of made ground	0.02	0.04	0.16	0.06	0.02	0.30
excavatability	0.29	0.03	0.16	0.29	0.10	0.88
TOTAL	1.00	1.00	1.00	1.00	1.00	

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	TOTAL
aquifer designation	0.10	0.33	0.28	0.24	0.27	0.05	1.27
groundwater vulnerability	0.01	0.05	0.06	0.15	0.19	0.05	0.51
depth to source	0.10	0.23	0.28	0.21	0.23	0.40	1.45
presence of made ground	0.01	0.01	0.04	0.03	0.01	0.04	0.15
excavatability	0.01	0.01	0.05	0.09	0.04	0.06	0.26
bedrock aquifer potential	0.77	0.37	0.28	0.27	0.27	0.40	2.37
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	TOTAL
aquifer designation	0.07	0.27	0.05	0.28	0.07	0.75
groundwater vulnerability	0.01	0.05	0.03	0.20	0.09	0.39
depth to source	0.22	0.27	0.15	0.20	0.13	0.97
presence of made ground	0.01	0.01	0.03	0.04	0.09	0.18
bedrock aquifer potential	0.67	0.38	0.74	0.28	0.63	2.71
TOTAL	1.00	1.00	1.00	1.00	1.00	

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability	TOTAL
suitability of foundations	0.11	0.31	0.12	0.33	0.07	0.95
re-usability of fill	0.02	0.06	0.07	0.07	0.09	0.31
groundwater levels	0.32	0.31	0.36	0.27	0.37	1.63
presence of made ground	0.02	0.06	0.09	0.07	0.09	0.33
excavatability	0.53	0.25	0.36	0.27	0.37	1.78
TOTAL	1.00	1.00	1.00	1.00	1.00	

Appendix C - Relative weights calculated for all geo-resources tools. Original relative weights in red box on right (Table 3.8 highlighted in red text), adjusted final relative weights following step 4.4 on left).

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	TOTAL	Relative weights fo	X100
aquifer designation	0.05	0.07	0.06	0.06	0.02	0.26	0.0518	5
groundwater vulnerability	0.05	0.07	0.08	0.12	0.03	0.35	0.0692	7
groundwater levels	0.35	0.36	0.39	0.35	0.47	1.92	0.3838	38
presence of made ground	0.30	0.21	0.39	0.35	0.36	1.61	0.3216	32
excavatability	0.25	0.29	0.10	0.12	0.12	0.87	0.1736	17
TOTAL	1.00	1.00	1.00	1.00	1.00			

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	TOTAL	Relative weights fo	X100
aquifer designation	0.05	0.07	0.06	0.07	0.02	0.27	0.0535	5
groundwater vulnerability	0.05	0.07	0.08	0.12	0.02	0.33	0.0667	7
groundwater levels	0.30	0.33	0.38	0.35	0.48	1.84	0.3688	37
presence of made ground	0.25	0.20	0.38	0.35	0.36	1.54	0.3081	31
excavatability	0.35	0.33	0.10	0.12	0.12	1.02	0.2030	20
TOTAL	1.00	1.00	1.00	1.00	1.00			

Appendix D1 - Ratio for relative weights calculated for ground heat horizontal closed. Adjusted final ratio for relative weights following step 4.4 on top. Original ratio for relative weights in red box on bottom.

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	TOTAL	Relative weights fo	X100
aquifer designation	0.12	0.10	0.15	0.22	0.06	0.66	0.1316	13
groundwater vulnerability	0.24	0.20	0.15	0.28	0.38	1.25	0.2507	25
depth to source	0.36	0.60	0.45	0.28	0.38	2.07	0.4150	41
presence of made ground	0.03	0.04	0.09	0.06	0.04	0.26	0.0518	5
excavatability	0.24	0.07	0.15	0.17	0.13	0.75	0.1509	15
TOTAL	1.00	1.00	1.00	1.00	1.00			

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	TOTAL	Relative weights fo	X100
aquifer designation	0.10	0.13	0.10	0.29	0.03	0.66	0.1313	13
groundwater vulnerability	0.10	0.13	0.10	0.18	0.52	1.03	0.2057	21
depth to source	0.49	0.66	0.48	0.18	0.31	2.13	0.4258	43
presence of made ground	0.02	0.04	0.16	0.06	0.02	0.30	0.0610	6
excavatability	0.29	0.03	0.16	0.29	0.10	0.88	0.1762	18
TOTAL	1.00	1.00	1.00	1.00	1.00			

Appendix D2 - Ratio for relative weights calculated for ground heat vertical closed. Adjusted final ratio for relative weights following step 4.4 on top. Original ratio for relative weights in red box on bottom. (Table 3.9 highlighted in red text).

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	TOTAL
aquifer designation	0.15	0.34	0.28	0.27	0.26	0.09	1.40
groundwater vulnerability	0.03	0.07	0.09	0.09	0.11	0.07	0.47
depth to source	0.15	0.20	0.28	0.27	0.23	0.37	1.51
presence of made ground	0.02	0.02	0.03	0.03	0.02	0.04	0.16
excavatability	0.02	0.02	0.05	0.06	0.04	0.04	0.23
bedrock aquifer potential	0.62	0.34	0.28	0.27	0.34	0.37	2.22
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	

Relative weights fo	X100
0.2339	23
0.0784	8
0.2516	25
0.0269	3
0.0385	4
0.3707	37

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	TOTAL
aquifer designation	0.10	0.33	0.28	0.24	0.27	0.05	1.27
groundwater vulnerability	0.01	0.05	0.06	0.15	0.19	0.05	0.51
depth to source	0.10	0.23	0.28	0.21	0.23	0.40	1.45
presence of made ground	0.01	0.01	0.04	0.03	0.01	0.04	0.15
excavatability	0.01	0.01	0.05	0.09	0.04	0.06	0.26
bedrock aquifer potential	0.77	0.37	0.28	0.27	0.27	0.40	2.37
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	

Relative weights fo	X100
0.2110	21
0.0848	8
0.2423	24
0.0249	2
0.0427	4
0.3942	39

Appendix D3 - Ratio for relative weights calculated for ground heat vertical open. Adjusted final ratio for relative weights following step 4.4 on top. Original ratio for relative weights in red box on bottom.

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	TOTAL	Relative weights fo	X100
aquifer designation	0.12	0.32	0.10	0.22	0.11	0.86	0.1729	17
groundwater vulnerability	0.03	0.08	0.10	0.13	0.11	0.45	0.0891	9
depth to source	0.24	0.16	0.19	0.22	0.18	0.99	0.1979	20
presence of made ground	0.02	0.03	0.04	0.04	0.06	0.19	0.0386	4
bedrock aquifer potential	0.59	0.41	0.58	0.39	0.54	2.51	0.5015	50
TOTAL	1.00	1.00	1.00	1.00	1.00			

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	TOTAL	Relative weights fo	X100
aquifer designation	0.07	0.27	0.05	0.28	0.07	0.75	0.1498	15
groundwater vulnerability	0.01	0.05	0.03	0.20	0.09	0.39	0.0778	8
depth to source	0.22	0.27	0.15	0.20	0.13	0.97	0.1947	19
presence of made ground	0.01	0.01	0.03	0.04	0.09	0.18	0.0362	4
bedrock aquifer potential	0.67	0.38	0.74	0.28	0.63	2.71	0.5416	54
TOTAL	1.00	1.00	1.00	1.00	1.00			

Appendix D4 - Ratio for relative weights calculated for groundwater. Adjusted final ratio for relative weights following step 4.4 on top. Original ratio for relative weights in red box on bottom.

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability		TOTAL		Relative weights fo	X100
suitability of foundations	0.12	0.28	0.17	0.25	0.08		0.89		0.1789	18
re-usability of fill	0.02	0.06	0.07	0.06	0.07		0.28		0.0551	6
groundwater levels	0.24	0.28	0.34	0.25	0.39		1.50		0.2996	30
presence of made ground	0.03	0.06	0.08	0.06	0.07		0.30		0.0596	6
excavatability	0.59	0.33	0.34	0.38	0.39		2.03		0.4068	41
TOTAL	1.00	1.00	1.00	1.00	1.00					

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability		TOTAL		Relative weights fo	X100
suitability of foundations	0.11	0.31	0.12	0.33	0.07		0.95		0.1892	19
re-usability of fill	0.02	0.06	0.07	0.07	0.09		0.31		0.0630	6
groundwater levels	0.32	0.31	0.36	0.27	0.37		1.63		0.3256	33
presence of made ground	0.02	0.06	0.09	0.07	0.09		0.33		0.0666	7
excavatability	0.53	0.25	0.36	0.27	0.37		1.78		0.3556	36
TOTAL	1.00	1.00	1.00	1.00	1.00					

Appendix D5 - Ratio for relative weights calculated forsubsurface space. Adjusted final ratio for relative weights following step 4.4 on top. Original ratio for relative weights in red box on bottom.

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	Relative Weight
aquifer designation	1.00	1.00	0.17	0.20	0.14	0.05
groundwater vulnerability	1.00	1.00	0.20	0.33	0.20	0.07
groundwater levels	6.00	5.00	1.00	1.00	4.00	0.37
presence of made ground	5.00	3.00	1.00	1.00	3.00	0.31
excavatability	7.00	5.00	0.25	0.33	1.00	0.20
Total	20.00	15.00	2.62	2.87	8.34	

Inconsistency Values

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability
aquifer designation	1.00	0.80	0.02	0.03	0.04
groundwater vulnerability		1.00	0.04	0.07	0.07
groundwater levels			1.00	1.20	7.27
presence of made ground				1.00	4.55
excavatability					1.00

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	Relative Weight
aquifer designation	1.00	1.00	0.20	5.00	0.33	0.13
groundwater vulnerability	1.00	1.00	0.20	3.00	5.00	0.21
depth to source	5.00	5.00	1.00	3.00	3.00	0.43
presence of made ground	0.20	0.33	0.33	1.00	0.20	0.06
excavatability	3.00	0.20	0.33	5.00	1.00	0.18
TOTAL	10.20	7.53	2.07	17.00	9.53	

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability
aquifer designation	1.00	0.64	0.06	10.77	0.25
groundwater vulnerability		1.00	0.10	10.12	5.84
depth to source			1.00	20.94	7.25
presence of made ground				1.00	0.07
excavatability					1.00

