Government
Office for Science

Future of the Subsurface

What would happen if we turned planning upside down?

June 2024

Foresight

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Artwork credit: Cleo Zhang

Foresight

Foreword

Use of the subsurface has been vital for people for thousands of years. The availability of subsurface resources such as water, fertile soil, and building materials, has long influenced where we choose to live. The UK's diverse geology also plays a significant role in shaping its landscape, and influences various aspects of land use, planning, and society.

The subsurface today houses different assets and services required for everyday life. These include water supply, sewers, energy, waste storage, building foundations and transportation, as well as resources like minerals and aggregates that are essential to our economy. With the demand for these set to increase, pressures on the subsurface are likely to grow over the coming decades.

The subsurface will play an increasingly vital role in reaching our net zero ambitions, in how we adapt to climate change, and in how we grasp the opportunities presented by technological innovation. As these needs drive competition for space, there is a risk that congestion could limit our options for how we use it in the future.

This report is part of the Government Office for Science's long-standing Foresight programme. It draws together evidence from a wide range of sources and extensive engagement with over 350 experts from academia, industry, local and central government, and other public sector bodies. We set out the key current issues and challenges to subsurface management and consider future trends and scenarios that we may need to adapt and respond to. The report is not a highly technical document, rather a review of the current and future role of the subsurface in the UK for non-experts, including those who may have never thought about the subsurface in detail.

As is common in our Foresight work, we have taken a 'systems thinking' approach to the issue, which means exploring the interconnections within the subsurface system that policy makers will need to consider. It also highlights unintended consequences that can occur if we ignore these complex system interactions and highlights how decisions regarding the subsurface can be difficult to undo once they are made.

In order to explore what the future of the subsurface might involve, the report sets out three scenarios that explore a plausible worst-case for subsurface development in three thematic areas (net zero, climate change adaptation, and technological advancements).

This is not a statement of government policy.

These are deliberately challenging in nature and assume no significant changes to the current system of planning, policies, and regulations (as of June 2024). Scenarios are not meant to predict the future, rather they are used here to help policy makers consider solutions that might help to avoid the worst outcomes in each case.

One thing that this project has highlighted is the importance of collaboration, particularly with the regions and nations of the UK, and between public, private and the third sector, to how we think about and use the subsurface. I hope this report encourages those whose work involves the subsurface to engage far and wide in their work, as this is how innovative solutions may be reached.

I would like to thank everyone, including the wide range of academic, government and industry experts, who supported this work as well as the brilliant team in the Government Office for Science.

Professor Dame Angela McLean
Government Chief Scientific Adviser

Contents

Glossary

Term	**Definition**
AI	Artificial intelligence.
AR/VR	Augmented reality/virtual reality.
CCS	Carbon capture and storage. Capturing carbon dioxide at emission sources and transporting it to store or bury in an appropriate underground location.
CCUS	Carbon capture, usage and storage.
CSIC	Centre for Smart Infrastructure and Construction.
Digital Twin	A digital representation of a physical asset, or a physical process contextualised within a digital version of its environment.
EV	Electric vehicle.
Feedback loop	A system structure in which an output from one node causes changed which eventually influence the input that same node.
Geodiversity	The variety of rocks, minerals, fossils, landforms, sediments and soils, together with the natural processes which form and alter them.
Geohazard	An adverse geological process which can put people at risk and damage property and infrastructure.

Glossary

Geothermal heat	Geothermal heat is heat energy which comes from the Earth.
Groundwater	Groundwater is water below the earth's surface between rocks and in the soil.
Node	A term used in systems thinking to refer to a single element of a system.
NPPF	National Planning Policy Framework.
NSIP	Nationally Significant Infrastructure Projects.
NUAR	National Underground Asset Register.
Rainwater harvesting	The collection and storage of rain, preventing it being lost as run-off down drains.
Subsurface	The space below the Earth's surface and below the ocean floor.
SuDS	Sustainable drainage systems.
Systems map	A visual depiction of a system, showing different parts of the system and the ways these interact.
Systems thinking	An approach which looks at a system at a whole by considering its constituent parts and the way these interact with each other. This can help solve problems involving many individual organisations or parts with competing priorities.
Urban heat islands	Urban areas experiencing higher temperatures than surrounding rural areas.

Executive summary

The 'subsurface' comprises everything below the land or sea-floor surface. While often 'out of sight, out of mind', the subsurface is a natural habitat, a source of critical resources, and a space for the infrastructure that underpins modern economies. The diverse services directly and indirectly enabled by the subsurface are set to increase in variety and importance over the coming decades, due to drivers including urban densification, technology demand, climate change adaptation, and net zero targets.

This report sets out available evidence on current challenges and trends related to the UK's subsurface, then explores how these might evolve in future and what we need to do now to prepare. The report's primary audience is government departments, local authorities, regulators, and others engaged in developing subsurface policy. Our key findings are informed by a wide range of evidence and methods, including a literature review, expert workshops, systems mapping, and development of future scenarios.

Background

- There are more than 4 million kilometres of pipes and cables installed below ground in the UK, including water, sewers, gas, electricity, and communications (Geospatial Commission, 2023). The subsurface is also home to many other assets and features that we rely on in the UK, including transport infrastructure, building foundations, and tree roots.
- A lack of accessible data on the subsurface has been identified as a key challenge by project stakeholders, which makes it more difficult and expensive to plan, build, and maintain subsurface assets.
- Some subsurface data are available for these purposes, such as geological data from the British Geological Survey. Since 2019, government has also been developing the National Underground Asset Register (NUAR), a platform for

sharing data on of buried pipes and cables (Depaartment for Science, Innovation and Technology & Geospatial Commission, 2022). A similar scheme has been running in Scotland since 2012 (Office of the Scottish Roadworks Commissioner, 2018).

- These initiatives are supporting subsurface use in the UK, helping to reduce uncertainty for infrastructure construction and maintenance. But they only cover a subset of data on the subsurface, and access is currently limited to certain uses, so they are unlikely to address the range of existing and future challenges identified in this report unless this changes.

Mapping the subsurface system

The subsurface is a complex, multifunctional 'system of systems.' Unintended consequences can result from interactions between its different features and functions.

To explore this, we adopted a systems thinking approach and developed a basic systems map of the subsurface. We ran expert workshops to help create an initial map, which we then refined through iterative peer review. From this, we have developed three example interactions, which illustrate how different subsurface uses could potentially interact with each other and lead to unintended consequences.

Subsurface 2040 scenarios

To help policy makers think through key issues for the future, we also developed three hypothetical 2040 scenarios. These explore a plausible worst-case for subsurface development in three thematic areas assuming no significant change to the current system of planning, policies, or regulations (as of June 2024). They are designed to help policy makers consider solutions that might help avoid the worst outcomes in each case:

- **Net Zero, Targets At Risk**: The UK's net zero 2050 target is at risk, as planning barriers have delayed delivery of the required net zero infrastructure, particularly in the subsurface.

- **Climate Change Adaptation, Under Pressure**: The world has seen 3 degrees of warming, with more frequent and intense extreme weather and pressures on water management. Subsurface assets have not been adequately prepared.
- **Technological Change, Falling Behind**: UK regulatory barriers slow the rollout of emerging technologies such as for tunnelling and robotics. We lack new capabilities to measure and use the subsurface and fall behind other countries.

Key findings

The key findings of this report are:

1. **The subsurface is a space, much the same as the above ground, whose use needs to be monitored, planned, and managed. But the data, technologies, and policy tools needed for this lag behind those available for the surface**. Evidence gathered for this project suggests that moving to a three-dimensional planning approach that manages how space is used vertically as well as horizontally would be a major step towards parity between the subsurface and the surface.
2. **The subsurface faces specific challenges to using it more effectively and sustainably**:
    - **Data availability, accessibility, and quality**. It is difficult to collect data on the subsurface as it is opaque to most sensors. The data that are collected often have accessibility or quality issues. Datasets have either good geographical coverage or good coverage of different subsurface features, but rarely both.
    - **Space competition and congestion**. Subsurface space is often used on a 'first come first served' basis and is congested with various uses, particularly in urban areas. When combined with a lack of data on existing uses, this competition and congestion makes it challenging to optimise future uses.
    - **Complex system interactions**. As subsurface assets and features are physically connected by the earth, they often interact with one another via transmission mechanisms like the ground, water, and heat. These

interactions are generally not monitored but can lead to adverse unintended consequences across sectors.

- **Coordination and regulation**. Subsurface use is not comprehensively coordinated in the way that use of surface space is by the planning system. This can make it difficult to plan and prioritise important future uses, including coordination with uses of space above ground. Furthermore, some subsurface uses are only regulated to a certain extent (e.g. geothermal energy).

3. **These challenges contribute to increased costs and delays for delivery of critical infrastructure**. Unintentional 'strikes' of subsurface utilities are estimated to cost the UK around £2.4 bn per year, with around 30% of strikes thought to be avoidable with better data (Cabinet Office & Geospatial Commission, 2021). In addition, 20-60% of linear and transport infrastructure projects experience delays due to unforeseen ground conditions (Bricker et al, 2022).
4. **These challenges also threaten societal resilience and emergency response capabilities, which depend on our ability to monitor and manage the subsurface**. Floods and other hazards have the potential to disrupt the vital services that our use of subsurface space enables.
5. **Future trends are set to make it more important to address these challenges**. These include the need to accommodate more people in cities, build net zero infrastructure, and adapt to worse floods and heatwaves caused by climate change. Long-term solutions to cross-cutting subsurface challenges will need to be developed in a way that accounts for these trends.
6. **New technology offers potential solutions, but policy makers will need to be proactive to ensure the UK benefits from these changes**. New technologies that make it easier and cheaper to measure, monitor, excavate, tunnel, and maintain the subsurface are on the horizon, but may need new policy or regulation to enable their widespread use. Measures to promote wider adoption of existing technology should be considered alongside supporting new technological developments
7. **Our analysis has identified 'low regret' areas** that policy makers should consider, which focus on data, building on the progress made through NUAR:

  - **Collecting more data and improving quality**: Progress has been made in collection of data on geology and subsurface infrastructure, but improving the quality and granularity of this data would make it more useful for informing decisions. This is also true for other subsurface features where data is not comprehensively collected, such as groundwater. Data collection systems should prioritise ongoing maintenance and interoperability of datasets.
  - **Making data more accessible**: Datasets that do exist are held in disparate places and are often not widely accessible, such as geothermal energy. Systems that improve access to datasets, standardise them, and bring them together for analysis would help provide the insight needed to make more effective decisions about the subsurface. Any move to do this would need to address the national security risks and commercial considerations of making data on critical national infrastructure more accessible.
  - **Investing in tools to help use data in decision making**: Once datasets are collected and assembled, policy makers should consider investing in tools that can further inform decision making, such as digital twins to simulate the impacts of subsurface interventions or changes in environmental conditions.
  - **Developing technological capability to solve subsurface challenges**: Policy makers should ensure that technology policy helps to develop capabilities that address the challenges set out above. Such capabilities include lower cost or higher performance measurement, excavation, and maintenance, which could be achieved through developments in technologies including quantum sensors, AI, and robotics.

8. **Addressing the other challenges identified will require policy makers to consider trade-offs**:
    - **How devolved?** Coordination could plausibly be improved through stronger national frameworks, by devolution of decision making to a local or regional level, or a solution that sits somewhere between these extremes. Wherever coordination responsibilities sit, they will need to be

supported by the data, tools, and skills required to inform decision making.

- **How regulated and planned?** The market can bring investment and a state-of-the-art understanding of subsurface solutions, but without effective regulation and coordination is unlikely to optimise overall subsurface use for long-term public goods. Policy makers will need to consider how best to balance this trade-off.

How to use this report and the outputs

The primary audience for this report is government departments, local authorities, regulators, and expert stakeholders engaged in developing subsurface policy.

The report does not make specific policy recommendations, but it does set out important challenges to resolve and issues for policy makers to consider in a format we hope policy makers will find useful in developing solutions. The systems mapping and scenarios approaches covered below also provide tools to help policy makers develop more effective and resilient subsurface policies. GO-Science can advise policy makers on use of the report findings and other outputs.

The report is also supported by a set of evidence reviews published alongside this report. These cover tunnelling; urban water management; subsurface space management; and geothermal energy generation.

We hope you find this report useful. It's important for us to monitor the impact our work has so we'd appreciate if you'd contact us at foresight@go-science.gov.uk to let us know how this report has informed and influenced your work.

Chapter One
Introduction

Introduction

The 'subsurface' refers to everything below the land or sea-floor surface. It has been used by humans for thousands of years, and the availability of subsurface services and resources, such as water, building materials, and fertile soil, has long influenced where we choose to settle (Tann, 2018). Beyond being a simple physical space, the subsurface contains geological, hydrological, and biological features and processes, as well as engineered components such as utilities, foundations, and other infrastructure. With these different interacting components, the subsurface can be understood as a complex and dynamic 'system of systems', which is also connected to features above ground.

The uppermost few hundred metres below the surface - sometimes referred to as 'shallow subsurface' - form the primary 'zone of human interaction' below the ground (Price, 2010).

Society relies on the shallow subsurface for a range of purposes, including as a habitat for plants and animals and a physical space for assets such as digital networks and energy infrastructure, especially in urban areas.

Below the shallow subsurface is the 'deep subsurface', in which human activity is generally limited to exploration and mining activities, including the extraction of oil and gas, geothermal energy, and the storage of nuclear waste and CO_2.

The subsurface houses over 4 million kilometres of underground services in the UK. Seven of the UK's 13 critical national infrastructure sectors rely directly on the subsurface. These include civil nuclear, communications, defence, energy, food, transport, and water. As well as having an essential role for society in the past and present, the subsurface is set to become increasingly important in the future. It has been identified as being crucial in achieving resilient and sustainable cities (Volchko, 2020), with the use of urban underground space expected to contribute to seven of 17 UN sustainable development goals (SDGs) (Admiraal, 2016). England's urban population grew by over 6% between 2011 and 2019 and is now at over 80% of the total. With this growth, the demand and competition for subsurface resources and space will likely increase over the coming decades (Government Office for Science, 2021).

Space in the subsurface is finite and once decisions are made about its use, they are difficult to undo. The regulation and governance of these decisions is complex and sector dependent, and interactions between sectors or with the environment can lead to unintended consequences. As we have identified these as the most significant challenges associated with subsurface use, this report is primarily concerned with sectors and use cases for which systemic interactions and space congestion are most acute.

This report is not intended to be a scientific deep dive, rather a review of the overall role of the subsurface in the UK aimed at non-technical audiences, including those who may have never thought about the subsurface in detail.

The Foresight team has touched on similar issues in the past, such as our Future of Cities report which included an essay on 'Development underground', and our Land Use Futures project, which used systems thinking to explore future land use changes both above and below ground (Government Office for Science, 2016), (Government Office for Science, 2010). But we decided that now is a timely moment to revisit these issues in more depth, given the relevance to national infrastructure priorities (including net zero and adapting to climate change), and the advent of the National Underground Asset Register (NUAR), which provides a foundation on which further improvements in subsurface management can be built.