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	Relative Weight
aquifer designation	1.00	7.00	1.00	8.00	7.00	0.13	0.21
groundwater vulnerability	0.14	1.00	0.20	5.00	5.00	0.13	0.08
depth to source	1.00	5.00	1.00	7.00	6.00	1.00	0.24
presence of made ground	0.13	0.20	0.14	1.00	0.33	0.11	0.02
excavatability	0.14	0.20	0.17	3.00	1.00	0.14	0.04
bedrock aquifer potential	8.00	8.00	1.00	9.00	7.00	1.00	0.39
TOTAL	10.41	21.40	3.51	33.00	26.33	2.50	

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential
aquifer designation	1.00	17.42	0.87	67.81	34.56	0.07
groundwater vulnerability		1.00	0.20	17.03	9.92	0.03
depth to source			1.00	68.13	34.01	0.61
presence of made ground				1.00	0.19	0.01
excavatability					1.00	0.02
bedrock aquifer potential						1.00

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	Relative Weight
aquifer designation	1.00	5.00	0.33	7.00	0.11	0.15
groundwater vulnerability	0.20	1.00	0.20	5.00	0.14	0.08
depth to source	3.00	5.00	1.00	5.00	0.20	0.19
presence of made ground	0.14	0.20	0.20	1.00	0.14	0.04
bedrock aquifer potential	9.00	7.00	5.00	7.00	1.00	0.54
TOTAL	13.34	18.20	6.73	25.00	1.60	

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential
aquifer designation	1.00	9.62	0.26	28.98	0.03
groundwater vulnerability		1.00	0.08	10.76	0.02
depth to source			1.00	26.91	0.07
presence of made ground				1.00	0.01
bedrock aquifer potential					1.00

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability	Relative Weight
suitability of foundations	1.00	5.00	0.33	5.00	0.20	0.1892
re-usability of fill	0.20	1.00	0.20	1.00	0.25	0.0630
groundwater levels	3.00	5.00	1.00	4.00	1.00	0.3256
presence of made ground	0.20	1.00	0.25	1.00	0.25	0.0666
excavatability	5.00	4.00	1.00	4.00	1.00	0.3556
TOTAL	9.40	16.00	2.78	15.00	2.70	

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability
suitability of foundations	1.00	15.02	0.19	14.21	0.11
re-usability of fill		1.00	0.04	0.95	0.04
groundwater levels			1.00	19.56	0.92
presence of made ground				1.00	0.05
excavatability					1.00

Appendix E1 - Original inconsistency values calculated for all geo-resources (Table 3.11 highlighted in red text).

Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability	Relative Weight
aquifer designation	1.00	1.00	0.14	0.17	0.20	0.0518
groundwater vulnerability	1.00	1.00	0.20	0.33	0.25	0.0692
groundwater levels	7.00	5.00	1.00	1.00	4.00	0.3838
presence of made ground	6.00	3.00	1.00	1.00	3.00	0.3216
excavatability	5.00	4.00	0.25	0.33	1.00	0.1736
Total	20.00	14.00	2.59	2.83	8.45	

Inconsistency Values	Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability
	aquifer designation	1.00	0.75	0.02	0.03	0.06
	groundwater vulnerability		1.00	0.04	0.07	0.10
	groundwater levels			1.00	1.19	8.84
	presence of made ground				1.00	5.56
	excavatability					1.00

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	Relative Weight
aquifer designation	1.00	0.50	0.33	4.00	0.50	0.1316
groundwater vulnerability	2.00	1.00	0.33	5.00	3.00	0.2507
depth to source	3.00	3.00	1.00	5.00	3.00	0.4150
presence of made ground	0.25	0.20	0.20	1.00	0.33	0.0518
excavatability	2.00	0.33	0.33	3.00	1.00	0.1509
TOTAL	8.25	5.03	2.20	18.00	7.83	

Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability
aquifer designation	1.00	0.26	0.11	10.16	0.44
groundwater vulnerability		1.00	0.20	24.19	4.98
depth to source			1.00	40.05	8.25
presence of made ground				1.00	0.11
excavatability					1.00

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential	Relative Weight
aquifer designation	1.00	5.00	1.00	9.00	7.00	0.25	0.2339
groundwater vulnerability	0.20	1.00	0.33	3.00	3.00	0.20	0.0784
depth to source	1.00	3.00	1.00	9.00	6.00	1.00	0.2516
presence of made ground	0.11	0.33	0.11	1.00	0.50	0.11	0.0269
excavatability	0.14	0.33	0.17	2.00	1.00	0.11	0.0385
bedrock aquifer potential	4.00	5.00	1.00	9.00	9.00	1.00	0.3707
TOTAL	6.45	14.67	3.61	33.00	26.50	2.67	

Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential
aquifer designation	1.00	14.91	0.93	78.22	42.53	0.16
groundwater vulnerability		1.00	0.20	8.74	6.11	0.04
depth to source			1.00	84.16	39.23	0.68
presence of made ground				1.00	0.35	0.01
excavatability					1.00	0.01
bedrock aquifer potential						1.00

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential	Relative Weight
aquifer designation	1.00	4.00	0.50	5.00	0.20	0.1729
groundwater vulnerability	0.25	1.00	0.50	3.00	0.20	0.0891
depth to source	2.00	2.00	1.00	5.00	0.33	0.1979
presence of made ground	0.20	0.33	0.20	1.00	0.11	0.0386
bedrock aquifer potential	5.00	5.00	3.00	9.00	1.00	0.5015
TOTAL	8.45	12.33	5.20	23.00	1.84	

Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential
aquifer designation	1.00	7.76	0.44	22.41	0.07
groundwater vulnerability		1.00	0.23	6.93	0.04
depth to source			1.00	25.65	0.13
presence of made ground				1.00	0.01
bedrock aquifer potential					1.00

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability	Relative Weight
suitability of foundations	1.00	5.00	0.50	4.00	0.20	0.1789
re-usability of fill	0.20	1.00	0.20	1.00	0.17	0.0551
groundwater levels	2.00	5.00	1.00	4.00	1.00	0.2996
presence of made ground	0.25	1.00	0.25	1.00	0.17	0.0596
excavatability	5.00	6.00	1.00	6.00	1.00	0.4068
TOTAL	8.45	18.00	2.95	16.00	2.53	

Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability
suitability of foundations	1.00	16.25	0.30	12.00	0.09
re-usability of fill		1.00	0.04	0.92	0.02
groundwater levels			1.00	20.10	0.74
presence of made ground				1.00	0.02
excavatability					1.00

Appendix E2 - Adjusted inconsistency values calculated for all geo-resources (following step 4.4).

New Scoring = 9.4% consistency Index	Ground heat horizontal closed system (GT_Hor)	aquifer designation	groundwater vulnerability	groundwater levels	presence of made ground	excavatability
	aquifer designation	1	1	1/7	1/6	1/5
	groundwater vulnerability	1	1	1/5	1/3	1/4
	groundwater levels	7	5	1	1	4
	presence of made ground	6	3	1	1	3
	excavatability	5	4	1/4	1/3	1
	Total	20.00	14.00	2.59	2.83	8.45

New Scoring = 9.4% Consistency Index	Ground heat vertical closed system (GT-Ver Closed)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability
	aquifer designation	1	1/2	1/3	4	1/2
	groundwater vulnerability	2	1	1/3	5	3
	depth to source	3	3	1	5	3
	presence of made ground	1/4	1/5	1/5	1	1/3
	excavatability	2	1/3	1/3	3	1
	TOTAL	8.25	5.03	2.20	18.00	7.83

New Scoring = 9.3% Consistency Index	Ground heat vertical open system (GT-Ver Open)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	excavatability	bedrock aquifer potential
	aquifer designation	1	5	1	9	7	1/4
	groundwater vulnerability	1/5	1	1/3	3	3	1/5
	depth to source	1	3	1	9	6	1
	presence of made ground	1/9	1/3	1/9	1	1/2	1/9
	excavatability	1/7	1/3	1/6	2	1	1/9
	bedrock aquifer potential	4	5	1	9	9	1
	TOTAL	6.45	14.67	3.61	33.00	26.50	2.67

New Scoring = 10% Consistency Index	Groundwater (GW)	aquifer designation	groundwater vulnerability	depth to source	presence of made ground	bedrock aquifer potential
	aquifer designation	1	4	1/2	5	1/5
	groundwater vulnerability	1/4	1	1/2	3	1/5
	depth to source	2	2	1	5	1/3
	presence of made ground	1/5	1/3	1/5	1	1/9
	bedrock aquifer potential	5	5	3	9	1
	TOTAL	8.45	12.33	5.20	23.00	1.84

New Scoring = 9.3% Consistency Index	Subsurface Space (SS)	suitability of foundations	re-usability of fill	groundwater levels	presence of made ground	excavatability
	suitability of foundations	1	5	1/2	4	1/5
	re-usability of fill	1/5	1	1/5	1	1/6
	groundwater levels	2	5	1	4	1
	presence of made ground	1/4	1	1/4	1	1/6
	excavatability	5	6	1	6	1
	TOTAL	8.45	18.00	2.95	16.00	2.53

Appendix F - Adjusted comparison matrices for all geo-resource tools with tolerant consistency indexes.

Appendix G - PostGIS code to create spatial mapping tool for Ground heat vertical closed (Chestnut and Aspen Mews)

Create aquifer designation data for superficial deposits greater than 10m thick combined with bedrock aquifer designations:

(aquifer designation dataset requirement prep:
1 - create superficial thickness model (and superficial aquifer designation dataset) only where superficials are greater than 10m in thickness (minimum depth for vertical open gshps))

```
create table bstm_morethan10_cy AS
select * from vector_bstm_classified where grid_code>10;

CREATE TABLE bstm_morethan10_bl AS
SELECT * FROM vector_bstm_classified2 WHERE grid_code>10;
----------------
```

In ArcGIS need to clip bstm_morethan10 to superficial_aquifer_designation and then to site areas. Then import site files (e.g. burton_area_aqu_des_sup_morethan10).