Throughout the project, we engaged with over 350 experts, including from national and local institutions, academia, the public sector, and industry. We have completed three detailed evidence reviews on urban water management, space management, and geothermal energy, and commissioned Arup to complete a review of tunnelling technologies relevant to the subsurface. We have also explored systems interactions within the subsurface, and developed 2040 scenarios to help policy makers develop solutions to the issues we have identified.

Chapter Two
Current UK Status

The Subsurface of the UK – Current Status

In the UK, effective use of the subsurface is challenged by issues including data availability, congestion, and complex interactions between use cases. Focusing on urban areas, this section outlines current subsurface use by sector, then highlights major cross-cutting current challenges, which were identified through a literature review and stakeholder consultation.

2.1 Main categories of subsurface use

The subsurface provides space for engineered structures and holds resources used across multiple sectors, as well as being a natural habitat that supports plant and animal life (Frisk, 2022). It comprises a range of important geological, hydrological, and biological features, incorporating vital functions such as water supply. These include pores, groundwater aquifers, and varying rock types which have different physical, mechanical, and chemical properties.

Burying infrastructure and other engineered structures brings many benefits. It creates less visible impact for the public and can reduce the risk that certain types of damage pose to infrastructure. It also frees up space above ground for services which people benefit from interacting with directly. However, there are increased costs associated with burying infrastructure, including installation and maintenance, and disruption costs from both of these. For example, it has been estimated that the costs of underground electricity transmission lines are 5-10 times those of overhead lines (UK Parliament, 2024).

Human use of the subsurface also displaces non-human uses, such habitats for organisms like worms and fungi that are important for soil health and other ecosystem services. Natural elements can also present challenges to subsurface planning. For example, plant life at the surface interacts with the subsurface through roots, which can grow through the shallow subsurface and interfere with infrastructure.

This section outlines some of the key sectors that rely on the subsurface, and their interaction with the natural subsurface environment. As mentioned above, this report is primarily concerned with sectors and subsurface uses for which systemic interactions and space congestion are most acute. For this reason, this section focuses on the subsurface within urban and built-up settings, rather than in offshore and rural areas (although these geographies are considered at a high level where there are systemic connections to the urban subsurface). This also means that the role of the subsurface in food production, as a source of minerals, and as a place of cultural significance and scientific exploration are not explored in detail.

As a habitat

Humans are just one of many living species on earth that use the subsurface. The subsurface supports and provides a habitat for plant, animal, and microbial life. Animals that burrow underground in the UK include badgers, moles, and foxes, and this burrowing affects the chemical and physical properties of soil. Their impact varies but can include changes to the soil's structure and increases in infiltration rates and permeability (Platt, 2016). Subsurface microbiomes have a crucial role in driving physical processes which affect nutrition cycling, soil health, ecosystem biochemical processes, and groundwater (Chu, 2016), (Hartmann, 2009). Plants also bring valuable benefits to the subsurface. Trees, for example, significantly increase soil infiltration rates which can help manage surface water (Forestry Commission, 2022).

Biodiversity within the subsurface provides benefits to humans too, as it is important for agricultural production (Brussaard, 2007), carbon sequestration, and reducing contaminants. Subsurface biodiversity therefore has implications for human health (Sun, 2023).

Water

The subsurface has a crucial role in supporting services provided by the water sector, including water supply, water storage for drought prevention, wastewater management, and mitigating flood risk.

For water supply, the subsurface provides both a source of water through groundwater and a physical space for pipes and aqueducts transporting water to where it is needed. Groundwater is the water found beneath the Earth's surface in spaces within rocks and soils. It accounts for a third of the UK's public water supply, and a far higher proportion in some regions, such as over 75% in South East England (British Geological Survey, n.d.). It supports natural habitats, such as rivers and wetlands, and can also be used as a source of geothermal energy extracted via open or closed loop heating systems. Pipes supplying water frequently leak and cause around a fifth of public water supply to be lost each year (Ofwat, 2022). Although the volume of water lost to leaks has been decreasing in recent years, they remain frequent and are difficult to detect.

The subsurface plays a key role in the management and treatment of wastewater, providing space for sewerage pipes which carry wastewater to treatment facilities. It also facilitates the drainage of surface water, both through natural drainage into the soil where it becomes groundwater, and by holding engineered traditional and sustainable drainage systems. In urban areas the ground is often covered with impermeable surfaces which limit natural drainage so that rainwater collects on the surface. Therefore, both traditional and sustainable engineered drainage systems are essential for managing flood risk, which is both dangerous to life and causes losses of around £700 million from flood damage annually (Gill & Stephens, 2023). Around a third of drains in the UK are 'combined drains', which mix rainwater and wastewater. This places the wastewater systems under significant pressure and can result in sewage overflow events. In the National Storm Overflows Plan for England, water companies have recently pledged to invest £10 billion this decade to modernise sewers and reduce sewage overflows aiming to remove an average 150,000 spills each year by 2030 (Water UK, 2024). For a more detailed description of water systems and the subsurface within an urban setting, see the evidence review on *urban water management in the UK*.

Energy

Energy generation, storage, and distribution in the UK rely heavily on the subsurface. The subsurface provides space for infrastructure needed to deliver energy, such as pipes for gas networks, and contains several natural sources of energy including geothermal energy, and conventional energy sources such as oil and gas.

Energy networks supply electricity and gas to homes and businesses across the UK, consisting of both transmission networks for transport over long distances, and distribution networks, for transport to where they are needed locally (Energy Networks Association, n.d.). A substantial amount of this infrastructure is underground, for example the electricity transmission network in England and Wales has around 7,200 km of overhead line, and over 1,400 km of cables underground (National Grid Electricity Transmission, n.d.). Distribution networks generally have a higher proportion of underground cables, for example the electricity distribution network supplying the Midlands, South West and South Wales is made up of 97,000 km of overhead line, and 135,000 km of underground cables (National Grid, n.d.). In the UK, around 29 million homes (the vast majority) are connected to electricity networks, and 22 million homes and businesses are connected to gas networks (around 15% of dwellings are not) (Energy Networks Association, n.d.). The electricity grid requires upgrading to support increases in electricity use required for net zero, such as upgrades for electric vehicle charging, which are already happening. Electricity companies now expect to install 200,000 to 600,000 km of new distribution cabling by 2050 (Street Works UK, 2022).

As there is likely to be some use of natural gas in a net zero energy system, albeit in much smaller volumes (IEA, 2021), there is ongoing interest in accessing subsurface sources of gas in the UK (Prime Minister's Office, 10 Downing Street & DESNZ, 2023).

Whilst this is currently mostly offshore, there have been moves in the UK to extract more gas onshore through hydraulic fracturing, or “fracking”, of shale rock that contains pockets of gas and oil. This can induce seismic activity, which is considered mild, but can sometimes be felt at the surface. This, along with environmental concerns, has contributed to strong public resistance to the use of fracking to explore for gas from shale rocks in the UK. The government has responded to this resistance with an effective moratorium on shale gas extraction using fracking, last reconfirmed in 2022 (Sutherland & Rankl, 2022).

Another important subsurface energy source is geothermal energy, heat that is either generated by the slow decay of radioactive particles in the Earth's core or from solar energy that is incident at the Earth’s surface and stored in the shallow subsurface. Geothermal energy is a renewable, secure, low-carbon energy source. It is accessible across the UK at depths ranging from a few metres to several kilometres, although most current extractions focus on heat in the shallow subsurface (GSI, n.d.). By 2020, around 43,700 ground source heat pump systems using shallow geothermal heat had been installed in the UK (Abesser & Jans-Singh, 2022). And in 2021, together with operational geothermal direct-use and mine water energy schemes, these supplied 0.3% of the annual heat demand in the UK (Abesser & Walker, 2022). The accessible geothermal energy potential within the UK is much greater than this, and estimated to be able to fulfil UK residential heat demand for 100 years (Gluyas, et al., 2018). For a more detailed description of the status of geothermal heat within the UK, see the evidence review on *geothermal energy generation in the UK*.

The energy sector could also become increasingly dependent on the subsurface for storage as it decarbonises, including hydrogen and waste products such as nuclear waste and carbon from carbon capture and storage.

Transport infrastructure

All land-based modes of transport interact with the subsurface and rely on subsurface space for essential assets and elements of their networks. All infrastructure at the surface, including roads and rail tracks which underpin our transport system, is in contact with the subsurface and exposed to associated geohazards, such as subsidence, heave, and sinkholes. Land-based transport networks often rely on subsurface assets, such as drainage infrastructure, and have below ground elements that provide passageways to cross the infrastructure or for the infrastructure itself to avoid obstacles such as rivers. These include underpasses and tunnels for pedestrians, trains, and road vehicles. London, Glasgow, and the Tyne and Wear area have distinct underground train systems, while Liverpool has one underground train route connecting to a nearby rail network. Underground carparks, such as those beneath London's Hyde Park or Nottingham's Victoria Centre, also take up subsurface space but free up surface space for other uses.

Essential utilities are often installed to run along linear transport routes in the shallow subsurface. In the future, this will increasingly include geothermal installations and district heating. In cities, streets also provide space for trees, drainage and infrastructure for streetlights, and EV charging networks, making them heavily utilised and engineered spaces. An estimated 4 million road excavations are carried out per year in the UK for utilities maintenance and repairs, which constitute a major source of disruption and delay to surface travel. Potholes are another significant expense associated with the subsurface and transport, costing over £90 million per year to fix in England and Wales (Asphalt Industry Alliance, 2024). They are caused by a combination of factors. Poor drainage, for example, can lead to water accumulating on roads so that it seeps through cracks, which can cause water damage and damage through freezing and thaw cycles which create potholes (Hazell & Jefferies Lt, n.d.).

*Figure 1: Roads carry utility pipes providing essential services, and are excavated to maintain and repair this infrastructure. Source: [© Crown copyright](). *

Buildings

All buildings interact with the subsurface, both structurally, as they rely on the ground's bearing capacity, and for their operation, as they require subsurface infrastructure to supply essential services, such as pipes and cables.

Buildings also impact the subsurface through their basements and foundations which are required for stability. In London, 7,328 new residential basements underneath houses were granted planning permission between 2008 and 2019 (Burrows, et al., 2021). Foundations range in depth and type, depending on the specific circumstance such as ground conditions and access, and the load-bearing requirements of the building being constructed. Foundations typically start with shallow spread footings and are between 0.6 m to around 3 m deep. Beyond this, if more stability is needed, or ground conditions are unstable, then pile foundations are used. These are typically 12-

28 metres deep, but can be deeper. Skyscrapers can include deep basements, which provide space for functions such as car parking and storage space (e.g. for facility infrastructure such as heating and air conditioning), as well as to reduce their net load on the ground. For example, London's 310 m high Shard has a 16.5 m deep basement and up to 60 m deep piles (Beadman, et al., 2012).

Buildings interact with the geology and water in the subsurface through their foundations and basements and can be susceptible to subsurface-related issues such as groundwater flooding, gas or vapour intrusion and subsidence (Holt, 2019). For example, in 2022 the record-breaking heatwave, which peaked at 40.3˚C, caused the highest annual insurance claims due to subsidence since 2006 with an expected payout value of £219 million (ABI, 2023).

Digital infrastructure

The subsurface holds vital digital infrastructure, including cables for telecommunications and fibre broadband. Installing these cable routes underground creates more secure networks compared with overhead cable installations, which are less susceptible to surface hazards and tearing or crushing (Evennett, 2024). Burying cable routes also creates fewer visible impacts and frees up space at the surface for other uses.

There are significant ongoing upgrades to digital and telecommunications infrastructure which impact the subsurface. These include two overarching programs being delivered by Building Digital UK, which are rolling out gigabit-capable broadband and expanding 4G mobile coverage in hard-to-reach areas of the UK, totalling £6 billion investment (Building Digital UK, n.d.). Additionally, the UK is transitioning from analogue to digital phone lines which requires all properties to be connected to broadband, with the move due to be complete in 2025.

Waste

The subsurface is also used as a location to store waste products, including as municipal domestic and commercial waste disposal sites, and for future storage uses such as captured CO_2 waste, and geological disposal of nuclear waste, which each have their own policy and regulatory challenges. Whilst waste sites are important, they are often outside urban areas, which are the focus of this report. We therefore provide some background here on these uses, but do not return to them again later in the report.

Carbon Capture, Use and Storage (CCUS) is expected to be deployed to reach net zero emissions within the UK by 2050. CCUS involves capturing carbon dioxide produced at point sources for purposes such as power generation and storing it in deep geological formations within the subsurface, for example in depleted oil and gas reservoirs. Whilst there are currently no commercial applications of CCUS in the UK, the government has plans to develop a commercial and competitive market for CCUS. This involves creating four CCUS clusters and to capture and store 20-30 Mt CO_2 per year by 2030 and establishing a regulatory framework for the sector that eventually supports a competitive market (DESNZ, 2023).

The subsurface will also provide a space for nuclear waste storage, thus playing a key role in supporting nuclear power generation. Geological disposal has been selected as the long-term management method for high level nuclear waste in the UK, in which waste will be transferred from temporary stores at the surface to engineered underground geological disposal facilities. These are expected to store the waste safely for thousands of years (UKRWI, n.d.). Over the past 50 years there have been multiple attempts to select a site for the permanent disposal of nuclear waste in the UK, and so far, none of these have been successful except for the lowest-level categories of waste. Site selection processes were initially directed by identifying an ideal site and then implementing it, however this resulted in local opposition. Now local community consent is incorporated as an essential initial step in selecting a site for disposal (Thomas, 2023), (BBC, 2022). Current plans anticipate that a facility will be ready to receive high level waste by 2075 and be in operation over the following century when it will be closed (Nuclear Waste Services, 2020).

Construction in the subsurface generates a huge volume of waste. A lot of this waste is landfilled, depending on contamination, but some of this waste can be re-used, particularly when planned effectively. The Tideway Tunnel, for example, is a 25km long tunnel currently being constructed beneath the Thames in London to help manage sewage. In its early planning phase, Tideway committed to beneficially re-using 85% of its excavated spoil, and for 90% of this to be transported by river. This led to a collaboration with a site in Rainham to build what is reported to be the largest habitat creation scheme within the M25, using almost one million tonnes of chalk and almost half a million tonnes of clay from the Tideway project (Tideway, 2022). Understanding the characteristics of the material being excavated, including any known contamination, is crucial to re-using excavated waste.

2.2 Cross-Cutting Challenges

The previous section outlined how the subsurface plays a crucial role across different sectors. But there are significant cross-cutting challenges currently experienced across these sectors for coordination, planning, and delivery of subsurface projects. This section outlines existing challenges, identified through an extensive literature review and stakeholder engagement. The next chapter explores how these existing challenges could be affected by future trends, including climate change and technological developments.

Space competition and congestion

There are more than 4 million kilometres of pipes and cables installed in the UK, including water, sewers, gas, electricity, and communication (Geospatial Commission, 2023). Growing urban populations and economies have led to growing demand for subsurface utilities, as well as taller buildings with large basements and foundation structures. This is increasing congestion and competition for space within the shallow subsurface.