(aquifer designation dataset requirement prep:

2 - combine aquifer designations from bedrock and superficial datasets)

```
create table unionystuff as select ST_UNION(t1.geom) as geom from
burton_area_aqu_des_sup_morethan10 as t1;

CREATE TABLE burton_area_aqu_des_comb AS
(SELECT t1.gid, t1.objectid, t1.typology, ST_area(ST_Difference(t1.geom2,
t3.geom)) as area_sq_km, ST_Difference(t1.geom2, t3.geom) as geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM burton_area_aqu_des_bed) as t1
JOIN unionystuff as t3
ON '1' = '1')
Union (SELECT t1.gid, t1.objectid, t1.typology, ST_area(t1.geom) as area_sq_km,
geom from burton_area_aqu_des_sup_morethan10 as t1 )
;
```

END OF INDIVIDUAL DATASET PREP

Need to rename the score columns from all datasets so that each column can be kept in final map output:

```
ALTER TABLE burton_area_aqu_des_comb_join
RENAME COLUMN score TO scoreaqu;

ALTER TABLE burton_area_artificial_all_join
```

```
RENAME COLUMN score TO scoreart;

ALTER TABLE burton_area_exc_typ_fixed_join
RENAME COLUMN score TO scoreexc;

ALTER TABLE burton_area_dts_join
RENAME COLUMN score TO scoredts;

ALTER TABLE burton_area_gw_vul_join
RENAME COLUMN score TO scorevul;

---------------------------------

STEP 1 - ADDING TOGETHER GEOMETRIES AND SCORES OF AQUIFER DESIGNATION AND GW
VULNERABILITY, KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

SELECT *, ST_IsValid(geom) FROM burton_area_gw_vul_join ORDER BY
ST_IsValid(geom) ASC;

/* some boolean false in gw_vul dataset - created valid version below */

CREATE TABLE burton_area_gw_vul_join_valid as
SELECT gid , comb_vuln, scorevul, ST_MakeValid(geom) as geom FROM
burton_area_gw_vul_join;

---------------

CREATE TABLE    overlap1        AS
SELECT  t2.typology     AS      aquifer_designation,
                t2.scoreaqu     AS      scoreaqu,
                t1.comb_vuln AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.scorevul + to_number(t2.scoreaqu, '0.999') AS total,
                ST_CollectionExtract(CASE
                WHEN ST_Contains(t1.geom,t2.geom)
                THEN  t2.geom
                WHEN ST_Within(t1.geom,t2.geom)
                THEN t1.geom
                ELSE ST_Intersection(t1.geom,t2.geom)
                END, 3) as geom
FROM            burton_area_gw_vul_join_valid   AS      t1
INNER JOIN      burton_area_aqu_des_comb_join           AS      t2
ON              ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul as
        (SELECT t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap1 as t1 WHERE st_area(geom)> 0)
```

STEP 2 - ADDING GEOMETRIES AND SCORES OF DEPTH TO SOURCE ONTO ABOVE CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM burton_area_dts_join ORDER BY ST_IsValid(geom)
ASC;

/* some boolean false in this dataset - create valid version */

CREATE TABLE burton_area_dts_join_valid as
SELECT gid, details, scoredts, ST_MakeValid(geom) as geom FROM
burton_area_dts_join;

CREATE TABLE    overlap2        AS
SELECT          t2.details AS depthtosource,
                        t2.scoredts AS scoredts,
                        t1.aquifer_designation  AS      aquifer_designation,
                        t1.scoreaqu     AS      scoreaqu,
                        t1.gw_vulnerability AS gw_vulnerability,
                        t1.scorevul AS  scorevul,
                        t1.total + to_number(t2.scoredts, '0.999') AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
                        END, 3) as geom
FROM                    aqu_vul AS      t1
INNER JOIN              burton_area_dts_join_valid              AS      t2
ON                              ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul_dts as
        (SELECT t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap2 as t1 WHERE st_area(geom)> 0)
```

STEP 3 - ADDING GEOMETRIES AND SCORES OF EXCAVATABILITY ONTO ABOVE CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY, DEPTH TO SOURCE), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM burton_area_exc_typ_fixed_join ORDER BY
ST_IsValid(geom) ASC;

/* some boolean false in this dataset - create valid version */

CREATE TABLE burton_area_exc_typ_fixed_join_valid as
SELECT gid, typ_ex, scoreexc, ST_MakeValid(geom) as geom FROM
burton_area_exc_typ_fixed_join;

CREATE TABLE    overlap3        AS
SELECT                  t2.typ_ex AS excavation_requirements,
                        t2.scoreexc AS scoreexc,
                        t1.depthtosource AS depthtosource,
                        t1.scoredts AS scoredts,
                        t1.aquifer_designation  AS      aquifer_designation,
                        t1.scoreaqu     AS      scoreaqu,
                        t1.gw_vulnerability AS gw_vulnerability,
                        t1.scorevul AS  scorevul,
                        t1.total + t2.scoreexc AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
                        END, 3) as geom
FROM                    aqu_vul_dts     AS      t1
INNER JOIN              burton_area_exc_typ_fixed_join_valid            AS
t2
ON                      ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul_dts_exc as
        (SELECT
                t1.excavation_requirements AS excavation_requirements,
                t1.scoreexc AS scoreexc,
                t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap3 as t1 WHERE st_area(geom)> 0)
```

STEP 4 - ADDING GEOMETRIES AND SCORES OF ARTIFICIAL GROUND ONTO ABOVE CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY, DEPTH TO SOURCE, EXCAVATABILITY), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM burton_area_artificial_all_join ORDER BY
ST_IsValid(geom) ASC;

/* some boolean false in this dataset - create valid version */

CREATE TABLE burton_area_artificial_all_join_valid as
SELECT gid, lex_d, scoreart, ST_MakeValid(geom) as geom FROM
burton_area_artificial_all_join;

CREATE TABLE    overlap4        AS
SELECT                  t2.lex_d AS mg_type,
                        t2.scoreart AS scoreart,
                        t1.excavation_requirements AS excavation_requirements,
                        t1.scoreexc AS scoreexc,
                        t1.depthtosource AS depthtosource,
                        t1.scoredts AS scoredts,
                        t1.aquifer_designation  AS      aquifer_designation,
                        t1.scoreaqu     AS      scoreaqu,
                        t1.gw_vulnerability AS gw_vulnerability,
                        t1.scorevul AS  scorevul,
                        t1.total + to_number(t2.scoreart, '0.999') AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
                        END, 3) as geom
FROM                    aqu_vul_dts_exc AS      t1
INNER JOIN              burton_area_artificial_all_join_valid           AS
t2
ON                      ST_INTERSECTS(t1.geom,t2.geom);


CREATE TABLE aqu_vul_dts_exc_art as
        (SELECT
                t1.mg_type AS mg_type,
                t1.scoreart AS scoreart,
                t1.excavation_requirements AS excavation_requirements,
                t1.scoreexc AS scoreexc,
                t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap4 as t1 WHERE st_area(geom)> 0)
```

END OF GT_VER_CLOSED BURTON_AREA DATASET

Appendix H1 - PostGIS code to create spatial mapping tool for Groundwater (North West Cambridge Site)

Create aquifer designation data for superficial deposits greater than 10m thick combined with bedrock aquifer designations:

(aquifer designation dataset requirement prep:
1 - create superficial thickness model (and superficial aquifer designation dataset) only where superficials are greater than 10m in thickness (minimum depth for vertical open gshps))

```
CREATE TABLE bstm_morethan10 AS
SELECT * FROM vector_bstm_classified WHERE grid_code>10;
----------------
```

In ArcGIS need to clip bstm_morethan10 to superficial_aquifer_designation and then to site areas. Then import site files (e.g. cambridge_area_aqu_des_sup_morethan10).

(aquifer designation dataset requirement prep:

2 - combine aquifer designations from bedrock and superficial datasets)

```
create table unionystuff as select ST_UNION(t1.geom) as geom from
cambridge_area_aqu_des_sup_morethan10 as t1;

CREATE TABLE cambridge_area_aqu_des_comb AS
(SELECT t1.gid, t1.objectid, t1.typology, ST_area(ST_Difference(t1.geom2,
t3.geom)) as area_sq_km, ST_Difference(t1.geom2, t3.geom) as geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM cambridge_area_aqu_des_bed) as
t1
JOIN unionystuff as t3
ON '1' = '1')
Union (SELECT t1.gid, t1.objectid, t1.typology, ST_area(t1.geom) as area_sq_km,
geom from cambridge_area_aqu_des_sup_morethan10 as t1 )
;

--------------------
```

THE ABOVE CODE WILL NOT WORK FOR CAMBRIDGE SITE BOUNDARIES AS THEY DO NOT CONTAIN ANY SUPERFICIAL DEPOSITS GREATER THAN 10M IN THICKNESS.
NEED TO CREATE CUT OUT OF BEDROCK AREA WITH NO SUPERFICIAL COVERAGE AND COMBINE WITH SUPERFICIAL COVERAGE OF MORE THAN 10M TO BRING BACK GEOMETRIES FOR SITE AREAS WITHOUT SUPERFICIAL COVERAGE:

(aquifer designation dataset requirement prep:
1 - create union shape of superficial aquifer designation greater than 10m thick):

```
DROP TABLE union1;
CREATE TABLE union1 AS
```

```
SELECT ST_Union(t2.geom2) as geom from (Select *, ST_MakeValid(geom) as geom2,
'1' as fred from cambridge_area_aqu_des_sup_morethan10) as t2 GROUP BY fred;
```

(2 - create shape of the site area with areas of superficial aquifer designation greater than 10m thick 'cut' out):

```
DROP TABLE cambridge_area_sup_cut;
CREATE TABLE cambridge_area_sup_cut AS
SELECT gid, objectid, typology, ST_area(t1.geom) as area_sq_km,
ST_Difference(t1.geom2,t3.geom) as geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM cambridge_area_aqu_des_bed) as
t1
JOIN union1 as t3
ON '1' = '1';
```

(3 - combine union shape of superficial aquifer designation greater than 10m thick and 'cut out' area, carrying the relevant id and joining classifiers (ie.-gid, objectid and typology)):

```
drop table cambridge_area_aqu_des_all;
create table cambridge_area_aqu_des_all as
select gid, objectid, typology, geom from cambridge_area_aqu_des_sup_morethan10
union select gid, objectid, typology, ST_MakeValid(t1.geom) from
cambridge_area_sup_cut as t1
```

AFTER REMEMBER TO USE ARCGIS TO CUT SITE BOUNDARIES FOR CAMBRIDGE FROM DATASET

ARTIFICIAL DATASET PREP. FIRST CLIP ARTIFICIAL GEOLOGY TO SITE AREAS. NAME THE FILES: CAMBRIDGE_AREA_ART, CAMBRIDGE_ART.

(Artificial dataset requirement prep:
1 - create union shape of artificial cover)

```
DROP TABLE bits_union;
CREATE TABLE bits_union AS
SELECT ST_Union(t2.geom2) as geom from (Select *, ST_MakeValid(geom) as geom2,
'1' as fred from cambridge_area_art) as t2 GROUP BY fred;
```

(Artificial dataset requirement prep:
2 - create shape of the site area with areas of artificial cover 'cut' out)