Existing congestion means that finite subsurface space has been increasingly used up and no longer available for future uses. This can create constraints for infrastructure projects, particularly in urban areas. For example, during the design of Crossrail 1 tunnels that are now part of the Elizabeth line, certain London subsurface areas were found to be so congested that tunnel alignment needed to be adjusted to avoid other tunnels and foundations. In one instance, at Tottenham Court Road, the tunnel had to be threaded between a set of escalators and the Northern line, with just 700mm separating the Crossrail and the Northern line tunnels (Arup, n.d.). A number of future trends are likely to exacerbate such space competition and congestion issues in the coming years, which is covered in more detail in Chapter 3.

More detail is provided in the evidence review on *subsurface space management in the UK*.

This is not a statement of government policy.

Data availability

Knowing what is where is essential for efficient planning of subsurface projects. However, as the subsurface is opaque to most sensors, much data collection is carried out either during excavation or via boreholes, and often in an ad hoc way as part of individual projects. This means there is a lack of comprehensive, accessible data about subsurface assets and geology which can cause costly and disruptive damage and delays to delivery of critical infrastructure.

Whilst datasets do exist, the central challenge for planners is that these can be spread across different sectors and regions, and public and private data is not always shared for legal or commercial reasons.

Organisations that hold subsurface data include a mix of private sector companies, public sector organisations, including the British Geological Survey (BGS), the Coal Authority (coal mining data), the North Sea Transition Authority (e.g., seismic, oil and gas data), local authorities, environmental regulators, and universities (BGS, n.d.), (Coal Authority, 2019), (North Sea Transition Authority, n.d.).

Sourcing information on buried utility assets currently involves contacting multiple organisations who will deliver data of varying quality. Data is presented in different formats, may be incomplete or inaccurate, and has been collected in the context of specific projects rather than in a systematic manner (Cabinet Office & Geospatial Commission, 2021). Datasets for historic or abandoned infrastructure may be missing, or presented in an outdated format. Ground source heat pumps, pile foundations, and basements constitute a below ground construction hazard that may not be discovered via the normal documentary searches by design and construction companies. Accessing and processing this data to make it usable can cause significant delays to infrastructure projects below ground.

These data issues can also lead to damage. For example, utility strikes cause project delays and extended road closures and additional costs to repair the damage caused.

Current UK Status

The cost of utility strikes to the UK economy is estimated to be £2.4 billion per year, with 60,000 strikes on buried service pipes and cables occurring annually (Cabinet Office & Geospatial Commission, 2021). Around 30% of these strikes are estimated to have been avoidable with better data (Cabinet Office & Geospatial Commission, 2021).

Geological data has also been identified as being key in supporting construction and infrastructure developments, with 20-60% of linear and transport infrastructure developments in the UK experiencing delays due to unforeseen ground conditions (Bricker, et al., 2022). A lack of accessible data about geothermal energy potential also hinders utilising deep geothermal heat and mine water heat at scale, and is a particular barrier to identifying locations for its development (Abesser, et al., 2023).

In order to deal with some of these data issues, the Geospatial Commission is developing the National Underground Asset Register (NUAR), which provides an example of how legal, commercial, and security barriers can be overcome to compile and integrate national subsurface datasets. NUAR is a digital map of underground pipes and cables. This is now live across parts of the UK and will be fully operational by 2025, representing a significant step in addressing issues with subsurface data.

However, access to NUAR is limited due to security concerns and is only granted to companies with particular use cases, such as avoiding strikes or reducing the number of holes that are dug. Extended access to NUAR could see it adapted to allow use by different users such as those concerned with tree planting or environment teams from local authorities by displaying the data to the level of granularity needed. This could enable more efficient subsurface use by a wide range of groups. NUAR data also currently consists of information about the horizontal placement of infrastructure, but integration of other datasets could include vertical and geological data, such as information on natural features including tree roots and geothermal wells. New discovery work was launched in November 2023 to explore potential market opportunities and increased benefits from widened secure and controlled access (Department for Science, Innovation and Technology & Geospatial Commission, 2023).

In Scotland, the Scottish Road Works Register (SRWR) is a system used by all roads authorities and undertakers in Scotland to coordinate their works, allows them to share details of where intended work will take place and the nature of the work (Office of the Scottish Roadworks Commissioner, n.d.). Part of the information shared relates to requests for information on the location of underground assets which may affect these works, historically provided using a combination of different systems. The Community Apparatus Data Vault system (Vault) aims to centralise this information on the register, adding apparatus information alongside details of where works take place. Vault allows the display of information from disparate GIS systems on one screen at the same time, and was implemented on a voluntary basis in 2012 to make data of buried pipes and cables accessible through the Scottish Road Works Register. Participation was then made mandatory through the Transport (Scotland) Act 2019 (Office of the Scottish Roadworks Commissioner, n.d.), (Transport Scotland, 2019).

In the future, data availability could improve through expanding initiatives such as NUAR and Vault, and more advanced technology could help with digitising legacy datasets and sensing what is below the ground (see Chapter 4 on Emerging Technologies). Availability of such data is critical but may not by itself guarantee favourable outcomes. Strategic planning and decision-making processes that make use of this data will also need to be considered to help mitigate other challenges identified in this section.

Complex system interactions

Effective planning for the subsurface is challenging, perhaps more so than above ground, because the subsurface and the structures and features within it are both hidden and often physically connected. The different engineered infrastructure components in the subsurface often interact with each other and with neighbouring geological and hydrological features. Due to the siloed nature of subsurface use across sectors, these complex system interactions can lead to unintended consequences and impacts. Unlike at the surface, many subsurface elements are ‘out of sight, out of mind’, which increases the challenge in tracking and predicting interactions.

The presence and operation of engineered structures often influences the local geological and hydrological conditions, which, in turn, has an effect on other structures or subsurface services we rely on. For example, the installation of sustainable drainage systems (SuDS) can help with flood risk management and improve biodiversity, but in certain types of rock they may wash fine minerals from the ground and increase susceptibility to geohazards such as sinkhole formation (Cooper, 2020). The uncontrolled extension of basements can locally impede and divert groundwater flow, leading to local rising of the water table. This, in turn, can lead to increased groundwater flooding in nearby basements and interference with other subsurface structures.

In general, groundwater levels are continuously changing, as a result of groundwater abstraction on the one hand and groundwater recharge on the other. These fluctuations can lead to ground movements that can affect buried infrastructure (Agarwal, et al., 2021). Groundwater rebound, where water levels recover due to decreases in abstraction has been a particular problem in cities that have deindustrialised such as London, Birmingham and Nottingham.

Effective subsurface planning and coordination of uses requires an understanding of these complex subsurface system interactions and resulting unintended consequences. There have been calls from both the National Infrastructure Commission and the Climate Change Committee to better understand infrastructure interdependencies and cascading failures across sectors (National Infrastructure Commission, 2023) (Climate Change Committee, 2022).

Developing such an understanding requires high-quality data to be available and a ‘systems approach’ to be adopted to consider the subsurface as a whole. This was explored by the GO-Science team by bringing together a range of experts across different sectors of subsurface use, to better understand interdependencies and interactions between siloed subsurface uses as a starting point for developing a 'systems map' (see Chapter 5). If adequate data is available, such systems interactions can be represented through approaches like Digital Twinning, which can simulate the consequences of potential changes in the subsurface environment (see Chapter 4).

Coordination and regulation

In the UK, the governance and regulation of the subsurface and its various uses is multi-layered, sector-dependent and spread across national, regional, and local bodies. These policies are generally a mix of spatial planning and regulation of specific uses.

Except for nationally significant infrastructure projects (NSIPs), subsurface spatial planning generally falls under the responsibility of local government, although there is variation in this across the devolved administrations. For NSIPs, the use of underground space can be approved at a national level through specific Acts of Parliament, such as the Crossrail Act (2008) and the NSIPs scheme that was introduced with the Planning Act 2008 (UK Government, 2008), (UK Government, 2008). Within local government, responsibilities are typically divided between planning and highways, with highways departments generally managing subsurface uses that run under roads and pavements.

For local planning, taking England as an example, the National Planning Policy Framework (NPPF) and the Planning Practice Guidance (PPG) set out guidelines for local authorities to prepare their local plans (Department for Levelling Up, Housing and Communities, 2023), (Department for Levelling Up, Housing and Communities, 2024). Local authorities can emphasise specific planning topics or include additional aspects in their local plans. Whilst the NPPF covers a series of use cases or issues associated with the subsurface, such as flood risk and SuDS, it does not explicitly mention the subsurface as a space in need of a specific planning approach.

In addition, there are also policies that regulate specific subsurface uses, such as environmental licensing for oil, gas, and groundwater abstraction. But these tend to be mostly sector-specific, which can result in conflicts of interest. For example, subsurface groundwater is managed for the two competing objectives of flood management and ensuring water availability (von der Tann, et al., 2018).

Whilst regulations and standards generally guide all stages of subsurface spatial planning development processes, there are some gaps (Turner, et al., 2021). For example, incomplete and inconsistent regulation for uses such as basement extensions mean that such subsurface developments can often proceed without due strategic planning of consideration of unintended consequences. This can worsen congestion issues, as outlined above, and has led to the subsurface being described as 'the final urban frontier waiting to be exploited by those who place the first stake and thereby claim their space' (Admiraal & Cornaro, 2016).

These complexities and shortcomings can also create barriers to implementing new technologies. For example, in the UK geothermal heat is not recognised by law as a natural resource. When extracting heat using closed loop systems, no planning or regulation applies. This means individual landowners can install heat pumps, removing heat from the ground, and limiting the potential for other ground source heat pumps nearby. This lack of regulation, alongside issues of undocumented congestion, could challenge the effective scaling up of this technology due to uncertainties over ownership, access, and investment returns. Conversely, additional regulatory requirements to manage this uncertainty could risk slowing the adoption of this important net zero technology.

Solutions to these coordination and governance issues have been proposed at different levels, from national to local. At the national level, many subsurface stakeholders we spoke to for this project suggested that consideration of the subsurface in national planning policy, such as more explicit coverage in the NPPF, could improve the coordination of decision making.

There are also schemes exiting improving coordination at the city level. For example, a recent 'Cubic Mile' project for London investigated how urban subsurface space could be better used to improve the City's resilience to the impacts of long-term climate change and extreme weather (Freeborough, et al., 2023). The London Infrastructure Group has also been established by the mayor to agree a common vision for long-term infrastructure planning and jointly tackle issues in the infrastructure sector, including those related to the subsurface (Mayor of London, 2023).

Glasgow City Council was the first local authority in the UK to formally recognise the subsurface within its proposed City Development Plan and are also a signatory to the Scottish Geodiversity Charter, making a commitment to enhance and protect geodiversity[1] (Whitbread, et al., 2016), (Glasgow City Council, n.d.). As there is no overarching national plan for subsurface management in Scotland, most of the developments in subsurface planning in Glasgow have come from collaboration and partnerships (von der Tann, et al., 2018). This is explored in greater detail in the evidence review on *subsurface space management in the UK*.

Multiple stakeholders highlighted increased and more strategic use of shared infrastructure, such as service ducts, as a practical way of improving coordination across subsurface uses. These ducts can house multiple services, improving access for asset maintenance, and keeping infrastructure separate from natural features like tree roots. Some local authorities proactively promote the use of these, particularly to service new buildings, but it would be more costly and challenging to comprehensively retrofit these across urban areas. There is no government guidance on use of such ducts, but the Chartered Institute of Highways and Transportation (CIHT) highlights their benefits in its Manual for Streets guidance (CIHT, 2010). If there is a desire to improve subsurface coordination, policy makers will need to assess the relative benefits and costs of shared infrastructure in different circumstances and proactively promote this accordingly.

Other approaches to improving coordination are demonstrated by several other countries around the world including Singapore and Finland, who have a particularly forward-looking approach to subsurface management. Another key example is the

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[1] Geodiversity is defined as the variety of rocks, fossils, minerals, natural processes, landforms, and soils that underlie and determine the character of our landscape and environment.

Netherlands, where large amounts of data on the architecture and properties of the subsurface have been used to create detailed 3D maps, which have allowed more effective subsurface planning (Government of the Netherlands, n.d.). Each of these countries takes a slightly different approach, with some having a stronger role for national government and others seeing local government taking more responsibility for data, analysis, and strategic planning. This is shown in Table 1 below. Further evidence of how this relates to subsurface management is provided in the evidence review on *subsurface space management in the UK*.

Current UK Status

Table 1: International examples and their approach to governance and spatial planning.

Country	Governance approach
Netherlands	• Spatial planning policy and its implementation are mostly shaped at the municipal level (Government of the Netherlands, 2013). • Municipalities are able to set appropriate regulations based on their knowledge of the local situation (Government of the Netherlands, 2013). • The country takes a 3D approach to spatial planning, and the subsurface is included in spatial plans. • The Basic Registration Subsoil came into effect on 1st of January 2018, aiming to create a uniform and detailed register of subsurface data in the country (Ministry of Housing and Spatial Planning, 2024).
Finland	• Governance is based on the principle of decentralisation (Purkarthofer & Mattila, 2023). • Regional Land Use Plans are drawn up and approved by the Regional Councils. These are strategic in nature, leaving room for local interpretation and implementation. • Municipalities are able to purchase land for future development needs due to the several statutory land-policy instruments available to them, such as Local Master Plans (Ministry of the Environment, 2024). • Helsinki is the first city in the world with an Underground Master Plan (City of Helsinki, 2009).
Singapore	• Singapore is a city state with a centralised model and no local government (Commonwealth Network, 2020). • The country has many nationalised companies across various industries, and taxes are low and there are minimal regulations to encourage private investment (Startup Decisions, 2024). • Singapore is increasingly considering underground space in planning to optimise land use (Urban Redevelopment Authority, 2024). • A 3D Special Detailed Control Plan (SDCP) has been introduced to enable better planning of underground space (Urban Development Authority, 2024).

Key findings from this chapter

- **Data availability, accessibility, and quality**. It is difficult to collect data on the subsurface as it is opaque to most sensors. The data that are collected often have accessibility or quality issues. Datasets have either good geographical coverage or good coverage of different subsurface features, but rarely both.
- **Space competition and congestion**. Subsurface space is often used on a 'first come first served' basis and is congested with various uses, particularly in urban areas (Volchko, et al., 2020). When combined with a lack of data on existing uses, this competition and congestion makes it challenging to optimise future uses.
- **Complex system interactions**. As subsurface assets and features are physically connected by the earth, they often interact with one another via transmission mechanisms like the ground, water and heat. These interactions are generally not monitored but can lead to adverse unintended consequences across sectors.
- **Coordination and regulation**. Subsurface use is not comprehensively coordinated in the way that use of surface space is by the planning system. This can make it difficult to plan and prioritise important future uses. Furthermore, some subsurface uses are only regulated to a certain extent (e.g. geothermal energy).
- **These challenges contribute to increased costs and delays for delivery of critical infrastructure**. Unintentional 'strikes' of subsurface utilities are estimated to cost the UK around £2.4 bn per year, with around 30% of strikes thought to be avoidable with better data (Cabinet Office & Geospatial Commission, 2021). In addition, 20-60% of linear and transport infrastructure projects experience delays due to unforeseen ground conditions (Bricker, et al., 2022).
- **These challenges also threaten societal resilience, which depends on our ability to monitor and manage the subsurface**. Floods and other hazards have the potential to disrupt the vital services that our use of subsurface space enables.
- **There are a number of potential solutions available to address these challenges**, drawn from expert input and international case studies. These are described in more detail in the report's conclusions in Chapter 7.