```
CREATE TABLE cambridge_area_art_cut AS
SELECT gid, ST_area(t1.geom) as area_sq_km, ST_Difference(t1.geom2,t3.geom) as
geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM cambridge_area) as t1
JOIN bits_union as t3
ON '1' = '1';
```

(Artificial dataset requirement prep:
3 - union artificial cover and 'cut out' area, carrying the relevant id and joining classifiers (ie.- gid and lex_d)

```
create table cambridge_area_artificial_all as
select gid, lex_d, geom from cambridge_area_art
union select gid, 'No artificial cover recorded' as lex_d, geom from
cambridge_area_art_cut
```

END OF INDIVIDUAL DATASET PREP

Need to rename the score columns from all datasets so that each column can be kept in final map output:

```
ALTER TABLE cambridge_area_aqu_des_all_join
RENAME COLUMN score TO scoreaqu;

ALTER TABLE cambridge_area_artificial_all_join
RENAME COLUMN score TO scoreart;

ALTER TABLE cambridge_area_aqu_pot_join
RENAME COLUMN score TO scorepot;

ALTER TABLE cambridge_area_dts_join
RENAME COLUMN score TO scoredts;

ALTER TABLE cambridge_area_gw_vul_join
RENAME COLUMN score TO scorevul;
```

STEP 1 - ADDING TOGETHER GEOMETRIES AND SCORES OF AQUIFER DESIGNATION AND GW VULNERABILITY, KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
SELECT *, ST_IsValid(geom) FROM cambridge_area_gw_vul_join ORDER BY
ST_IsValid(geom) ASC;

/* no boolean false in gw_vul dataset - no valid version required */
```

```
CREATE TABLE    overlap1        AS
SELECT          t2.typology     AS      aquifer_designation,
                t2.scoreaqu     AS      scoreaqu,
                t1.comb_vuln AS gw_vulnerability,
                t1.scorevul AS  scorevul,
```

```
                t1.scorevul + to_number(t2.scoreaqu, '0.999') AS total,
                ST_CollectionExtract(CASE
                WHEN ST_Contains(t1.geom,t2.geom)
                THEN  t2.geom
                WHEN ST_Within(t1.geom,t2.geom)
                THEN t1.geom
                ELSE ST_Intersection(t1.geom,t2.geom)
                END, 3) as geom
FROM            cambridge_area_gw_vul_join      AS      t1
INNER JOIN      cambridge_area_aqu_des_all_join         AS      t2
ON              ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul as
        (SELECT t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap1 as t1 WHERE st_area(geom)> 0)

-------------------------
```

STEP 2 - ADDING GEOMETRIES AND SCORES OF DEPTH TO SOURCE ONTO ABOVE CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM cambridge_area_dts_join ORDER BY
ST_IsValid(geom) ASC;

/* some boolean false in this dataset - create valid version */

CREATE TABLE cambridge_area_dts_join_valid as
SELECT gid, details, scoredts, ST_MakeValid(geom) as geom FROM
cambridge_area_dts_join;

CREATE TABLE    overlap2        AS
SELECT          t2.details AS depthtosource,
                        t2.scoredts AS scoredts,
                        t1.aquifer_designation  AS      aquifer_designation,
                        t1.scoreaqu     AS      scoreaqu,
                        t1.gw_vulnerability AS gw_vulnerability,
                        t1.scorevul AS  scorevul,
                        t1.total + to_number(t2.scoredts, '0.999') AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
```

```
                        END, 3) as geom
FROM                    aqu_vul AS      t1
INNER JOIN              cambridge_area_dts_join_valid          AS      t2
ON                              ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul_dts as
        (SELECT t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap2 as t1 WHERE st_area(geom)> 0)

-----------------------------

STEP 3 - ADDING GEOMETRIES AND SCORES OF BEDROCK AQUIFER POTENTIAL ONTO ABOVE
CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY, DEPTH TO SOURCE),
KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM cambridge_area_aqu_pot_join ORDER BY
ST_IsValid(geom) ASC;

/* some boolean false in this dataset - create valid version */

CREATE TABLE cambridge_area_aqu_pot_join_valid as
SELECT gid, details, scorepot, ST_MakeValid(geom) as geom FROM
cambridge_area_aqu_pot_join;

CREATE TABLE    overlap3        AS
SELECT                  t2.details AS bed_aquifer_potential,
                        t2.scorepot AS scorepot,
                        t1.depthtosource AS depthtosource,
                        t1.scoredts AS scoredts,
                        t1.aquifer_designation  AS      aquifer_designation,
                        t1.scoreaqu     AS      scoreaqu,
                        t1.gw_vulnerability AS gw_vulnerability,
                        t1.scorevul AS  scorevul,
                        t1.total + t2.scorepot AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
                        END, 3) as geom
FROM                    aqu_vul_dts     AS      t1
INNER JOIN              cambridge_area_aqu_pot_join_valid               AS
t2
```

```
ON                        ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE aqu_vul_dts_pot as
        (SELECT
                t1.bed_aquifer_potential AS bed_aquifer_potential,
                t1.scorepot AS scorepot,
                t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap3 as t1 WHERE st_area(geom)> 0)

-------------------------
```

STEP 4 - ADDING GEOMETRIES AND SCORES OF ARTIFICIAL GROUND ONTO ABOVE CUMULATIVE FILE (AQUIFER DESIGNATION, GW VULNERABILITY, DEPTH TO SOURCE, EXCAVATABILITY), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM cambridge_area_artificial_all_join ORDER BY
ST_IsValid(geom) ASC;

/* all boolean true in this dataset - no valid version required */

CREATE TABLE    overlap4        AS
SELECT                    t2.lex_d AS mg_type,
                          t2.scoreart AS scoreart,
                          t1.bed_aquifer_potential AS bed_aquifer_potential,
                          t1.scorepot AS scorepot,
                          t1.depthtosource AS depthtosource,
                          t1.scoredts AS scoredts,
                          t1.aquifer_designation  AS      aquifer_designation,
                          t1.scoreaqu     AS      scoreaqu,
                          t1.gw_vulnerability AS gw_vulnerability,
                          t1.scorevul AS  scorevul,
                          t1.total + to_number(t2.scoreart, '0.999') AS total,
                          ST_CollectionExtract(CASE
                          WHEN ST_Contains(t1.geom,t2.geom)
                          THEN  t2.geom
                          WHEN ST_Within(t1.geom,t2.geom)
                          THEN t1.geom
                          ELSE ST_Intersection(t1.geom,t2.geom)
                          END, 3) as geom
FROM                      aqu_vul_dts_pot AS      t1
INNER JOIN                cambridge_area_artificial_all_join              AS
t2
ON                        ST_INTERSECTS(t1.geom,t2.geom);
```

```
CREATE TABLE aqu_vul_dts_pot_art as
        (SELECT
                t1.mg_type AS mg_type,
                t1.scoreart AS scoreart,
                t1.bed_aquifer_potential AS bed_aquifer_potential,
                t1.scorepot AS scorepot,
                t1.depthtosource AS depthtosource,
                t1.scoredts AS scoredts,
                t1.aquifer_designation  AS      aquifer_designation,
                t1.scoreaqu     AS      scoreaqu,
                t1.gw_vulnerability AS gw_vulnerability,
                t1.scorevul AS  scorevul,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap4 as t1 WHERE st_area(geom)> 0)
```

END OF GW CAMBRIDGE_AREA DATASET

Appendix H2 - PostGIS code to create spatial mapping tool for Subsurface Space (Canary Wharf Crossrail Station)

(Excavatability dataset requirement prep:
1 - combine density/strength columns so no entries read 'na')

```
create table london_exc_typ_fixed as
select *, case when  str_typ_ex = 'na'  and den_typ_ex = 'na' then 'HAND TOOLS'
when str_typ_ex = 'na' then den_typ_ex else str_typ_ex end as typ_ex from
london_excavatability
```

```
create table london_area_exc_typ_fixed as
select *, case when  str_typ_ex = 'na'  and den_typ_ex = 'na' then 'HAND TOOLS'
when str_typ_ex = 'na' then den_typ_ex else str_typ_ex end as typ_ex from
london_area_excavatability
```

(Artificial dataset requirement prep:
1 - create union shape of artificial cover)

```
CREATE TABLE bits_union AS
SELECT ST_Union(t2.geom2) as geom from (Select *, ST_MakeValid(geom) as geom2,
'1' as fred from london_art) as t2 GROUP BY fred;
```

(Artificial dataset requirement prep:
2 - create shape of the site area with areas of artificial cover 'cut' out)

```
CREATE TABLE london_art_cut AS
SELECT gid, ST_area(t1.geom) as area_sq_km, ST_Difference(t1.geom2,t3.geom) as
geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM london_50) as t1
JOIN bits_union as t3
ON '1' = '1';
```

(Artificial dataset requirement prep:
3 - union artificial cover and 'cut out' area, carrying the relevant id and joining classifiers (ie.- gid and lex_d)

```
create table london_artificial_all as
select gid, lex_d, geom from london_art
union select gid, 'No artificial cover recorded' as lex_d, geom from
london_art_cut
```

(Artificial dataset requirement prep:
1 - create union shape of artificial cover)

```
DROP TABLE bits_union;
CREATE TABLE bits_union AS
SELECT ST_Union(t2.geom2) as geom from (Select *, ST_MakeValid(geom) as geom2,
'1' as fred from london_area_art) as t2 GROUP BY fred;
```

(Artificial dataset requirement prep:
2 - create shape of the site area with areas of artificial cover 'cut' out)

```
CREATE TABLE london_area_art_cut AS
SELECT gid, ST_area(t1.geom) as area_sq_km, ST_Difference(t1.geom2,t3.geom) as
geom
FROM (SELECT *, ST_MakeValid(geom) as geom2 FROM london_area) as t1
JOIN bits_union as t3
ON '1' = '1';
```

(Artificial dataset requirement prep:
3 - union artificial cover and 'cut out' area, carrying the relevant id and joining classifiers (ie.- gid and lex_d)

```
create table london_area_artificial_all as
select gid, lex_d, geom from london_area_art
union select gid, 'No artificial cover recorded' as lex_d, geom from
london_area_art_cut
```

Convert groundwater levels data from raster to vector:

1. Remove floating point data by multiplying data points out.
   Use raster calculator (spatial analyst) tool to do this. For example ‘layer x 1000000’.

2. Use reclassify (▯ spatial analyst tools ▯ reclass ▯ reclassify)
   Input raster = ‘rastercalc1’ (the name of the output raster file from step 1).
   Reclass field = ‘value’

Reclassification table:

Old values	New values
0 – 1000000	1
1000001 – 5000000	5
Etc	etc

NOTE:
- NEW VALUES CAN ONLY HAVE ONE ENTRY – MAKE IT THE HIGHER LIMIT SO YOU

KNOW THAT CLASS REPRESENT EVERYTHING BETWEEN THE PREVIOUS VALUE AND THIS ONE.
- PUT SPACES IN BETWEEN THE NUMBERS AND COLONS IN OLD VALUES – THIS IS SENSITIVE.
3. Convert (Conversion Tools From raster Raster to polygon)

Save as new shape file layer - groundwater levels

END OF INDIVIDUAL DATASET PREP

Need to rename the score columns from all datasets so that each column can be kept in final map output:

```
ALTER TABLE london_area_fil_join
RENAME COLUMN score TO scorefil;

ALTER TABLE london_area_artificial_all_join
RENAME COLUMN score TO scoreart;

ALTER TABLE london_area_exc_typ_fixed_join
RENAME COLUMN score TO scoreexc;

ALTER TABLE london_area_gw_levels_join
RENAME COLUMN score TO scoregwl;

ALTER TABLE london_area_fnd_join
RENAME COLUMN score TO scorefnd;
```

To change data type of column to number (so that scores can be added), use the following example:

```
select to_number(t2.scoreaqu, '0.999')
from london_area_aqu_des_comb_join AS t2
```

STEP 1 - ADDING TOGETHER GEOMETRIES AND SCORES OF SUITABILITY FOR FOUNDATIONS AND EXCAVATABILITY, KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* (IF THIS IS READING ANY FALSE BOOLEAN ENTRIES, NEED TO MAKE SURE
'ST_MAKEVALID' IS USED) */

SELECT *, ST_IsValid(geom) FROM london_area_fnd_join ORDER BY ST_IsValid(geom)
ASC;
SELECT *, ST_IsValid(geom) FROM london_area_exc_typ_fixed_join ORDER BY
```

```
ST_IsValid(geom) ASC;

/* all boolean true in both datasets */

CREATE TABLE    overlap1        AS
SELECT  t2.typ_ex AS excavation_requirements,
                t2.scoreexc AS scoreexc,
                t1.condition AS foundation,
                t1.scorefnd AS  scorefnd,
                to_number(t1.scorefnd, '0.999') + t2.scoreexc AS total,
                ST_CollectionExtract(CASE
                WHEN ST_Contains(t1.geom, t2.geom)
                THEN t2.geom
                WHEN ST_Within(t1.geom,t2.geom)
                THEN t1.geom
                ELSE ST_Intersection(t1.geom,t2.geom)
                END, 3) as geom
FROM            london_area_fnd_join    AS      t1
INNER JOIN      london_area_exc_typ_fixed_join          AS      t2
ON              ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE found_exc as
        (SELECT t1.excavation_requirements      AS      excavation_requirements,
                        t1.scoreexc     AS      scoreexc,
                        t1.foundation AS foundation,
                        t1.scorefnd AS  scorefnd,
                        t1.total AS total,
                        st_area(t1.geom),
                        ST_MakeValid(t1.geom) as geom
         FROM overlap1 as t1 WHERE st_area(geom)> 0)

-------------------------------------------
```

STEP 2 - ADDING GEOMETRIES AND SCORES OF GW LEVELS ONTO ABOVE CUMULATIVE FILE (FOUNDATIONS, EXCAVATABILITY), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/

SELECT *, ST_IsValid(geom) FROM london_area_gw_levels_join ORDER BY
ST_IsValid(geom) ASC;


/* all boolean true in dataset */

CREATE TABLE    overlap2        AS
SELECT                  t2.gridcode AS depthtogw,
                        t2.scoregwl AS scoregwl,
                        t1.excavation_requirements      AS
excavation_requirements,
                        t1.scoreexc     AS      scoreexc,
                        t1.foundation AS foundation,
```

```
                          t1.scorefnd AS  scorefnd,
                          t1.total + to_number(t2.scoregwl, '0.999') AS total,
                          ST_CollectionExtract(CASE
                          WHEN ST_Contains(t1.geom,t2.geom)
                          THEN  t2.geom
                          WHEN ST_Within(t1.geom,t2.geom)
                          THEN t1.geom
                          ELSE ST_Intersection(t1.geom,t2.geom)
                          END, 3) as geom
FROM                      found_exc       AS      t1
INNER JOIN                london_area_gw_levels_join              AS      t2
ON                                ST_INTERSECTS(t1.geom,t2.geom);


CREATE TABLE found_exc_gwl as
        (SELECT t1.depthtogw AS depthtogw,
                t1.scoregwl AS scoregwl,
                t1.excavation_requirements      AS      excavation_requirements,
                t1.scoreexc     AS      scoreexc,
                t1.foundation AS foundation,
                t1.scorefnd AS  scorefnd,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap2 as t1 WHERE st_area(geom)> 0)

-------------------------------------
```

STEP 3 - ADDING GEOMETRIES AND SCORES OF FILL USE ONTO ABOVE CUMULATIVE FILE (FOUNDATIONS, EXCAVATABILITY, GW LEVELS), KEEPING THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

```
/* check all is valid first*/
SELECT *, ST_IsValid(geom) FROM london_area_fil_join ORDER BY ST_IsValid(geom)
ASC;

/* all boolean true in dataset */

CREATE TABLE    overlap3        AS
SELECT          t2.fill_uses AS fill_uses,
                t2.scorefil AS scorefil,
                t1.depthtogw AS depthtogw,
                t1.scoregwl AS scoregwl,
                t1.excavation_requirements      AS      excavation_requirements,
                t1.scoreexc     AS      scoreexc,
                t1.foundation AS foundation,
                t1.scorefnd AS  scorefnd,
                t1.total + t2.scorefil AS total,
                ST_CollectionExtract(CASE
                WHEN ST_Contains(t1.geom,t2.geom)
                THEN  t2.geom
                WHEN ST_Within(t1.geom,t2.geom)
```

```
                THEN t1.geom
                ELSE ST_Intersection(t1.geom,t2.geom)
                END, 3) as geom
FROM                    found_exc_gwl   AS      t1
INNER JOIN              london_area_fill_join           AS      t2
ON                      ST_INTERSECTS(t1.geom,t2.geom);

CREATE TABLE found_exc_gwl_fil as
        (SELECT
                t1.fill_uses AS fill_uses,
                t1.scorefil AS scorefil,
                t1.depthtogw AS depthtogw,
                t1.scoregwl AS scoregwl,
                t1.excavation_requirements      AS      excavation_requirements,
                t1.scoreexc     AS      scoreexc,
                t1.foundation AS foundation,
                t1.scorefnd AS  scorefnd,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap3 as t1 WHERE st_area(geom)> 0)


-----------------------------------

STEP 4 - ADDING GEOMETRIES AND SCORES OF ARTIFICIAL GROUND ONTO ABOVE CUMULATIVE
FILE (AQUIFER DESIGNATION, GW VULNERABILITY, GW LEVELS, EXCAVATABILITY), KEEPING
THE INDIVIDUAL CLASSIFICATION AND SCORE COLUMNS:

/* check all is valid first*/

SELECT *, ST_IsValid(geom) FROM london_area_artificial_all_join ORDER BY
ST_IsValid(geom) ASC;

/* all boolean true in this dataset - no valid version created */

CREATE TABLE    overlap4        AS
SELECT                  t2.lex_d AS mg_type,
                        t2.scoreart AS scoreart,
                        t1.fill_uses AS fill_uses,
                        t1.scorefil AS scorefil,
                        t1.depthtogw AS depthtogw,
                        t1.scoregwl AS scoregwl,
                        t1.excavation_requirements      AS
excavation_requirements,
                        t1.scoreexc     AS      scoreexc,
                        t1.foundation AS foundation,
                        t1.scorefnd AS  scorefnd,
                        t1.total + to_number(t2.scoreart, '0.999') AS total,
                        ST_CollectionExtract(CASE
                        WHEN ST_Contains(t1.geom,t2.geom)
                        THEN  t2.geom
                        WHEN ST_Within(t1.geom,t2.geom)
```

```
                        THEN t1.geom
                        ELSE ST_Intersection(t1.geom,t2.geom)
                        END, 3) as geom
FROM                    found_exc_gwl_fil       AS      t1
INNER JOIN              london_area_artificial_all_join         AS      t2
ON                      ST_INTERSECTS(t1.geom,t2.geom);


CREATE TABLE found_exc_gwl_fil_art as
        (SELECT
                t1.mg_type AS mg_type,
                t1.scoreart AS scoreart,
                t1.fill_uses AS fill_uses,
                t1.scorefil AS scorefil,
                t1.depthtogw AS depthtogw,
                t1.scoregwl AS scoregwl,
                t1.excavation_requirements      AS      excavation_requirements,
                t1.scoreexc     AS      scoreexc,
                t1.foundation AS foundation,
                t1.scorefnd AS  scorefnd,
                t1.total AS total,
                st_area(t1.geom),
                ST_MakeValid(t1.geom) as geom
         FROM overlap4 as t1 WHERE st_area(geom)> 0)
```

END OF SS LONDON_AREA DATASET

Appendix I1 - Urban Design Geo-resource (UDG) Matrix for Water (North West Cambridge). Potential methods of geo-resource use across the horizontal axis, and the sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Intersecting boxes are marked with a 1 where the criteria is supported by the geo-resource use (or the geo-resource use can fulfil the criteria), and a 0 where there is no link.