The next chapter looks at future trends affecting the subsurface and in many cases exacerbating the challenges outlined above.

Chapter Three

Future Trends for the Subsurface

Future Trends for the Subsurface

Whilst there are major challenges to effective subsurface use today, these are likely to become exacerbated in the future due to environmental and societal changes such as climate change and increased urbanisation. This chapter outlines trends and demand drivers that are anticipated to affect subsurface activity in the future, and how these may intensify existing pressures or create new pressures on the subsurface.

3.1 Trends and demand drivers affecting future subsurface activity

This section summarises key trends likely to affect future subsurface activity: urbanisation and population increases; technological change, net zero, climate change, and ageing infrastructure. These were identified by the project team in consultation with expert stakeholders who supported the project (see Acknowledgements section).

Urbanisation and population increase

Urban populations are increasing, and at a faster rate than in rural areas (Government Office for Science, 2021). Population densities are also increasing, particularly in city centres. These changes are likely to put additional pressure on existing infrastructure and drive demand for buildings above and below ground, including the installation of new utilities, foundations, and transportation tunnels. This will exacerbate the competition and congestion already seen in urban areas. For example, the population of London is projected to increase by 27% from 2011 to 2050, reaching 11.3 million. London's Infrastructure Plan 2050, first devised in 2014, states that 'this growth alone will increase demand, both for existing and for new infrastructure' and 'infrastructure requirements over the next thirty years will be substantial' (Mayor of London, 2014).

This is not limited to London - between 2001 and 2019, the population of Manchester grew by 30% (Government Office for Science, 2021). This population growth, in combination with other changes like rising incomes, is likely to drive demand for infrastructure in Greater Manchester where, for example, travel demand is forecasted to increase by more than 600,000 trips per day by 2040, a 10% increase from 2021 (Transport for Greater Manchester, 2021). Similarly, the population density in central city regions is also increasing, for example the population of central Leeds (within one mile of City Square/City Station) more than tripled in the years 2002 – 2020 (Forth, 2021).

Anthropogenic activity in urban areas can lead to variations in temperatures below ground, which are exacerbated by increases in air temperature above ground, creating subsurface urban heat islands. These can lead to deformation of soil, rocks, and construction materials, which in turn could damage underground infrastructure including building foundations and affect their operational performance (Rotta Loria, 2023). Continued growth in urban populations could further exacerbate this effect.

Technological change

Innovation in tunnelling and excavation technologies are decreasing the costs of underground construction (Tunnel Engineering, 2024). This could increase the opportunities for future subsurface development. Other technologies that could increasingly affect the way the subsurface is used in the future include AI, digital twins, quantum sensors, fibre optics, robotics, and cosmic ray muography. For a more detailed review see Chapter 4.

Net zero

The UK government is committed to reach net zero emissions by 2050, which will require cross-sector decarbonisation. Many of the infrastructure and technological solutions needed for net zero require subsurface space, often within already congested urban areas.

- **Transport**. In the transport sector, publicly accessible EV chargepoints will be needed to enable widespread EV uptake. Installing EV chargers involves the subsurface through extending the electricity network and attaching it to chargers, as well as some EV chargers involving subsurface space. The current rate of deployment of public EV chargepoints will need to rapidly accelerate, to raise numbers from 44,020 in 2023 to 300,000 in 2030 (Department for Transport, 2023), (Department for Transport, 2022). Chargepoints are currently distributed unevenly across the UK, and installation plans need to address this to ensure there is good access for all (Climate Change Committee, 2023).
- **Heating**. Ground source heat pumps (GSHPs) and low carbon district heating networks are likely to make important contributions to decarbonising the heating sector. The government has a target to install 600,000 heat pumps a year by 2028, which will mostly be air source heat pumps that extract heat from the air, but a significant minority will likely be ground source heat pumps. GSHPs perform better in winter compared with air source heat pumps, when the ground temperature is higher than air temperature. However, they require more space and are more expensive to install than air source heat pumps due to the ground works they require. Whilst the space requirement for GSHPs means they are more likely to be used in rural areas, they can be used to heat blocks of flats (The Energy Saving Trust, 2024). Networked GSHPs also offer a potential model for use in urban areas, in which third parties finance and own ground infrastructure, and individual properties pay a connection charge. Kensa, for example, is currently undergoing pilots to trial ground source heat as a utility, and has recently received enough investment to allow them to install 50,000 GSHPs by 2030.

  District heating uses underground pipes to supply heat from a central source to consumers and currently provides around 2% of the UK’s heat, with the Climate Change Committee estimating that this could increase to 18% by 2050

(Department for Energy Security and Net Zero, 2023). This will require creating new low-carbon district heat networks and retrofitting existing networks to low-carbon sources (Climate Change Committee, 2023). District heating is often the lowest cost low carbon heating option in high density urban areas, but this is where the subsurface challenges may be the greatest (Department for Energy Security and Net Zero, 2024).

- **Electricity transmission and distribution**. Many changes associated with net zero will require upgrades to parts of the electricity distribution system. The rollout of both EVs and heat pumps to people's homes will require upgrades to parts of the electricity distribution system which are currently operating at a low voltage. In urban areas, the majority of networks could need upgrading with many of these lines being underground.

  The electrification of heat and transport will also require the grid to double in capacity. As electricity generation shifts to more low carbon and net zero sources, the grid will also need to change shape to draw power from a greater distribution of locations. These changes mean that Britain will need to build four times more grid infrastructure in the next 7 years, compared with the last 30. This will, in general, mean more underground cables, for example underground power lines can be an alternative to overhead power lines.

- **Legacy fossil fuel infrastructure**. Net zero is also likely to affect the subsurface through the decommissioning of fossil fuel infrastructure. Various projects are ongoing to investigate how this infrastructure could be repurposed for alternative uses. The British gas network SGN, for example, is trialling the transport of hydrogen gas through a 30 km decommissioned gas pipeline due to its possible use in future heating. Although the role of hydrogen in heating will likely be limited due to its estimated cost, projects like this will build an evidence base to inform the UK government on heating policy decisions which are planned for

2026. Alternative uses for decommissioned gas grid infrastructure could include using it to transport water or electricity cables.

As noted above, there are other important net zero solutions that rely heavily on subsurface use not covered in detail here, including nuclear power, carbon capture and storage (CCS), hydrogen, and domestic exploration and extraction of critical minerals for net zero technologies.

Climate change

Climate change will bring more extreme weather, increasing the frequency of heatwaves and flood risk. For example, modelling suggests that the frequency of extreme daily rainfall events could be four times as frequent by 2080 compared to the 1980s (Kendon, et al., 2023).

The likely changes in rainfall and evaporation from climate change could affect groundwater recharge, cause groundwater levels to be more variable and heighten the risk of droughts (Environment Agency, 2019). There is also expected to be greater variation in the moisture levels of the soil, leading to increased ground movement (British Geological Survey, 2021). This can damage buried infrastructure such as cables and pipes and affect the infiltration of water into the subsurface.

Many measures designed to adapt to climate change involve the subsurface. For example, increased surface water flood risk will require the expansion of underground drainage systems in urban areas. SuDS can also be used to help manage flood risk, and planting trees can help reduce surface run-off in addition to helping with urban cooling (Schwaab, et al., 2021), (Woodland Trust, n.d.). For a more detailed description of how urban water systems could be impacted by climate change, see the evidence review on *urban water management in the UK*.

Other subsurface related measures that could be implemented to adapt to climate change include cool spaces below ground and the prevention of damage to buried utility services (Freeborough, et al., 2023).

Ageing infrastructure

Infrastructure below ground deteriorates as it ages and needs to be maintained to continue to provide the required level of service. Both the National Infrastructure Commission and the National Audit Office have highlighted the need for improved maintenance, including addressing backlogs in certain areas, to ensure resilient service provision and reduce overall costs in the long run (National Infrastructure Commission, 2023), (Davies, 2024).

Assets may also need upgrading to address issues such as frequent leaks or to accommodate increased demand. These upgrades may constitute major projects. For example, the aqueduct which supplies most of Greater Manchester with its drinking water from the Haweswater reservoir is almost 100 years old and is currently undergoing significant upgrades with an investment of £1.75 billion (Arup, 2022), (Jacobs, 2023).

Key findings from this chapter

Future trends are set to make it more important to address subsurface challenges. These include the need to accommodate more people in cities, build net zero infrastructure and adapt to worse floods and heatwaves caused by climate change. Long-term solutions to cross-cutting subsurface challenges will need to be developed in a way that accounts for these trends.

Future technological developments have the potential to help address these challenges. Technologies such as AI, digital twins, quantum sensors, fibre optics, and robotics have the potential to reduce the costs, disruptions, and delivery challenges associated with our current and future use of the subsurface. These opportunities are explored in more detail in the next chapter.

Chapter Four
Emerging Technologies for the Subsurface

Emerging Technologies for the Subsurface

Our research for this project suggests that emerging technologies could help address some of the future challenges and increased demands identified above. We also found that the available evidence on these technologies has not previously been summarised for policy makers.

To address this gap and to better understand how emerging technologies could present new opportunities in subsurface use in the future, we conducted a review of emerging technologies that could be used to address subsurface challenges.

We conclude the section with a high-level review of the future of tunnelling, as a deeper dive into an important subsurface activity that could be significantly impacted by the development of new technology.

4.1 Emerging technologies relevant for subsurface management

The following technologies were identified as relevant for subsurface exploration and use: Artificial Intelligence (AI), digital twins, robotics, quantum sensing, fibre optics, and cosmic ray muography. Their current uses, UK based research and international examples are summarised below. It was not feasible to quantify the costs or level of commercial readiness, but the case studies should provide readers with some information on how well developed each technology is. Some technologies, notably AI and digital twins, are already having an impact, but are not yet widely used, and in these cases policy makers will need to consider measures to promote adoption of existing technology alongside supporting new technological developments.

Artificial Intelligence

Artificial intelligence (AI) refers to machine-driven capability to perform tasks and solve problems that imitate human intelligence (Government Office for Science, 2023). AI is a rapidly expanding field with many capabilities. As AI use grows across the economy and society, this is likely to be mirrored in the areas of subsurface exploration and management. An example of this is in tunnelling, where AI is beginning to be used more widely, for instance machine learning being used to predict ground type and behaviour. This is explored further in the *Future of tunnelling review*. As AI continues to advance, its integration into geophysical exploration techniques is also likely to become more widespread. Applications include more accurate subsurface imaging and analysis, seismic data processing, analysis of gravity and magnetic data, and improving the accuracy of subsurface models (Cameron, 2023).

Current uses include the analysis and interpretation of geophysical data and geological sample information and the use of AI-based scanners for ground and infrastructure monitoring (Zeiss, 2022).

The UK has a strong base in AI research and applications, ranking 4th globally for research publications on AI between 2017 and 2022 (Government Office for Science, 2023). Notable research topics include new energy efficient models for CO_2 capture and low-cost modelling for geological CO_2 storage sites, and text mining projects by the British Geological Survey (BGS) (Heriot Watt University, 2023), (British Geological Survey, 2020). An example for a real-world application in the UK is US tech start-up Exodigo, a company that creates underground maps for construction that has expanded to the UK (Exodigo, 2024). They look to solve subsurface challenges by improving the completeness and accuracy of underground maps to improve safety and prevent rework/redesigns during the construction process. They are currently working with Colas Rail on the Eastside Metro Expansion project in Birmingham (Exodigo, 2023).

International examples include:

- Optimatics, a company that has used AI to determine a pipe renewal strategy in the City of Melbourne that minimises costs and reduces future risk (Optimatics, 2024).
- The Society for the Protection of Underground Networks (SPUN) that is using remote sensing technology and machine learning to map and predict the presence of mycorrhizal fungi around the world (Society for the Protection of Underground Networks, 2024).

Digital Twins

Digital twins are digital representations of physical assets, entities, or processes within a digital version of their environment. They can enable the remote monitoring of hard-to-reach places and control of complicated physical processes (Government Office for Science, 2023).

Current uses include real-world monitoring and testing. This can reduce risks to safety, reduce time and costs, and enable predictive maintenance of underground sites.

The UK has put an emphasis on building expertise in the technologies required to build digital twins and is gaining international recognition. For example, the National Digital Twin programme aims to grow national capability in digital twinning technologies and processes throughout the country. It looks to develop standards, processes, and tools to build a functioning market in digital twins, and then test the programme in real world situations (University of Cambridge, 2022). The interdisciplinary network hosted by the Alan Turing Institute aims to facilitate knowledge exchange and cross-disciplinary collaboration, accelerate academic research, encourage thought leadership, and support outreach, skills development, and sustainability for digital twins (The Alan Turing Institute, 2023). The UK government has announced its intention to facilitate the development of digital twins for the infrastructure for all modes of transportation by 2035 (Transport Research and Innovation Board, 2023).

International examples include:

- **Singapore,** which has developed the world's first national digital twin, and is now developing an underground digital twin (Walker, 2023).
- **Estonia,** which is developing a full 3D model of the country, including buildings, pipelines, cables, and plants (Invest in Estonia, 2019).
- **The Netherlands**' Basic Registration Subsoil (BRO), digital twins that make information both above ground and below ground transparent, understandable, and accessible for experts in civil engineering, policy makers and residents (Government of the Netherlands, n.d.).

Quantum sensing

Traditional sensing techniques, such as ground penetrating radar, require a signal to be induced into the ground, then the reflected signal provides information on the properties of the targeted subsurface area (Wang & Birken, 2009). But such actively induced signals are naturally weakened as they move further away from the surface, meaning they can only provide useful information to a limited depth (South East Scanning, 2023). Quantum sensors can overcome this issue by measuring a passive response that cannot be blocked or weakened. They manipulate the quantum properties of atoms to measure minute variations in gravitational fields, a technique that can reveal the contours and properties of subterranean areas, including underground voids (Simsek, 2024).

Current uses. Quantum sensors gather and carry information via quantum bits or qubits, which can include photons, ions, and neutral atoms (Simsek, 2024). This allows them to sensitively measure the environment, by extracting information from individual atoms instead of a large number of atoms. Quantum sensors have significant potential for use across a wide range of applications below and above ground. They have the potential to replace GPS in future, as they do not require satellite signals which can be vulnerable to hacking. This could provide opportunities in the fields of navigation and defence (Tegler, 2023). Quantum sensors are already being used in certain sectors, such as mineral exploration, where they are being integrated into existing systems to enhance their ability to detect underground resources (Global Market Insights, 2024).

Examples in the UK include:

- The National Quantum Strategy, which provides a 10-year vision and actions for the UK to be a leading quantum-enabled economy (Department for Science, Innovation and Technology, 2023).
- The UK National Quantum Technologies Programme is a £1 billion collaboration between industry, academia, and government, including four hubs across the UK (UKRI, n.d.).
- The UK National Quantum Technology Hub in Sensors and Metrology at the University of Birmingham developed a gradiometer that leverages a quantum phenomenon known as superposition in which an atom can occupy two states at once, allowing researchers to isolate the gravitational data from the vibrational feedback. In 2022, their research reported the first demonstration of the instrument in a practical outdoor setting (Ferreira, 2022).
- UK-based company Delta g claims to have produced the world’s first field proven quantum sensor for gravity gradiometry. They have raised £1.5 million in a pre-seed round lead by Science Creates Ventures, and have been awarded a £500,000 innovation grant by Innovate UK, increasing investment in quantum sensing, and building on the research at the University of Birmingham highlighted above (Alston, 2023).