Levels	Technical Design Assessment	Design criteria	Green roofs	Simple rainwater harvesting (water butts)	Advanced rainwater harvesting	Greywater re-use	Permeable paving	Filter drain / perforated pipes	Swales	Infiltration basin	Soakaways	Infiltration trench	Filter strip	Constructed wetland	Retention (wet) pond	Detention basin	Underground attenuation and storage	Water saving devices - flow restricters, reduced capacity toilets, low water use washers, etc	Boreholes/ Wells	Drought tolerant planting to reduce watering demand	Water monitors/ meters
National	UK Government Design Guidance	**be functional** (fit for purpose, intuitive, comfortable, safe, easy for all to use, relate to its envrionmental circumstances so that events such as flooding do not prevent it from being used.)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
National	UK Government Design Guidance	**support mixed uses and tenures** (easy access to facilities, mix of uses to allow communities and places to respond to change more readily by allowing a turnover of activities.)	1	0	0	1	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0
National	UK Government Design Guidance	**include successful public spaces** (public spaces for everyone - hard and soft landscape elements, well orientated routes. Public art and sculpture.**)**	1	0	0	0	1	0	1	1	1	0	1	1	1	1	0	0	0	1	0
National	UK Government Design Guidance	**be adaptable and resilient** (flexible and able to respond to future needs, building change of use. Designing buildings that can be adapted to different needs offers real benefits in terms of the use of resources.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
National	UK Government Design Guidance	**have a distinct character** (aspects such as the local pattern of street blocks and plots; building forms; details and materials; style and vernacular; landform and gardens, parks, trees and plants; and wildlife habitats and micro-climates)	1	0	0	0	1	0	1	1	0	0	1	1	1	0	0	0	0	1	0
National	UK Government Design Guidance	**be attractive** (So too can more transient elements – such as the way sunshine and shadows move across an area or the way it is maintained and cleaned. Composition of elements and the relationship between colours, textures, shapes and patterns are all important)	1	0	0	0	0	0	1	1	0	0	1	1	1	1	0	1	0	1	0
National	UK Government Design Guidance	**encourage ease of movement** (appropriate number of routes to and through it. How direct and understandable these are, how closely they fit with desired lines of travel, and how well they connect with each other and destinations)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	encourage multiple benefits from both urban and rural land, including through the mixed use schemes and taking opportunities to achieve net environment gain	1	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0	0	0	1
National	National Planning Policy Framework (NPPF)	recognise that some undeveloped land can perform many functions	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	give substantial weight to the value of using suitable brownfield land...and support appropriate opportunities to remediate despoiled, degraded, derelict, contaminated or unstable land.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	promote and support the development of under-utilised land and buildings	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	support opportunities to the airspace above existing residential and commercial premises for new homes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	be developed with local communities so they reflect local aspirations	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
National	National Planning Policy Framework (NPPF)	. will function well and add to the overall quality of the area	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
National	National Planning Policy Framework (NPPF)	. are visually attractive	1	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0	0	1	0
National	National Planning Policy Framework (NPPF)	. are sympathetic to local character and history	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1
National	National Planning Policy Framework (NPPF)	. establish or maintain a strong sense of place	1	0	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	1	0
National	National Planning Policy Framework (NPPF)	. optimise the potential of the site to accommodate and sustain an appropriate amount and mix of development	0	1	1	1	0	1	0	1	1	1	0	0	0	0	1	1	1	1	1
National	National Planning Policy Framework (NPPF)	. Create places that are safe, inclusive and accessible and which promote health and well being	1	0	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	0
National	National Planning Policy Framework (NPPF)	avoid increased vulnerability to the range of impacts arising from climate change. When new development is brought forward in areas which are vulnerable, care should be taken to ensure that risks can be managed through suitable adaptation measures, including through the planning of green infrastructure.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
National	National Planning Policy Framework (NPPF)	Increase the use and supply of renewable and low carbon energy and heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	. Provide a positive strategy for energy from these sources that maximises the potential for sustainable development	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
National	National Planning Policy Framework (NPPF)	. Identify opportunities for development to draw its energy supply from decentralised renewable or low carbon energy supply systems	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0
National	National Planning Policy Framework (NPPF)	using opportunities provided by new development to reduce the causes and impacts of flooding (where appropriate through the use of natural flood management techniques)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
National	National Planning Policy Framework (NPPF)	. Protecting and enhancing valued landscapes, sites of biodiversity or geological value and soils.	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	. Recognising the intrinsic character and beauty of the countryside and the wider benefits from natural capital and ecosystem services	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
National	National Planning Policy Framework (NPPF)	plan for the enhancement of natural capital at a catchment or landscape scale	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
National	Planning Policy Statement 1: Delivering Sustainable Development	take account of environmental issues such as mitigation of the effects of, and adaptation to, climate change through the… protection of groundwater from contamination	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National	Planning Policy Statement 1: Delivering Sustainable Development	The prudent use of resources means ensuring that we use them wisely and efficiently, in a way that respects the needs of future generations…. The broad aim should be to ensure that outputs are maximised whilst resources used are minimised	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
National	Planning Policy Statement 1: Delivering Sustainable Development	minimise the need to consume new resources over the lifetime of the development by making more efficient use or reuse of existing resources, rather than making new demands on the environment	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
National	Planning Policy Statement 1: Delivering Sustainable Development	Regional planning authorities and local authorities should promote…the sustainable use of water resources; and the use of sustainable drainage systems in the management of run-off	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
National	Planning Policy Statement 1 Supplement: Planning and Climate Change	planning authorities should expect new development to…give priority to the use of sustainable drainage systems, paying attention to the potential contribution to be gained to water harvesting from impermeable surfaces and encourage layouts that accommodate waste water recycling	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
Regional	East of England Plan (2008)	make efficient use of land;	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	0	1	0	0
Regional	East of England Plan (2008) Policy ENV7	in the case of housing development, achieve the highest possible net density appropriate to the character of the locality and public transport accessibility	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Regional	East of England Plan (2008) Policy ENV7	provide a mix of uses and building types where appropriate	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Regional	East of England Plan (2008) Policy ENV7	have regard to the needs and well being of all sectors of the community	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	1	0	0	0

Regional	East of England Plan (2008) Policy ENV7	address crime prevention, community safety and public health;	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Regional	East of England Plan (2008) Policy ENV7	promote resource efficiency and more sustainable construction, including maximum use of re-used or recycled materials and of local and traditional materials	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Regional	East of England Plan (2008) Policy ENV7	reduce pollution, including emissions, noise and light pollution	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Regional	East of England Plan (2008) Policy ENV7	maximise opportunities for the built heritage to contribute to physical, economic and community regeneration.	1	0	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	1	0
Local	Cambridge Local Plan (2006)	reducing the use of natural resources, including energy and water throughout the lifecycle of the development	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
Local	Cambridge Local Plan (2006)	The open space provided could also be used for the storage/recycling of water to benefit flood protection and encourage sustainable drainage systems. However, open space used in this way must be designed to be enjoyed and used by the public if it is to count towards meeting the standards.	1	1	0	0	1	0	1	1	0	0	0	1	1	1	0	0	0	1	0
Local	Cambridge Local Plan (2006)	It is important that any development proposed alongside these watercourses or that use the watercourses protects and, where possible, enhances this vital resource.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	0
Local	Cambridge Local Plan (2006)	It is preferable to manage surface water runoff on site where possible through the use of sustainable drainage techniques.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
Local	Cambridge Local Plan (2006)	Developers will be required to demonstrate that runoff will be controlled to those levels in perpetuity after development.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
Local	Cambridge Local Plan (2006)	Planning permission will not be granted where there is an inadequate water supply, sewerage or land drainage system available to meet the demands of development,	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Local	Cambridge Sustainable Development Guidelines (CSDG) (2003)	Use permeable materials… re-use or recycle water on site… Use grass swales and basins… Use balancing ponds and wetlands… Use infiltration trenches… Consider green roofs	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Local	North West Cambridge Area Action Plan (NW25)	the SuDs on site should control the run-off volumes to mitigate any risks associated with flooding and to prevent any negative impact local wildlife.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
Local	North West Cambridge Area Action Plan (NW24)	Non residential development and student housing will be required to demonstrate that…it will incorporate water conservation measures	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
Local	North West Cambridge Area Action Plan (NW24)	water conservation measures are applied to each building to ensure that there is a comprehensive strategy to water use reduction across the site	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
Local	Cambridge City Council Sustainable Design and Construction Supplementary Planning Document	water conservation approaches are encouraged for new developments. (Suggested actions include; installing water efficient fittings, rainwater harvesting systems or greywater recycling systems. In addition, the document sets a "desirable target" of 105 litres per capita per day for water use.)	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
National	BREEAM	BREEAM Wat01 (Water Consumption)	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
National	BREEAM	BREEAM Wat02 (Water Monitoring)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
National	BREEAM	BREEAM Pol03 (Surface Water Run-off)	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0

Appendix I2 - Urban Design Geo-resource (UDG) Matrix for Ground Heat (Chestnut and Aspen Mews). Potential methods of geo-resource use across the horizontal axis, and the sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Intersecting boxes are marked with a 1 where the criteria is supported by the geo-resource use (or the geo-resource use can fulfil the criteria), and a 0 where there is no link.

Level	**Technical Design Assessment**	**Design criteria**	open loop vertical	closed loop horizontal	closed loop vertical
National	UK Government Design Guidance	**be functional** (fit for purpose, intuitive, comfortable, safe, easy for all to use, relate to its envrionmental circumstances so that events such as flooding do not prevent it from being used.)	1	1	1
National	UK Government Design Guidance	**support mixed uses and tenures** (easy access to facilities, mix of uses to allow communities and places to respond to change more readily by allowing a turnover of activities.)	1	1	1
National	UK Government Design Guidance	**include successful public spaces** (public spaces for everyone - hard and soft landscape elements, well orientated routes. Public art and sculpture.)	0	0	0
National	UK Government Design Guidance	**be adaptable and resilient** (flexible and able to respond to future needs, building change of use. Designing buildings that can be adapted to different needs offers real benefits in terms of the use of resources.)	1	1	1
National	UK Government Design Guidance	**have a distinct character** (aspects such as the local pattern of street blocks and plots; building forms; details and materials; style and vernacular; landform and gardens, parks, trees and plants; and wildlife habitats and micro-climates)	0	0	0
National	UK Government Design Guidance	**be attractive** (So too can more transient elements – such as the way sunshine and shadows move across an area or the way it is maintained and cleaned. Composition of elements and the relationship between colours, textures, shapes and patterns are all important)	0	0	0
National	UK Government Design Guidance	**encourage ease of movement** (appropriate number of routes to and through it. How direct and understandable these are, how closely they fit with desired lines of travel, and how well they connect with each other and destinations)	0	0	0
National	National Planning Policy Framework (NPPF)	encourage multiple benefits from both urban and rural land, including through the mixed use schemes and taking opportunities to achieve net environment gain	1	1	1
National	National Planning Policy Framework (NPPF)	recognise that some undeveloped land can perform many functions	1	1	1