International examples include:

- Research on underwater quantum communications conducted at the University of Ottawa in Canada, which showed that under water quantum links can be established in turbulent waters and at greater distances than previously reported, which could secure quantum communications for submarines in future (Choi, 2020).

- In Sicily, Exail, funded through the H2020 program, installed their Absolute Quantum Gravimeter (AQG) at the summit active area of Mount Etna to test its potential for volcanic monitoring. The AQG has performed near-continuous gravity measurements since; these can determine whether magma is accumulating in magma reservoirs (iXblue, n.d.).

Fibre optics

Fibre optic sensors enable continuous, real-time measurements along the length of a fibre optic cable, providing an immediate alarm when a change is detected. They can also provide a pinpoint for the location of the event detected on the fibre (CIRIA, n.d.).

Current uses of fibre optics in the subsurface include monitoring of geotechnical structures and detection of ground movements. Fibre optic sensors can provide an early detection system for unpredictable ground movements and thus facilitate more efficient management of infrastructure assets.

The UK. The Smart Infrastructure and Construction (CSIC) based at Cambridge University develops sensing and data analysis models to enable smarter management decisions for new and existing infrastructure (University of Cambridge, 2023). For several years, CSIC has been developing distributed fibre optic sensors (DFOS) for monitoring infrastructure (Frawley, 2017).

International examples include:

- Researchers at the California Institute of Technology and the City of Pasadena, California collaborating in 2019 to use Distributed Acoustic Sensing (DAS) to monitor the effects of the Covid-19 lockdown on traffic patterns using underground fibre optic cables (Wang, et al., 2021).

- Research at Stanford University using a 4.8km test loop of optical fibres installed on campus to record vibrations caused by earthquakes and distinguish those from vibrations caused by other sources such as passing cars (Perry, 2017).

Robotics

Traditional pipe maintenance techniques can be physically demanding and can cause strain or injury to operatives. Use of robots could minimise this risk. Robots could also reduce the need for excavations, minimising environmental impacts, costs, and traffic disruption.

Current uses of robotics in the subsurface include research into underground utilities maintenance, and the development of underground robots further in the defence sector. These are further highlighted below.

The UK. BT's research facility at Adastral Park provides a research environment to simulate environments in the real world to test how robots act in different situations, including in the subsurface (Smith, 2022). UK researchers based at the universities of Sheffield, Bristol, Birmingham, and Leeds are developing tiny robots capable of locating blockages and leaks in water and sewage pipes through the PipeBots project (Pipebots , 2024).

International examples include:

- The Bandicoot robot in India, the world's first manhole cleaning robot (Perinchery, 2023).
- Testing robots for emergency response in the United States that can be used, for example, in collapsed basements (Kleiner, 2023).
- A collaboration between the Agency for Defence Development in South Korea who conducted research in collaboration with the Ground Vehicle System Centre in the US for an Autonomous Tunnel Exploration Robot (Kim, 2022).

Muography

Muon imaging is a non-invasive technique which uses cosmic ray particles, called muons, to see inside solid objects, detecting changes in density and composition, and therefore enabling scientists to create 3D models of their interiors. Muography can be used to see further into apparently solid objects, and can scan objects through tens of metres of solid rock, whereas ground penetrating radar (GPR) often struggles to go beyond a few meters in many soils. No equipment is required to generate the signal to be analysed, therefore muon detectors can be installed and do not need to be monitored whilst gathering data (Adam, 2021). This reduces costs and makes projects simpler.

Current uses include in the field of volcanology, where cosmic-ray muons are used to image volcanoes. Other uses include imaging underground structures and monitoring capture storage sites, and in nuclear safety and security (Kaiser, 2018). Muon tomography has also been used for imaging a railway tunnel in Nottinghamshire, proving it to be a useful tool to identify any density abnormalities in infrastructure that is difficult to access (Thompson, et al., 2020).

The UK. Muon imaging is still in its early development in the UK. Lynkeos is a Scottish company that is developing a muon imaging system for commercial applications, seeking to develop a portable muography capability for monitoring underground, ageing reinforced infrastructure (Lynkeos Technology, 2023).

International examples include:

- Ideon, a Canada-based company active in brownfield mineral exploration using subsurface 'borehole' muography systems (Ideon, 2020).
- Research teams at the University of Naples producing underground maps of volcanoes in Italy (Thompson, et al., 2020).
- Researchers in Japan researching historic disasters using muography, and exploring its potential for earthquake warning systems (Tanaka, et al., 2020).

This is not a statement of government policy.

Resulting future opportunities and challenges related to subsurface management in the UK

There are numerous opportunities and challenges related to the application of emerging technologies to subsurface challenges in the UK. Further technological advancements could increase the need for subsurface space in future. For example, the rollout of the internet meant that fibre optic cables needed to be laid. It is possible that other new technologies and networks come along in the future that require further developments in the subsurface. Technological advancements are also set to assist subsurface management and assessment in the coming decades. Key opportunities emerging from these technologies and challenges with their development are shown in more detail in Table 2 below.

Table 2: Opportunities and challenges, focussing on how technologies address subsurface issues identified earlier in the report.

Technology	Opportunities	Challenges
Artificial Intelligence	• Underground utility mapping. • Processing subsurface datasets to improve interoperability. • Real-time monitoring of changes in the subsurface. • Exploration, characterisation and engineering of geothermal resources (Aljubran, et al., 2022). • Tracking biodiversity targets and loss (Orsini, 2023). • Supporting decisions on allocation of subsurface space (including for trees) (Francis, 2023).	• Shortage of data science skills within subsurface sectors.[2] • Development of AI systems that can produce reliably consistent outcomes (Rawashdeh, 2023). • Uncertainties regarding what future AI models will be capable of, who will own them, and their safety (Government Office for Science, 2023).
Digital Twins	• Improved safety through remote monitoring. • Simulating impacts of urban planning interventions (Pizzocolo,	• The need to upgrade and maintain IT infrastructure (Government Office for Science, 2023).

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[2] Informed by discussions with project stakeholders.

	2023). • Analysis to support prioritisation in planning, dealing with issues such as urbanisation and densification. • Modelling to support planning and decisions for climate adaptation. • Modelling to support infrastructure planning for net zero. • Employing technology to understand cross-sector interdependencies.	• Significant investment required in data and simulation platforms. • Maintaining robust data security (Simpson, 2023).
Quantum	• Monitoring underground conditions. • Monitoring climate (Q-CTRL, 2024). • Detection of underground hazards, improving societal resilience (UK Quantum Technology Hub Sensors and Timing , n.d.). • All of the above monitoring could reduce construction costs and project time.	• Demand and competition for skills (Department for science, Innovation and Technology, 2023). • Further development of technology required.
Fibre optics	• Monitoring infrastructure in difficult conditions. • Monitoring movements of people and traffic. • All of the above monitoring could reduce construction costs and project time.	• Data privacy and potential public trust impacts and implications for public engagement (Simon, 2021).
Robotics	• Updating ageing infrastructure in spaces that humans can’t easily access, reducing costs. • Disaster response, improving societal resilience. • Robotics can offer opportunities for better mapping and exploration of the subsurface (Martz, et al., 2020).	• Greater understanding of how piped systems interact with other urban systems required (Pipebots, 2019). • Lifecycle of materials potential environmental impacts. • Building public trust in the use of robots (Emmerich, 2019).
Muography	• More detailed mapping of subsurface assets. • Fewer unintentional strikes of subsurface utilities, reducing costs. • Managing the legacy of defence programmes (Kaiser, et al., n.d.). • Disaster prevention, improving societal resilience.	• Adoption at scale: recent supply chain issues, initial cost of the technology, and the physical size of technology have been highlighted as barriers to muography being adopted by industry at scale (Manaugh, 2022).

4.2 Review of the Future of Tunnelling

Tunnels provide essential services to society as critical components of transport, water, and waste infrastructure, as well as supporting other underground activities like mining. By moving infrastructure and activity underground, tunnels can create space and reduce conflict at the surface.

But tunnels are currently relatively high cost and challenging to deliver compared to other elements of infrastructure, particularly in UK transport projects (Department for Levelling Up, Housing & Communities, 2023). Space congestion is also a challenge for future tunnelling projects in urban areas. In planning for the future of the subsurface, it is important to consider what could change in future to affect these tunnelling cost and delivery issues.

To help address this, we conducted a high-level review of the future of tunnelling. This consists of a study into tunnelling technology, which we commissioned from Arup, and a brief evidence review of a future tunnelling case study on underground freight transport.

Key findings of Tunnelling Technology Study

We commissioned Arup to undertake a high-level study into emerging technologies affecting tunnelling at scales from trenchless drilling to large transport tunnels, as a deeper dive into how emerging technologies might transform underground use in the future. This study gathered evidence through interviews and a survey, primarily with the Arup global tunnel skills network. It suggests that adoption of emerging technologies in the tunnelling industry is likely to have significant implications for the costs and delivery of tunnelling projects. The main technologies considered are:

- **Digital technologies that support the whole project lifecycle:** these technologies are being adopted at all stages of the project, from design through construction to maintenance. AI systems are being used in a variety of applications, including automated design (in combination with Building

Information Modelling – BIM), and autonomous Tunnel Boring Machines and supporting vehicles. Digital twins are another digital technology increasingly being used to support the construction, monitoring, and maintenance of tunnels.

- **Robotics:** this technology is being adopted at various stages of the tunnel construction process including pre-construction investigations and sensing to post-construction maintenance and inspection. This offers health and safety benefits by removing or supporting operatives undertaking manually intensive and repetitive tasks.
- **Other construction technologies:** offsite construction technologies can be used for production of high-quality components with a modular design that enables rapid onsite installation. 3D printing is enabling prototyping of fixings and devices, is also being used in onsite applications like lining tunnel walls. There are also ongoing innovations in the materials used to construct tunnels, such as low carbon alternatives to cement.
- **Augmented reality/virtual reality (AR/VR) and wearable technology:** this technology is increasingly being used by people working on and off site to collect data, communicate with co-workers, and visualise new infrastructure proposals.
- **Technologies for data collection:** this includes drones for visual inspection and the sensor technologies outlined above (e.g. muography) to improve safety compared to manual data collection, as well as reducing the costs of construction and maintenance.

These technologies have the potential to improve efficiency, safety, and sustainability in the tunnelling process, which could result in cost savings and faster delivery times. The evidence gathering for the study suggest that to realise these potential benefits, the following enablers would likely need to be in place:

- **A clear pipeline of projects.** Experts consulted suggested that more certainty on future tunnelling projects in the UK would give the industry more confidence to invest in new technology that may have a high upfront cost but could be cost-saving over the course of multiple projects.
- **Skills.** Another important area identified by experts was addressing current and future skills shortages in the industry, through home grown skills development, providing highly visible career paths, and attracting global talent.
- **Clarity on regulation of new technologies.** Regulation that is timely and responsive to technological developments would help to ensure that innovative practice and technology adoption can be safely and effectively implemented.
- **Standardisation of tunnelling components** could offer significant benefits by, for example, supporting more automated design and route optimisation, and reducing construction lead-in time by reusing production facilities.

4.3 Case study: Underground freight transport

Our research identified underground freight transport as an informative case study that highlights issues around emerging technologies alongside other key themes in this report, including coordination and governance, and net zero infrastructure.

Background

Tunnels for freight transport are not a new concept. Underground postal trains ran in London from 1923 but were closed due to the high operating costs, falling demand for post, and closure of above ground offices. One of these underground lines has since been repurposed as part of the Postal Museum, allowing people to ride on a mail train under Mount Pleasant sorting office (The Postal Museum, n.d.).

This is not a statement of government policy.

Transport is the largest emitting sector of greenhouse gas emissions, and 26% of the UK's total carbon emissions were from road transport in 2021 (Department for Transport, 2023). Between 28,000 and 35,000 people die prematurely in the UK each year because of air pollution, the most significant source of which is road transport (UK Parliament, 2021). These trends have put pressure on delivery services to find innovative solutions that would enable them to become more environmentally friendly (World Economic Forum, 2020).

Simultaneously electrifying freight transport and moving it underground has the potential to help address these different challenges in parallel. Through the use of relatively small-scale tunnels and autonomous electric vehicles (EVs), it could also prove cost effective.

Status in the UK

In their 2022 Future of Freight report, Department for Transport outlined their vision of "a freight and logistics sector that is cost-efficient, reliable, resilient, environmentally sustainable, and valued by society" (Department for Transport, 2022). Moving freight transport underground could help achieve this by saving costs, increasing reliability, and reducing environmental impact.

One Mole Solutions Ltd is a company developing an underground freight pipeline for solid cargoes. The system is designed to integrate with existing supply chains and transfer some of the high volume of products that travel by road into capsules running in pipelines laid beside or under existing and planned transport infrastructure. Mole Solutions have also completed feasibility tests in the UK for its underground logistics system (Mole Solutions, 2024).

Another UK company working in this area is Magway. Their system uses linear motors and a network of underground/overground pipelines around 1m in diameter, which would move pods carrying payloads of up to 250kg. Magway have developed various working prototypes in an 8,500-square-foot facility in North Wembley (Magway, 2024).

They have secured a £470,000 Innovate UK grant and £5.6m from other investors (Crowdcube, n.d.).

International example: Cargo Sous Train, Switzerland

Mountains occupy over half of Switzerland, which means they have limited space for infrastructure and rely on tunnels for infrastructure, road, rail, and freight transport (Vignette Switzerland, 2024). 'Cargo Sous Terrain' is a privately funded project looking to develop a fully autonomous net zero transport system for smaller cargo to ease traffic congestion in the country. The system uses tunnels about 6m in diameter including three tracks for pods capable of carrying up to two pallets of goods.

The project is fully privately funded, with no government grants, but the Swiss government is playing an important role in enabling its rollout. In particular, the government is developing new legislation regulating the conditions under which the project will be approved. This is largely based on existing railway regulations and ensures providers of the infrastructure must fulfil certain public obligations and provide access to facilities on equal terms.

The company now has access to $100m worth of private investment and the project is now in its planning permission phase, surveying locations for the first ten hubs. Locations that will take more traffic off the roads being prioritised and the network is aiming to connect the country's key hubs from 2031 onwards (Bain, 2022).

Conclusions

Our research for this case study indicates that underground freight has the potential to be an important part of the future transport system, given its increasing technological feasibility and scope to reduce the negative impacts of road freight transport.

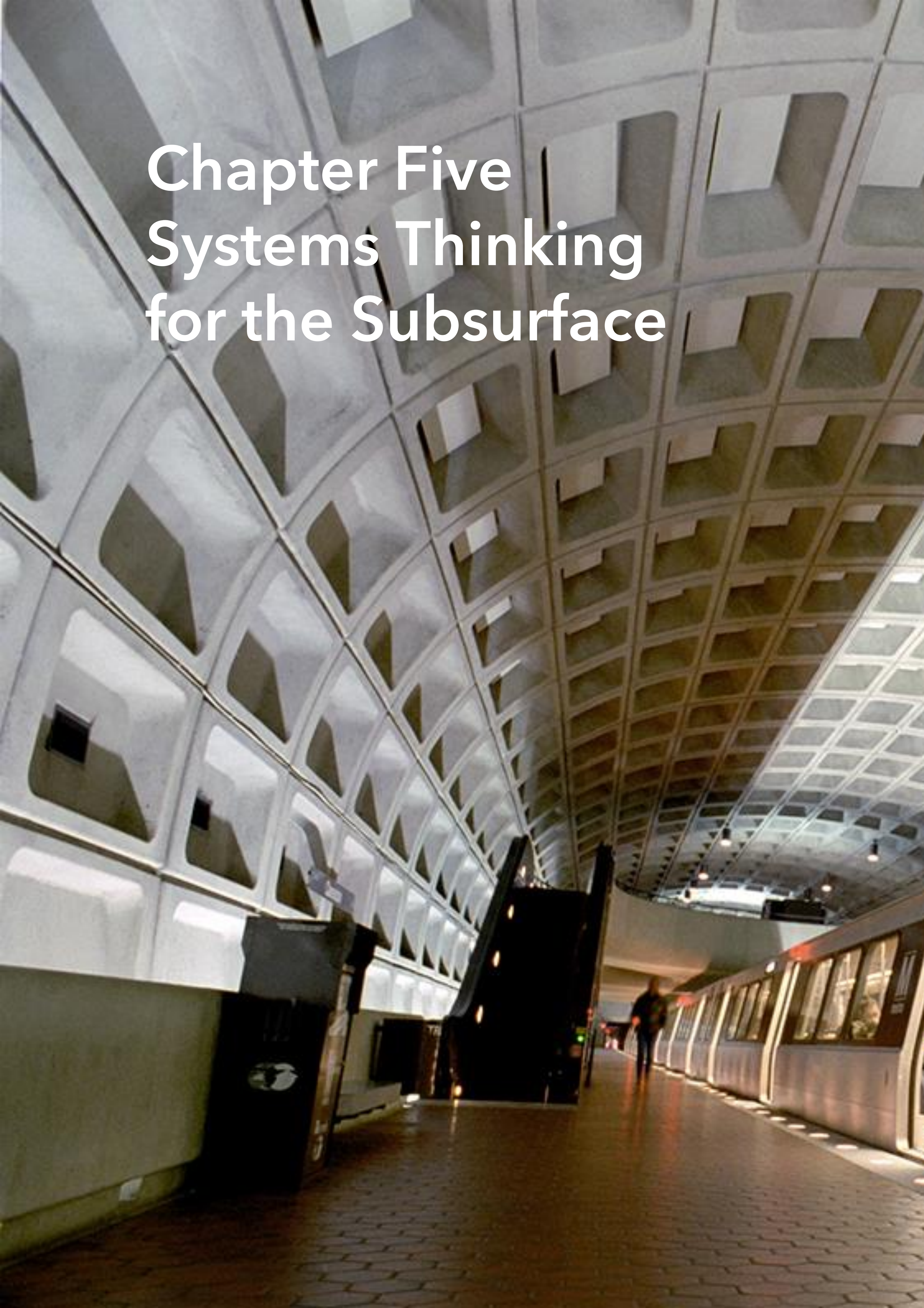
In the UK, this potential has been recognised through support for companies with competitions and grants to develop proof-of-concept systems. The Swiss example suggests that to translate these small-scale prototypes into a functional network, small-scale grant funding is likely be insufficient on its own. In particular, new government legislation would likely be needed to enable network planning and construction and to give infrastructure providers the certainty to invest. Whether or not the public and private costs of developing such a system in the UK would be outweighed by the economic and environmental benefits is uncertain, and a value-for-money assessment would be needed to inform the case for any such intervention.

Key findings from this chapter

New technology offers potential solutions, but policy makers will need to be proactive to ensure the UK benefits from these changes. New technologies that make it easier and cheaper to measure, monitor, excavate, tunnel, and maintain the subsurface are on the horizon, but may need new policy or regulation to enable their widespread use. Measures to promote wider adoption of existing technology should be considered alongside supporting new technological developments.

Developing technological capability to solve subsurface challenges is a ‘low regret’ action. Policy makers should ensure that technology policy helps to develop capabilities that address the challenges set out above. Such capabilities include more accurate and lower cost measurement, excavation, and maintenance, which could be achieved through developments in technologies including quantum sensors, AI, and robotics.

Chapter Five
Systems Thinking for the Subsurface



Systems Thinking for the Subsurface

Early feedback we received from subsurface expert stakeholders emphasised the complexity and interconnectedness of subsurface features and activities. Stakeholders suggested that these connections would need to be explored to be able to understand the subsurface and develop insights about what it might look like in the future. We identified systems thinking as an approach that could facilitate such exploration. The evidence gathered emphasises that a systems thinking approach is likely to be needed to tackle the complexities of subsurface planning and management.

Systems thinking is a way of looking at a situation through the interconnections between different elements, rather than looking at the individual elements in isolation. The approach also explicitly acknowledges that a variety of viewpoints on the same issue might exist. Approaches based on systems thinking can be used to represent entities - either physical things, or more abstract concepts like organisations - the way they affect each other, and their pattern of behaviour over time. Such representations can help to solve problems involving many organisations and individuals who have competing priorities.

Different subsurface uses interact with and affect each other. For example, planting trees in urban areas provides certain benefits such as storing carbon and improving wellbeing. However, tree roots seek water and nutrients. In clay-based soils, the action of trees sucking water out of the ground can cause shrinkage, sideways displacement in pipelines, and water pipes to crack causing leakage. Tree roots can also break into sewers and drainage pipes through cracks or displaced joints to access both water and nutrients. Systems thinking can help to highlight such competing priorities and illustrate the interdependencies within the subsurface system. This can facilitate an improved understanding of the subsurface, and ultimately help underground space to be used more efficiently and fairly (von der Tann, et al., 2020).

We chose to adopt a systems thinking approach in this project to represent interdependencies within the subsurface system and explore current and future relationships that may have relevance to policy makers. Whilst the development of a comprehensive map of the subsurface system was beyond the scope of the project, the evidence gathered in two stakeholder workshops and subsequent mapping of example systemic interactions has helped to demonstrate that a systems approach could support improved management of the interactions at play in the subsurface.

5.1 Exploring the subsurface system

To develop a visual representation of the subsurface system including relationships between different aspects, we hosted two online expert workshops with 10-12 subsurface experts. The participants were presented with a canvas split into three subsystems related to the subsurface: (a) the physical system, (b) the institutional system, (c) external change drivers. Using an online sketching tool, systems elements or 'nodes' were added representing separate aspects of the subsurface system and connections or 'links' drawn between them. Activity at the surface was also considered where this influences subsurface systems. For example, rainwater, demand for surface water drains, and the capacity of the ground to provide heat were described as systems elements, with a link showing that increasing rainwater would increase the demand for surface water drains.

The workshops provided insight across a range of subsurface uses, and allowed for a high level discussion of interdependencies. However, the limited time meant that specific topic areas could not be explored in detail/depth. The resulting map illustrated the complexity of the subsurface system and the variety of interactions within it. It also highlighted how these can vary depending on the specific geological and hydrogeological properties and the history of an area and include physical interactions as well as the regulatory framework surrounding them.

To illustrate some specific subsurface interactions within the map, we have isolated and refined three example interactions, chosen in consultation with stakeholders as particularly interesting and illustrative of subsurface challenges. These include both 'feedback loops' and linear chains of interactions, described below.

5.2 Example subsurface interactions

The interactions outlined below focus on a particular node in the system and how it interacts with other nodes, creating a series of direct and indirect effects (some of which loop back to the original node). The three interactions presented here focus on (a) streetworks and data, (b) transport tunnels and heat development in the subsurface, and (c) SuDS and flood risks. They provide a visual representation of potential interactions that could happen, rather than predicting what would happen in general. The development of such illustrations can help stakeholders to understand the complexity and interconnectedness of subsurface interactions, and the way in which these can have a balancing effect or lead to unintended consequences. The nodes and links within the images below are not exhaustive and would be affected by other subsurface components and external factors not shown in each diagram.

When one node causes a change to another, this relationship is shown through an arrow and can be in either the same or the opposite direction, denoted by '+' or '-' on the diagrams below. If the relationship is in the same direction, the increase or decrease in the first node causes the same effect in the second node (an increase causes another increase). If the relationship is opposite, when the first node increases or decreases, this causes the opposite effect in the second (so an increase causes a decrease). The relationships shown are qualitative and don't represent the scale of any increases or decreases. In each case the first image shows the connections, and the second image shows the resulting increases and decreases of nodes if the value of an initial node is increased.

Streetworks and data

The first set of interactions shown in Figure 2 is informed by the experience of developing the National Underground Asset Register (NUAR) and shows how initiating increased availability of reliable and accessible utility data could create a positive feedback loop. Increasing the sharing of high quality data could lead to fewer delays in streetworks caused by utility strikes. It could also increase opportunities for coordination between utility companies, which could reduce costs and disruption for road users by reducing the number of holes that need to be dug. These measurable benefits of having reliable and accessible utility data would help to create a strong business case which in turn could lead to an increase in reliable and accessible utility data.

Further consequences of increasing reliable and accessible utility data could allow underground space to be used more efficiently (e.g. higher density of assets in a given space) and increased confidence in other data sharing initiatives. Fewer holes dug would entail environmental benefits from reduced carbon emissions, and fewer utility strikes would improve worker safety. As noted above, this diagram is an illustrative example of potential consequences of increased reliable and accessible utility data, and in reality, there could be much bigger implications.

Transport tunnels and heat

The second set of interactions as shown in Figure 3 is specific to cities with public transport tunnels and the heat this generates, such as seen with the tube in London. It depicts the potential consequences of an increased use of transport tunnels below ground. Through the use of transport tunnels heat is ejected that for a long time was absorbed by the surrounding ground. However, the capacity of the ground to absorb heat is limited, so that transport tunnels today retain heat and overheat. Without efforts to reduce heat in the tunnels, the heat may lead to reduced train usage.

On the other hand, the excess heat could be harvested as geothermal heat, for example through fitting the tunnel liner with loops to extract heat from the tunnels, or through extracting heat ejected to the ground, which could be fed into district heating networks or supplied to nearby buildings. This happens in Islington, where waste heat from the London Underground network feeds into a district heating network, which is used to heat 1,350 homes, two leisure centres and a school (Islington Council, 2020).

SuDS and flood risk

This set of interactions includes the installation of SuDS to mitigate flood risks, the occurrence of surface floods, and how these interact over time.

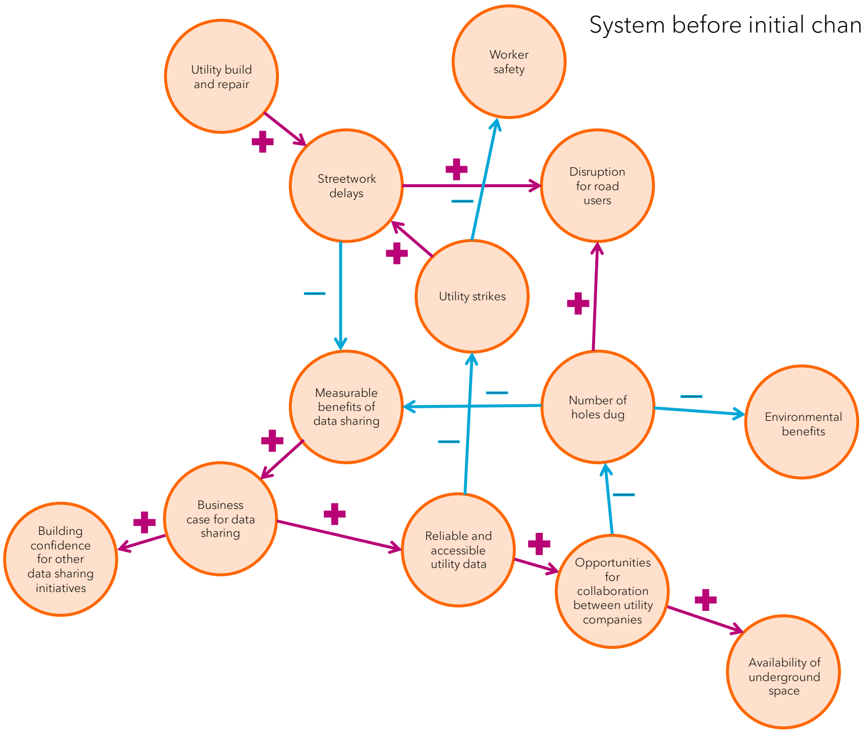
Installing SuDS will reduce surface runoff, thus decreasing surface flood risk. When flood risk is reduced, less new flood mitigation measures need to be installed. Depending on the specific site and scale of installation, reduced surface runoff could also entail a reduction in sewage overflow events, reducing pollution of open waters. This would also reduce the need for investment in new wastewater infrastructure.

SuDS installations have to be planned carefully not only to maximise their benefits but also to prevent negative effects such as the potential to trigger geohazards such as sinkhole formation. For simplicity, these side specific effects are not included in Figure 4.

See the evidence review on *urban water management in the UK* for more information on SuDS in the context of urban water systems.

This is not a statement of government policy.