National	National Planning Policy Framework (NPPF)	give substantial weight to the value of using suitable brownfield land…and support appropriate opportunities to remediate despoiled, degraded, derelict, contaminated or unstable land.	0	1	1
National	National Planning Policy Framework (NPPF)	promote and support the development of under-utilised land and buildings	1	1	1
National	National Planning Policy Framework (NPPF)	support opportunities to the airspace above existing residential and commercial premises for new homes	0	0	0
National	National Planning Policy Framework (NPPF)	be developed with local communities so they reflect local aspirations	1	1	1
National	National Planning Policy Framework (NPPF)	. will function well and add to the overall quality of the area	1	1	1
National	National Planning Policy Framework (NPPF)	. are visually attractive	0	0	0
National	National Planning Policy Framework (NPPF)	. are sympathetic to local character and history	0	0	0
National	National Planning Policy Framework (NPPF)	. establish or maintain a strong sense of place	0	0	0
National	National Planning Policy Framework (NPPF)	. optimise the potential of the site to accommodate and sustain an appropriate amount and mix of development	1	1	1
National	National Planning Policy Framework (NPPF)	. Create places that are safe, inclusive and accessible and which promote health and well being	0	0	0
National	National Planning Policy Framework (NPPF)	avoid increased vulnerability to the range of impacts arising from climate change. When new development is brought forward in areas which are vulnerable, care should be taken to ensure that risks can be managed through suitable adaptation measures, including through the planning of green infrastructure.	1	1	1
National	National Planning Policy Framework (NPPF)	Increase the use and supply of renewable and low carbon energy and heat	1	1	1
National	National Planning Policy Framework (NPPF)	. Provide a positive strategy for energy from these sources that maximises the potential for sustainable development	1	1	1
National	National Planning Policy Framework (NPPF)	. Identify opportunities for development to draw its energy supply from decentralised renewable or low carbon energy supply systems	1	1	1
National	National Planning Policy Framework (NPPF)	using opportunities provided by new development to reduce the causes and impacts of flooding (where appropriate through the use of natural flood management techniques)	0	0	0
National	National Planning Policy Framework (NPPF)	. Protecting and enhancing valued landscapes, sites of biodiversity or geological value and soils.	0	0	0
National	National Planning Policy Framework (NPPF)	. Recognising the intrinsic character and beauty of the countryside and the wider benefits from natural capital and ecosystem services	0	0	0
National	National Planning Policy Framework (NPPF)	plan for the enhancement of natural capital at a catchment or landscape scale	1	1	1
Regional	Regional Spatial Strategy for the West Midlands (2008)	Appropriate design and construction of buildings can avoid energy loss;	0	0	0

Regional	Regional Spatial Strategy for the West Midlands (2008)	minimise energy demand through use of natural lighting, heating and cooling;	1	1	1
Regional	Regional Spatial Strategy for the West Midlands (2008)	allow on-site generation of heat or electricity from renewable sources of energy;	1	1	1
Regional	Regional Spatial Strategy for the West Midlands (2008)	help reduce running costs.	1	1	1
Local	East Staffordshire Local Plan (2015)	SO1: Well designed communities: To develop green infrastructure-led strategic housing growth providing well designed communities that provide accessible green space, services and facilities, promote distinctiveness, wellbeing, whilst protecting and enhancing sensitive environments.	0	0	0
Local	East Staffordshire Local Plan (2015)	SO11: Prudent Use of Resources: To promote the prudent use of finite resources and the positive use of renewable resources, through the design, location and layout of development and by optimising the use of existing infrastructure.	1	1	1
Local	East Staffordshire Local Plan (2015)	Strategic Policy 1 -... high quality design which incorporates energy efficient considerations and renewable energy technologies;	1	1	1
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Help to create a sense of place, building on the urban, suburban and rural local character, respecting local patterns of development and the historic environment, and using heritage assets to their best advantage,	0	0	0
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Enhance the landscape and protect and enhance biodiversity;	0	0	0
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Retain, enhance and expand green infrastructure assets within the development as the basis of the green infrastructure-led development.	0	0	0
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Be adaptable in order to enable a change of uses where this is possible;	0	0	0
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Provide innovative and contemporary architecture where this is appropriate	1	1	1
Local	East Staffordshire Local Plan (2015)	Strategic Policy 24 - Minimise the production of carbon through sustainable construction and reuse of materials where possible and promote the use of renewable energy source technology solutions where possible	1	1	1
Local	East Staffordshire Local Plan (2015)	Strategic Policy 28 - The Council will promote and encourage all technologies and types of renewable and low-carbon energy generation, appropriate to the location in the Borough.	1	1	1
Local	East Staffordshire Local Plan (2015)	Strategic Policy 28 - Opportunities where development can draw its energy supply from decentralised, renewable or low carbon energy supply systems and for co-locating potential heat customers will be encouraged.	1	1	1
Local	East Staffordshire Design Guide SPD (2008)	Proper and appropriate response to context - where new development is designed for the site, for example through appropriate materials and detailing	0	0	0

Local	East Staffordshire Design Guide SPD (2008)	Effective use of the assets of the site - where latent design opportunities of the site inform the design of the development	1	1	1
Local	East Staffordshire Design Guide SPD (2008)	A good urban structure - where the layout of development is permeable and well related to the wider setting	0	0	0
Local	East Staffordshire Design Guide SPD (2008)	Effective parking and servicing solutions - which create more efficient layouts and better urban design, based on creative and innovative approaches	0	0	0
Local	East Staffordshire Design Guide SPD (2008)	Designing in flexibility and variety - to create places that are diverse and robust and can accommodate future change	1	1	1
Local	East Staffordshire Design Guide SPD (2008)	User needs considered early in the development process - to ensure the development is fit for purpose and meets existing and future needs.	1	1	1
Local	East Staffordshire Design Guide SPD (2008)	Design for more Sustainable Development - Consider on-site generation of renewable energy from the sun, from the wind or from the Earth.	1	1	1
Local	East Staffordshire Sustainability Appraisal (2014)	To reduce the causes and impacts of climate change, improve air quality, promote energy efficiency and encourage the use of renewable energy	1	1	1
Local	East Staffordshire Sustainability Appraisal (2014)	To encourage sustainable design and practice and create a high quality built environment	1	1	1
Local	East Staffordshire Sustainability Appraisal (2014)	To deliver more sustainable use of land in more sustainable locations	1	1	1
Local	East Staffordshire Sustainability Appraisal (2014)	To ensure the prudent use of natural resources and the sustainable management of existing resources	1	1	1
Local	Stapenhill Neighbourhood Plan (2016)	All new development should exhibit high quality design and should respond creatively to the function and identity of Stapenhill	1	1	1
Local	Stapenhill Neighbourhood Plan (2016)	Schemes should be demonstrating how they would deliver development which is energy efficient and aims to reduce carbon emissions	1	1	1
National	BREEAM	BREEAM Ene01 (Reduction of energy use and carbon emissions)	1	1	1

Appendix I3 - Urban Design Geo-resource (UDG) Matrix for Subsurface Space (Canary Wharf Crossrail Station). Potential methods of geo-resource use across the horizontal axis, and the sustainability and resilience aspirations and urban design and planning policies down the vertical axis (which are collectively referred to as criteria). Intersecting boxes are marked with a 1 where the criteria is supported by the geo-resource use (or the geo-resource use can fulfil the criteria), and a 0 where there is no link.

Level	Technical Design Assessment	Design criteria	transport infrastructure	service infrastructure	repository	underground building	geotechnical medium
National	UK Government Design Guidance	**be functional** (fit for purpose, intuitive, comfortable, safe, easy for all to use, relate to its envrionmental circumstances so that events such as flooding do not prevent it from being used.)	1	1	1	1	1
National	UK Government Design Guidance	**support mixed uses and tenures** (easy access to facilities, mix of uses to allow communities and places to respond to change more readily by allowing a turnover of activities.)	1	1	0	1	0
National	UK Government Design Guidance	**include successful public spaces** (public spaces for everyone - hard and soft landscape elements, well orientated routes. Public art and sculpture.)	1	1	0	1	0
National	UK Government Design Guidance	**be adaptable and resilient** (flexible and able to respond to future needs, building change of use. Designing buildings that can be adapted to different needs offers real benefits in terms of the use of resources.)	1	1	1	1	0
National	UK Government Design Guidance	**have a distinct character** (aspects such as the local pattern of street blocks and plots; building forms; details and materials; style and vernacular; landform and gardens, parks, trees and plants; and wildlife habitats and micro-climates)	1	1	1	1	0
National	UK Government Design Guidance	**be attractive** (So too can more transient elements – such as the way sunshine and shadows move across an area or the way it is maintained and cleaned. Composition of elements and the relationship between colours, textures, shapes and patterns are all important)	1	0	0	1	0
National	UK Government Design Guidance	**encourage ease of movement** (appropriate number of routes to and through it. How direct and understandable these are, how closely they fit with desired lines of travel, and how well they connect with each other and destinations)	1	1	0	1	0
National	Planning Policy Statement 1: Delivering Sustainable Development	The prudent use of resources means ensuring that we use them wisely and efficiently, in a way that respects the needs of future generations…. The broad aim should be to ensure that outputs are maximised whilst resources used are minimised	1	1	1	1	0
National	Planning Policy Statement 1: Delivering Sustainable Development	minimise the need to consume new resources over the lifetime of the development by making more efficient use or reuse of existing resources, rather than making new demands on the environment	0	0	0	0	1