System before initial change



System after initial change

If reliable and accessible utility data increases, this leads to:

<u>First order effects:</u>

- A decrease in utility strikes
- An increase in opportunities for collaboration between utility companies

<u>Second order effects:</u>

- A decrease in the number of holes dug
- An increase in the availability of underground space
- A decrease in streework delays
- An increase in worker safety

<u>Third order effects</u>

- An increase in environmental benefits
- A decrease in disruption for road users
- An increase in the measurable benefits of data sharing

<u>Fourth order effects</u>

- An increased business case for data sharing

<u>Fifth order effects</u>

- An increase in confidence for other data sharing initiatives

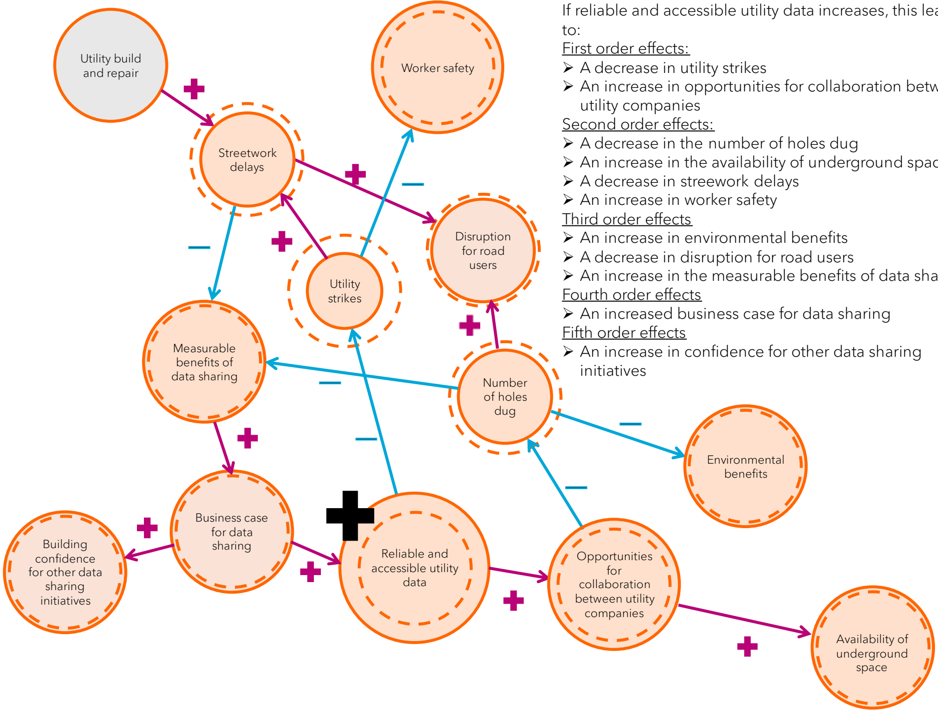
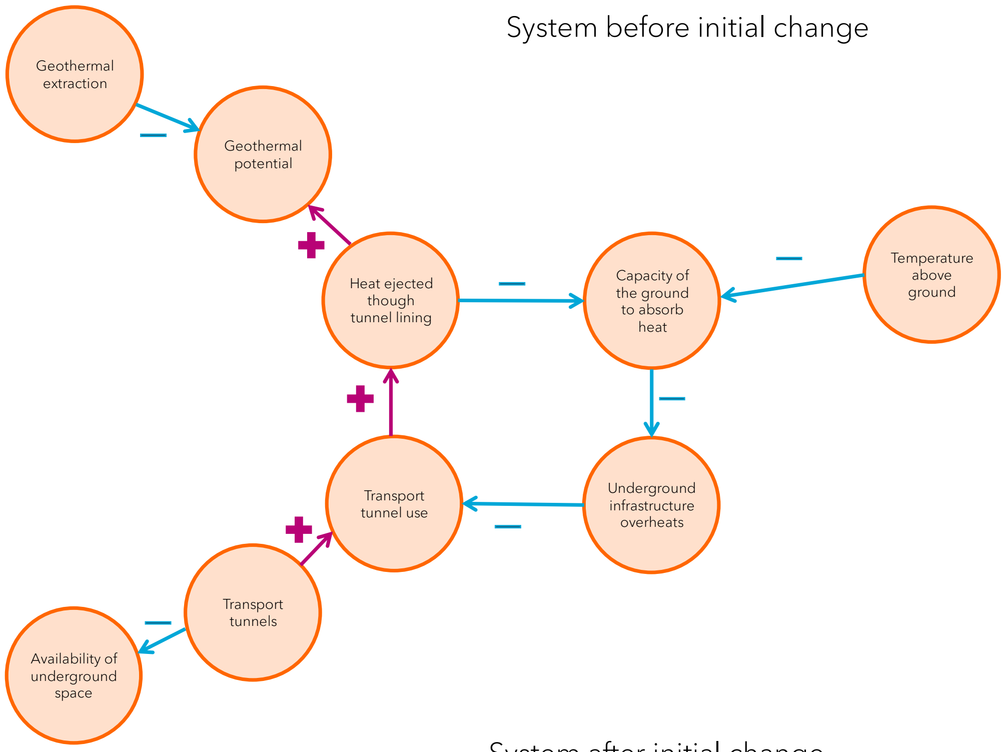


Figure 2: Example interaction showing some potential implications of increasing the amount of reliable and accessible utility data, including reduced disruption for road users.

System before initial change



System after initial change

If transport tunnel use increases, this leads to:

First order effect:

- An increase in heat ejected through the tunnel lining

Second order effect:

- A decrease in the capacity of the ground to absorb heat
- An increase in the geothermal potential of the ground

Third order effect:

- An increase in underground infrastructure overheating

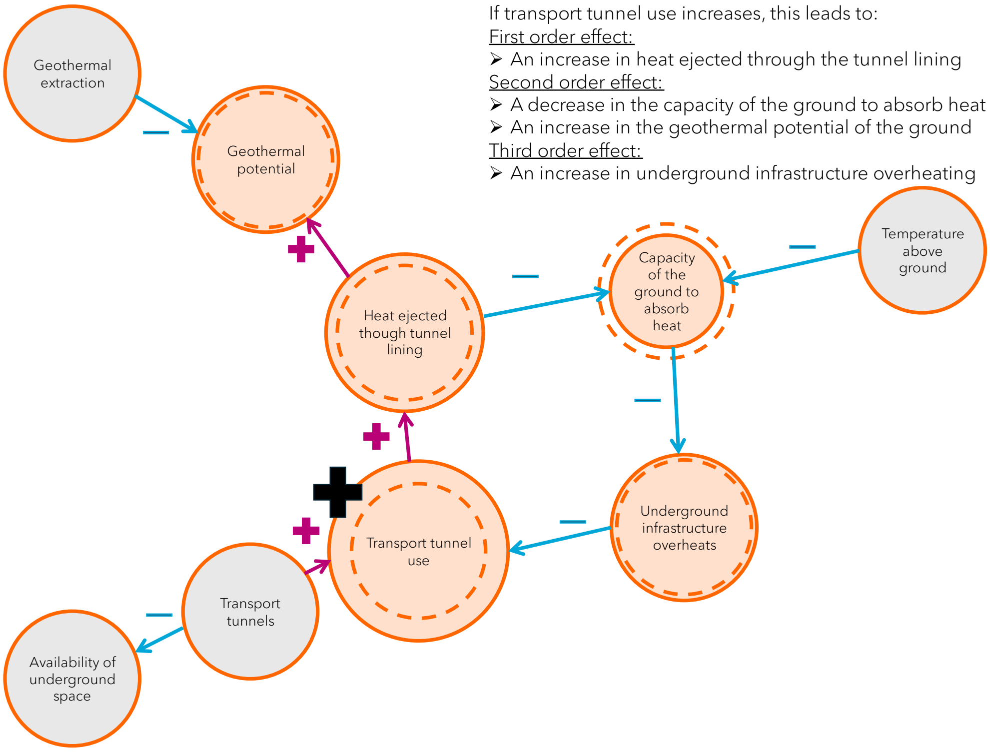
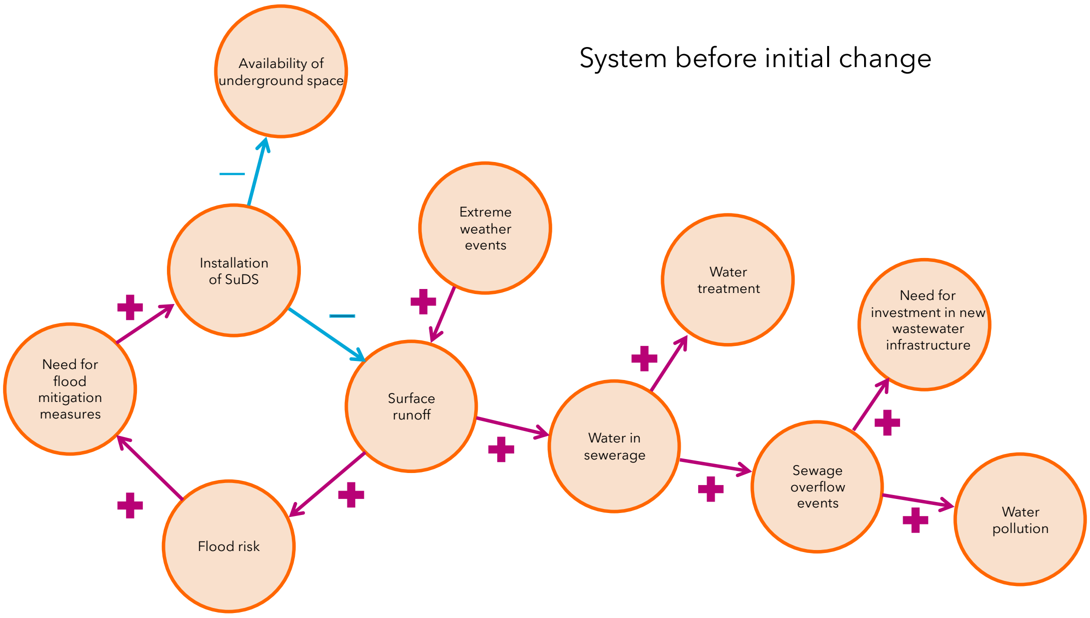


Figure 3: Example interaction showing how increasing the use of transport tunnels could impact the ground through the heat this produces.



System before initial change

System after initial change

If the installation of SuDs increases, this leads to:

First order effects:

- A decrease in the availability of underground space
- A decrease in surface water runoff

Second order effects:

- A decrease in water in sewerage, which leads to
- A decrease in flood risk

Third order effects:

- A decrease in water needing treatment
- A decrease in sewerage overflow events
- A decrease in need for flood mitigation measures

Fourth order effects:

- A decrease in investment needed for new wastewater infrastructure
- A decrease in water pollution

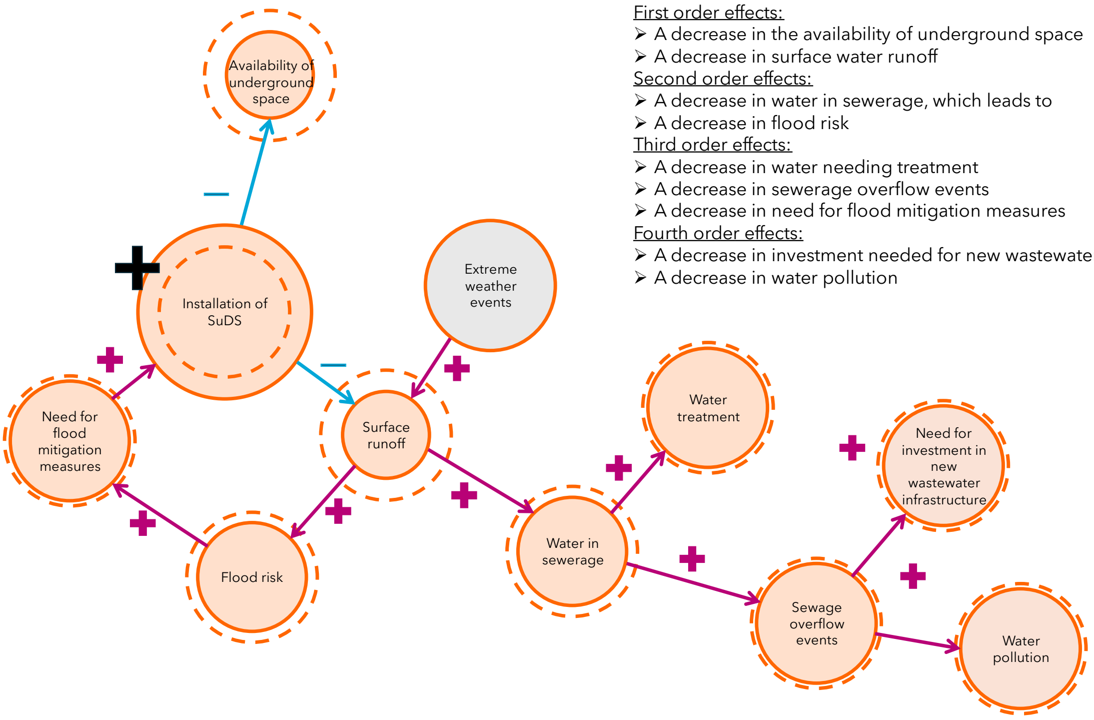
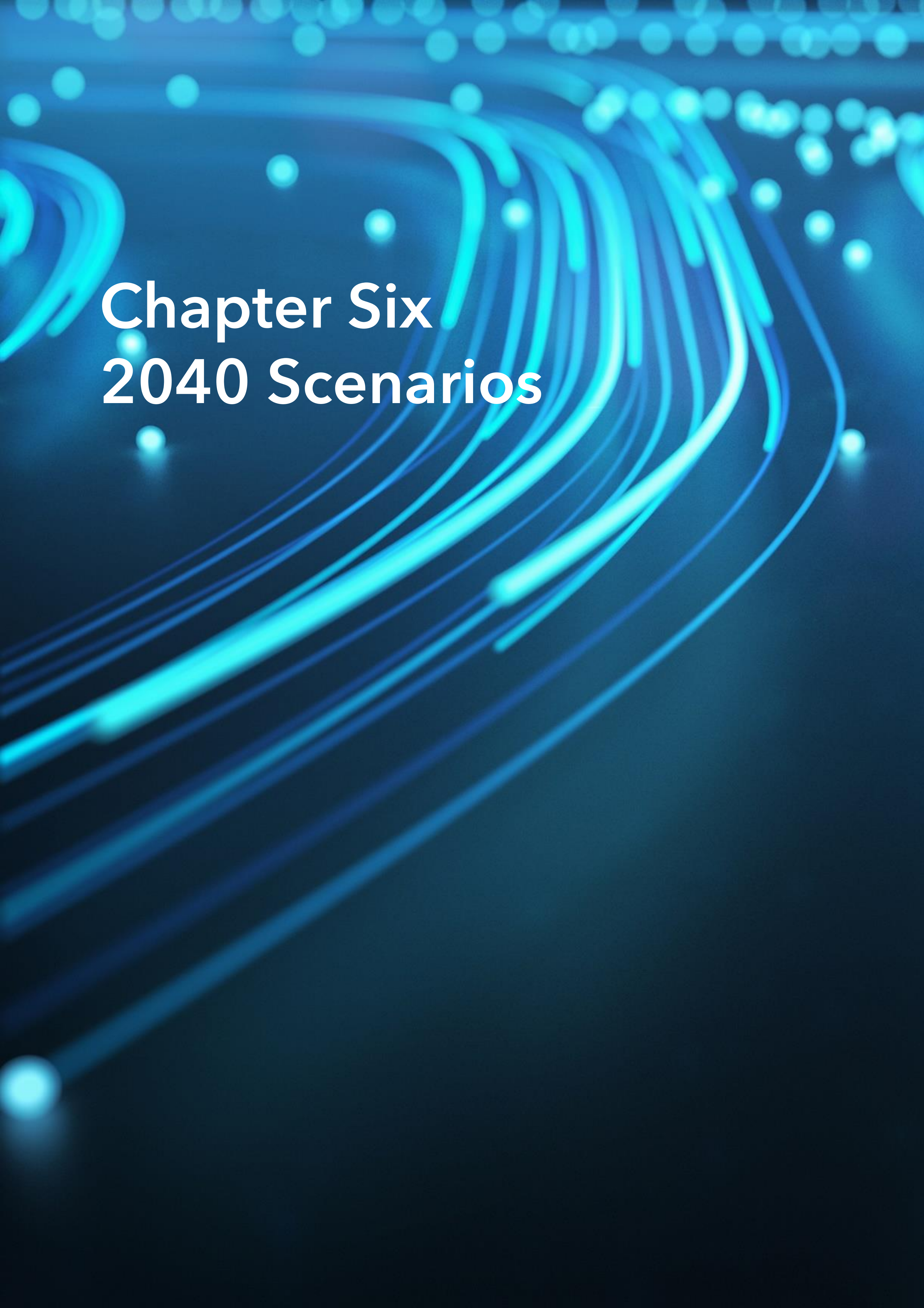


Figure 4: Example interaction showing how increasing the installation of SuDS could impact the wider water system.