National	Planning Policy Statement 1: Delivering Sustainable Development	Bring forward sufficient land of a suitable quality in appropriate locations to meet the expected needs for housing, for industrial development, for the exploitation of raw materials such as minerals, for retail and commercial development, and for leisure and recreation	1	1	0	1	1
National	Planning Policy Statement 1: Delivering Sustainable Development	Reduce the need to travel and encourage accessible public transport provision to secure more sustainable patterns of transport development. Planning should actively manage patterns of urban growth to make the fullest use of public transport and focus development in existing centres and near to major public transport interchanges.	1	1	0	0	0
National	Planning Policy Statement 1: Delivering Sustainable Development	Promote the more efficient use of land through higher density, mixed use development and the use of suitably located previously developed land and buildings	1	1	1	1	1
National	Planning Policy Statement 1:	carefully planned, high quality buildings and spaces that support the efficient use	1	1	1	1	0
National	Planning Policy Statement 1: Delivering Sustainable Development	Good design should...be integrated into the existing urban form and the natural and built environments;	1	1	1	1	0
National	Planning Policy Statement 13 (PPS 13) Transportation and Land Use	Accessibility by modes of transport other than the private car should be a key consideration in the allocation of land for development	1	0	0	0	0
National	Planning Policy Statement 13 (PPS 13) Transportation and Land Use	The potential to deliver an integrated land use/transport planning approach should be maximised by the identifi cation of key sites within larger urban areas that are most readily accessible.	1	0	0	0	0
National	Planning Policy Statement 13 (PPS 13) Transportation and Land Use	Higher density and mixed use developments should be focused in locations benefitting from high accessibility to public transport facilities.	1	0	0	0	0
National	Planning Policy Statement 13 (PPS 13) Transportation and Land Use	Land required to facilitate improvements in the transport network should be afforded protection.	1	0	0	0	0
National	Planning Policy Statement 13 (PPS 13) Transportation and Land Use	The integration of transport and land use planning should seek to create a more accessible environment for all.	1	0	0	1	0
National	Planning Policy Statement 7 (PPS 7) Sustainable Development in Rural Areas	To promote more sustainable patterns of development preventing urban sprawl	1	1	1	1	1
National	Planning Policy Statement 7 (PPS 7) Sustainable Development in Rural Areas	To promote more sustainable patterns of development discouraging the development of 'greenfield' land	1	1	1	1	1
National	Planning Policy Statement 7 (PPS 7) Sustainable Development in Rural Areas	Decisions on development proposals should be based on sustainable development principles, ensuring an integrated approach to the consideration of... prudent use of natural resources	1	1	1	1	1
National	Planning Policy Guidance 2: Green belts	aim of Green Belt policy is to prevent urban sprawl by keeping land permanently open	1	1	1	1	0
National	Planning Policy Guidance 25: Development and Flood Risk	consider at a strategic scale whether there are opportunities to be gained to reduce flood risk to existing settlements through large-scale flood water storage schemes.	0	0	1	0	0

National	Planning Policy Statement 10: Planning for Sustainable Waste Management	ensure the design and layout of new development supports sustainable waste management.	0	0	1	1	0
National	Planning Policy Statement 23: Planning and Pollution Control	ensure the sustainable and beneficial use of land (and in particular encouraging reuse of previously developed land in preference to greenfield sites).	1	1	1	1	0
National	Planning Policy Guidance 24: Planning and Noise	Plans should contain policies designed to ensure, as far as is practicable, that noise sensitive developments are located away from existing sources of significant noise (or programmed development such as new roads) and that potentially noisy developments are located in areas where noise will not be such an important consideration or where its impact can be minimised.	1	0	1	1	0
National	Planning Policy Statement 6: Planning for Town Centres	Wherever possible, growth should be accommodated by more efficient use of land and buildings within existing centres. Local planning authorities should aim to increase the density of development, where appropriate.	1	0	1	1	0
National	Planning Policy Statement 6: Planning for Town Centres	Developments should be accessible by a choice of means of transport, including public transport, walking, cycling, and the car	1	0	0	0	0
Regional	London Plan (2004)	Objective 1: To accommodate London's growth within its boundaries without encroaching on open spaces	1	1	1	1	1
Regional	London Plan (2004)	Objective 2: To make London a better city for people to live in	1	1	0	1	1
Regional	London Plan (2004)	Objective 3: To make London a more prosperous city with strong and diverse economic growth	1	1	1	1	1
Regional	London Plan (2004)	Objective 5: To improve London's accessibility	1	0	0	1	0
Regional	London Plan (2004)	Objective 6: To make London a more attractive, well-designed and green city	1	0	0	1	0
Regional	London Plan (2004)	Policy 2A.1 Sustainability criteria	1	1	0	1	1
Regional	London Plan (2004)	Policy 2A.2 Opportunity Areas	1	1	0	1	1
Regional	London Plan (2004)	Policy 2A.3 Areas for Intensification	1	1	1	1	1
Regional	London Plan (2004)	Policy 2A.7 Strategic Employment Locations	1	0	0	1	1
Regional	London Plan (2004)	Policy 3A.15 Protection and enhancement of social infrastructure and community facilities	1	0	0	1	0
Regional	London Plan (2004)	Policy 3A.18 Locations for health care	1	1	0	1	1
Regional	London Plan (2004)	Policy 3A.22 Higher and further education	1	1	0	1	1
Regional	London Plan (2004)	Policy 3B.1 Developing London's economy	1	1	0	1	1
Regional	London Plan (2004)	Policy 3B.10 Tourism industry	1	1	0	1	1
Regional	London Plan (2004)	Policy 3C.1 Integrating transport and development	1	0	0	0	0
Regional	London Plan (2004)	Policy 3C.2 Matching development to transport capacity	0	1	0	1	1
Regional	London Plan (2004)	Policy 3C.3 Sustainable transport in London	1	0	0	0	1
Regional	London Plan (2004)	Policy 3C.4 Land for transport functions	0	1	0	1	1
Regional	London Plan (2004)	Policy 3C.5 London's international, national and regional transport links	1	0	0	0	1
Regional	London Plan (2004)	Policy 3C.6 Airport development	1	0	0	0	1
Regional	London Plan (2004)	Policy 3C.8 Improving strategic rail services	1	0	0	0	1

Regional	London Plan (2004)	Policy 3C.9 Increasing the capacity, quality and integration of public transport to meet London's needs	1	1	0	0	0
Regional	London Plan (2004)	Policy 3C.11 New cross-London links within an enhanced London National Rail network	1	0	0	0	1
Regional	London Plan (2004)	Policy 3C.12 Improved Underground and DLR services	1	1	0	0	1
Regional	London Plan (2004)	Policy 3D.2 Town centre development	0	1	0	1	1
Regional	London Plan (2004)	Policy 3D.3 Maintaining and improving retail facilities	0	1	0	1	1
Regional	London Plan (2004)	Policy 3D.5 Sports facilities	0	1	0	1	1
Regional	London Plan (2004)	Policy 3D.6 Visitors accommodation and facilities	0	1	0	1	1
Regional	London Plan (2004)	Policy 3D.7 Realising the value of open space	1	1	1	1	1
Regional	London Plan (2004)	Policy 3D.8 Green Belt	1	1	1	1	1
Regional	London Plan (2004)	Policy 3D.14 Agriculture in London	1	1	1	1	1
Regional	London Plan (2004)	Policy 3D.15 Burial space	0	0	0	1	0
Regional	London Plan (2004)	Policy 4A.1 Waste strategic policy and targets	0	0	1	0	0
Regional	London Plan (2004)	Policy 4A.2 Spatial policies for waste management	0	0	1	0	0
Regional	London Plan (2004)	Policy 4A.5 Spatial policies to support the better use of aggregates	1	0	0	1	0
Regional	London Plan (2004)	Policy 4A.7 Energy efficiency and renewable energy	0	1	0	0	0
Regional	London Plan (2004)	Policy 4A.11 Water supplies	0	1	0	0	0
Regional	London Plan (2004)	Policy 4A.13 Water and sewerage infrastructure	0	1	0	1	1
Regional	London Plan (2004)	Policy 4A.14 Reducing noise	1	0	1	1	0
Regional	London Plan (2004)	Policy 4A.15 Climate change	1	1	1	1	1
Regional	London Plan (2004)	Policy 4A.17 Dealing with hazardous substances	0	0	1	0	0
Regional	London Plan (2004)	Policy 4B.1 Design principles for a compact city	1	1	1	1	1
Regional	London Plan (2004)	Policy 4B.2 Promoting world-class architecture and design	1	1	1	1	1
Regional	London Plan (2004)	Policy 4B.3 Maximising the potential of sites	1	1	1	1	1
Regional	London Plan (2004)	Policy 4B.4 Enhancing the quality of the public realm	1	1	0	1	1
Regional	London Plan (2004)	Policy 4B.5 Creating an inclusive environment	1	1	0	1	1
Regional	London Plan (2004)	Policy 4B.6 Sustainable design and construction	1	1	1	1	1
Regional	London Plan (2004)	Policy 4B.7 Respect local context and communities	0	0	0	1	1
Regional	London Plan (2004)	Policy 4B.9 Large-scale buildings – design and impact	0	1	0	1	1
Regional	London Plan (2004)	Policy 4B.14 Archaeology	1	1	1	1	0
Regional	London Plan (2004)	Policy 4C.4 Natural landscape	1	1	1	1	1
Regional	London Plan (2004)	Policy 4C.8 Sustainable drainage	0	0	1	0	0
Regional	London Plan (2004)	Policy 4C.21 Design statements	1	1	1	1	0
Regional	London Plan (2004)	Policy 5C.1 The strategic priorities for East London	1	1	0	1	1
Regional	London Plan (2004)	Policy 5C.2 Opportunity Areas in East London	1	1	0	1	1
Regional	Sustainable Design and Construction SPG (2014)	Developers should optimise the scale and density of their development, considering the local context, to make efficient use of London's limited land.	1	1	1	1	0
Regional	Sustainable Design and Construction SPG (2014)	Where there is pressure for basement developments, boroughs should consider whether there are any particular local geological or hydrological issues that could particularly effect their construction, and adopt appropriate policies to address any local conditions.	0	0	0	1	1

Regional	Sustainable Design and Construction SPG (2014)	When planning a basement development, developers should consider the geological and hydrological conditions of the site and surrounding area, proportionate to the local conditions, the size of the basement and lightwell and the sensitivity of adjoining buildings and uses, including green infrastructure.	0	0	0	1	1
Regional	Sustainable Design and Construction SPG (2014)	To provide space for individual or communal food growing, where possible and appropriate.	0	0	0	1	0
Regional	Sustainable Design and Construction SPG (2014)	Developments should contribute to ensuring resilient energy infrastructure and a reliable energy supply, including from local low and zero carbon sources.	0	1	0	0	0
Regional	Sustainable Design and Construction SPG (2014)	Developments and lighting schemes should be designed to minimise light pollution.	1	1	1	1	0
Regional	Sustainable Development Framework for London (2002)	We will limit and deal with our pollution, and use energy and material resources prudently, efficiently and effectively, including re-using and recycling our residual waste.	1	1	1	1	1
National	BREEAM Bespoke 2008	Pol 5 - Flood Risk - To encourage development in low flood risk areas or to take measures to reduce the impact of flooding on buildings in areas with a medium or high risk of flooding.	0	0	0	1	1
National	BREEAM Bespoke 2008	Wat 6 - Irrigtation Systems - To reduce the consumption of potable water for ornamental planting and landscape irrigation.	0	1	0	0	0
National	CEEQUAL 2010	12.4.5 - Human environment, aesthetics and employment - evidence that the needs of all different user groups have been considered and respected in the design solution	1	0	0	1	0