Chapter Six
2040 Scenarios



2040 Scenarios

Scenarios are a tool to help policy makers explore uncertainty and identify a resilient course of action that can withstand a range of future conditions. **They are not predictions.**

We have developed three hypothetical 2040 scenarios focussed on key drivers of change: net zero, climate change adaptation, and technology. The drivers were chosen from the key trends set out in Chapter 3, identified with expert stakeholders, and selected according to their relevance to major policy areas in the UK. Although in reality these issues will intersect and impact each other, the scenarios deliberately focus on a single theme. This is to help bring to life the specific impacts each driver of change could have if left unchecked, and the implications for subsurface related policy. The scenarios were developed for each thematic area around the following question:

"Based on previous and existing trends, what is a plausible worst-case scenario with no significant change to the current system of subsurface policies and regulations?"

A brief description of scenario development use is provided below, followed by and a short narrative for each of the scenarios.

6.1 Scenario development and use

Development: We developed the following scenarios using the evidence from literature reviews and earlier stakeholder engagement. Each narrative describes a 2040 end state in which the approach to underground planning and coordination has not changed relative to recent developments. Negative but plausible outcomes have been selected to highlight the risks of doing nothing and opportunities that might be missed. These scenarios are by no means inevitable, even with no changes to policy, but our evidence gathering and stakeholder engagement suggest they are plausible.

Use: The scenarios are designed to promote debate and help policy makers identify actions to navigate to a more favourable future. As you read these, ask yourself the following questions:

- What would a plausible, positive outcome look like for 2040 in this area?
- What action can be taken now to steer towards that positive outcome?
- Within this set of actions, which levers do you control and who else needs to act?

6.2 Scenarios

Scenario 1: Net zero, targets at risk

By 2040, the UK is at risk of missing its net zero targets. This is in large part due to delays in planning and delivery of key net zero infrastructure. Several sectors are behind on electrification and decarbonisation, and policymakers are struggling to find the additional emissions reductions needed to hit net zero.

One of the reasons for this shortcoming is that the UK failed to coordinate future-focused planning policies governing subsurface use in the 2020s: space was not sufficiently prioritised or safeguarded, underground congestion became acute, and developers and authorities lacked accessible data on buried assets. All this led to prohibitive costs, inefficiencies, and project delays for rolling out or retrofitting critical net zero infrastructure.

Other countries, such as Singapore and the Netherlands, created masterplans for subsurface planning and governance which allowed them to safeguard space for net zero infrastructure into the 2030s.

Three specific opportunities missed that would have contributed to meeting net zero targets were district heating networks, EVs, and upgrades to electricity distribution networks.

District heating networks offered great potential for cost-effective, large-scale, low-carbon energy for heating in dense urban areas. They were widely adopted in cities across Europe, such as Copenhagen, however the UK's urban areas failed to capitalise on the opportunity and were not able to move quickly enough. Many new-build developments failed to use district heat networks in the 2020s, and existing buildings were not retrofitted on time. A lack of ground data also increased the cost of digging projects. This left many existing buildings in urban centres continuing to rely on gas-based heating systems. Similar issues have affected the rollout of ground source heat pumps, although less so in rural areas where these have been more successfully used.

Figure 5: A visual illustration of the 'Net Zero – Targets at Risk' scenario. This has been generated using DALLE-3 AI using a prompt based on the scenario. As such it may have some issues with quality and realism. Credit: Policy Lab.

This is not a statement of government policy.

Rollout of EVs has been slower than anticipated, with 2040 seeing a failure to electrify the car and van fleet at a fast enough pace. While much of the fleet has been replaced, a significant proportion of vehicles on the road are still powered by fossil fuels.

Delays to provision of adequate public and on-street charging infrastructure is cited as the main barrier to switching, particularly for drivers for whom range anxiety remains a major concern. These delays were partly caused by competition for subsurface space and slow planning processes for public charge points in the 2030s, particularly in urban centres.

Upgrades to electricity distribution networks have also been slowed by a lack of coordinated subsurface planning. The planned upgrades were critical for improving efficiency, connecting new distributed electricity generation, meeting rising electricity demands while also strengthening resilience against more frequent extreme weather. This had a knock-on impact on EV and heat pump uptake, as mentioned above, as well as small-scale renewables schemes, meaning that there were many instances of these net zero technologies being introduced more slowly than planned.

Scenario 2: Climate change adaptation – under pressure

The world has seen three degrees of global warming, and the UK is experiencing worse impacts than many comparable countries due in part to issues with delivering the required subsurface engineering and infrastructure. More frequent and intense extreme weather events, and pressures on water management present the main challenges the UK is facing.

Extreme weather. The increased frequency and intensity of heat waves means that people frequently seek cool spaces from extreme heat. Underground spaces could have been used as part of cool space strategies designed to help the public during extreme temperatures. However, when this became relevant it was impossible to realise as no space had been safeguarded for development throughout the 2030s and new underground developments had not been mapped. This meant that subsurface spaces available to use in extreme weather in urban areas remained limited or could not be expanded.

The capacity of the urban areas to cope with extreme floods has also been impacted by subsurface planning. Despite the roll out of subsurface drainage infrastructure projects in urban areas storm overflow issues remained rife well into the 2030s. Due to concerns about tree roots damaging pipes and cables, tree planting was not done to a scale that would have been needed to alleviate the worst effects of flooding. This further contributed to the adverse effects of flood events on urban drainage systems.

Figure 6: A visual illustration of the 'Climate Change Adaptation – Under Pressure' scenario. This has been generated by DALLE-3 AI using a prompt based on the scenario. As such it may have some issues with quality and realism. Credit: Policy Lab.

Upgrading ageing underground infrastructure proved to be challenging in the 2020s and 2030s. Now, extreme weather events have compounding negative effects on the infrastructure's integrity and there is no other option but to replace old infrastructure on an ad hoc basis. For example, heatwaves are causing overheating of subsurface transport networks and subsidence that damages tunnels. This has resulted in delays to development, disruption to communities, and higher costs.

Water supply. During the 2020s, measures like sustainable urban drainage systems (SuDS) for new developments, resulted in improved groundwater recharge and wide uptake of groundwater augmentation, reducing water shortages that were becoming increasingly severe in the 2030s. This provided somewhat cost-effective methods of managing flood risk caused by more intense and frequent rainfall events. However, water shortages became increasingly severe towards the end of the decade, and the UK failed to follow the lead of countries like the Netherlands, in seeking out greater opportunities for rainwater harvesting.

As 2040 approaches, with more frequent and intense extreme weather events and pressures on water management policymakers are struggling to put in place the adaptation measures required in the face of climate change.

Scenario 3: Technological change – falling behind

Regulatory barriers in the 2020s slowed the rollout of emerging technologies in the fields of tunnelling and robotics. The UK benefits from a full register of underground assets, which was further developed in the 2020s and 2030s, and this has reduced delays in construction and infrastructure projects. However, a lack of more advanced technology has meant that benefits seen in some countries are not realised in the UK by 2040.

Small-scale tunnel networks for freight. Advancements in tunnelling and excavation technology throughout the 2020s dramatically reduced the costs of tunnelling, particularly smaller-scale tunnels. Enabled by an entirely new regulatory, licensing and planning regime, countries such as Switzerland have benefited from networks of these small-scale tunnels, which deliver goods around the country in small autonomous shuttles. This has significantly reduced the number of lorries and delivery vans on the road, contributing to reduced road congestion, improved air quality and lower carbon emissions. The UK has not experienced the same benefits due to the coordination challenge of building such networks to operate at a geographically useful scale.

Robotics. The UK was unable to replace all its ageing infrastructure in the 2020s and 2030s, and policymakers looked into alternative ways to address this challenge. Some underground infrastructure is now built, repaired, and monitored by autonomous robots. They feed information into digital twins, which came about as a result of the National Digital Twin Programme in the 2020s and have benefitted from a national map of underground assets. Robots have reduced the costs of building infrastructure and have reduced faults. While this does start to show signs of improving infrastructure, by 2040, the approach has not been rolled out widely due to a lack of skilled engineers, the high initial costs of the robots, and the public sector capacity to license them at scale. Regions that have invested into this technology benefit from higher quality, more resilient infrastructure than those that have not, resulting in/aggravating regional inequalities. Those that could afford it have moved to areas with greater investment in infrastructure, leaving those who could not afford to do so in areas with less investment in infrastructure.

Figure 7: A visual illustration of the 'Technological Change – Falling behind' scenario. This has been generated by DALLE-3 AI using a prompt based on the scenario. As such it may have some issues with quality and realism. Credit: Policy Lab.

This is not a statement of government policy.

Chapter Seven
Policy implications and key findings

Policy Implications and Key Findings

This final chapter synthesises the evidence set out above into a series of policy implications and key findings.

Policy implications

In this report, we have identified a series of cross-cutting challenges facing policy makers seeking to enable effective and sustainable use of the subsurface. We have also described a series of long-term drivers of change that are likely to exacerbate these challenges in the coming decades.

The chapters above also highlight some potential solutions to these challenges. These include using systems thinking for subsurface problem solving, taking a longer-term and more coordinated approach to subsurface planning, and using new technologies to address cross-cutting challenges. Foresight reports don't typically make recommendations on specific policy solutions, which would often require more than just evidence, and stray into making value judgements on contested issues. However, we can say which potential interventions are less contested – so-called 'low regret' activities - and describe the trade-offs that policy makers will need to consider in the more contested areas.

'Low regret' activities

Stakeholders we spoke to during this project emphasised the importance of an improved knowledge and understanding of the subsurface to address a range of challenges. This relates to both improved collection of and access to data, and to analytical insight into connections within the subsurface (e.g. via qualitative systems maps or in quantitative models).

Our stakeholder engagement and evidence reviews suggested the lack of high quality data and insight on the subsurface is a primary driver of other challenges. For example, if we don’t have a comprehensive understanding of what lies beneath the ground or what plans exist to use this space in future, that makes it more difficult to decide how best to govern and coordinate potential uses. Addressing the data issue was therefore seen as an important first step towards solving other problems, although it is likely to be insufficient on its own.

A greater focus on directing technological developments towards addressing cross-cutting subsurface challenges was also found to be critical. In particular, new technologies are likely to help with:

- **reducing the cost and improving the quality of data collection and use** (supported by quantum sensors, fibre options, muography, AI, digital twins); and
- **reducing the cost and disruption of excavation, construction, and maintenance** of subsurface assets (supported by VR/AR, robotics/drones, and data-related technologies listed above).

Whilst we found increasing the use of data and technology to be a low regret activity, there are undoubtedly implementation challenges to overcome. These include the availability of appropriate skills, and national security issues that could arise from increasing access to data on critical infrastructure. These points are summarised in the key findings below.

Trade-offs

The areas where we found less agreement amongst stakeholders and within the evidence base mostly relate to the governance and delivery models. Whilst there was general agreement that more coordination, long-term planning, and investment is needed to improve the efficacy and sustainability of subsurface use, there is a range of potential models that could be used to achieve this.

In general, subsurface challenges are highly local in nature and come about through the interaction of local infrastructure needs with the local geology and natural environment. More localised subsurface management has the advantage of being able to draw on local knowledge and understanding of these issues, as well as benefitting from the pre-existing place-based governance provided by local government. At the same time, there are advantages to having a consistent approach at broader geographies, such as common regulations and standards that subsurface users can consistently adhere to, or common datasets to facilitate planning of more significant projects that cut across local authority boundaries.

Touching on international examples, the Netherlands and Finland deliver coordination and planning through strong devolved government, supported by national, independent infrastructure delivery authorities. Whilst its circumstances are very different to the UK, Singapore achieves a noteworthy level of coordination and long-term planning, but through a high degree of centralisation alongside the investing power of publicly owned companies. Both approaches appear to be successful in delivering more positive outcomes than in the UK, suggesting there is no single right model of governance. It is also worth noting that all of these international examples are relatively advanced in delivery of the low regret activities outlined above.

In the UK, it is generally the case that those places that have had devolved subsurface-related responsibilities for longer and with more regional coordination, such as Greater London and Glasgow, have more well-developed solutions for subsurface management. Whilst this suggests that further devolution could make an important contribution to addressing the cross-cutting challenges identified in this report, there was no clear consensus amongst stakeholders which responsibilities were most important to devolve and whether these should sit at a local or regional level. There could also be risks and barriers associated with devolution of responsibilities, such as difficulties sourcing the right technical skills for subsurface management at a local level. Some stakeholders also suggested that certain responsibilities might be delivered more effectively at a national or UK level, including provision of consistent datasets and regulation of specific subsurface uses.

The new technologies and infrastructure solutions highlighted in the report will not only need public sector support, but also the private sector to drive their commercialisation, scale-up and rollout. As demonstrated in Chapter 4, many of the innovative applications of new technologies are being developed by private companies. But such technologies are unlikely to be successfully commercialised without regulatory certainty, particularly in areas that involve public safety. Infrastructure networks are also often monopolistic in nature and there are ongoing debates about the best public or private ownership and investment models for utilities. This suggests that there is no clear-cut answer on the best balance of public and private sector involvement in subsurface developments, making this another key trade-off for policy makers to consider.

These points are summarised in the key findings below.

Key findings

Below are the report's key findings, synthesised from the key findings from each chapter and the policy implications discussed above:

1. **The subsurface is a space much the same as the above ground whose use needs to be monitored, planned, and managed. But the data, technologies, and policy tools needed for this lag behind those available for the surface**. Evidence gathered for this project suggests that moving to a three-dimensional planning approach that manages how space is used vertically as well as horizontally would be a major step towards parity between the subsurface and the surface.
2. **The subsurface faces specific challenges to using it more effectively and sustainably**:
    - **Data availability, accessibility, and quality**. It is difficult to collect data on the subsurface as it is opaque to most sensors. The data that are collected often have accessibility or quality issues. Datasets have either good geographical coverage or good coverage of different subsurface features, but rarely both.
    - **Space competition and congestion**. Subsurface space is often used on a 'first come first served' basis and is congested with various uses, particularly in urban areas. When combined with a lack of data on existing uses, this competition and congestion makes it challenging to optimise future uses.
    - **Complex system interactions**. As subsurface assets and features are physically connected by the earth, they often interact with one another via transmission mechanisms like the groundwater and heat. These interactions are generally not monitored but can lead to adverse unintended consequences across sectors.

  - **Coordination and regulation**. Subsurface use is not comprehensively coordinated in the way that use of surface space is by the planning system. This can make it difficult to plan and prioritise important future uses, including coordination with uses of space above ground. Furthermore, some subsurface uses are only regulated to a certain extent (e.g. geothermal energy).

3. **These challenges contribute to increased costs and delays for delivery of critical infrastructure**. Unintentional 'strikes' of subsurface utilities are estimated to cost the UK around £2.4 bn per year, with around 30% of strikes thought to be avoidable with better data (Cabinet Office & Geospatial Commission, 2021). In addition, 20-60% of linear and transport infrastructure projects experience delays due to unforeseen ground conditions (Bricker et al, 2022).
4. **These challenges also threaten societal resilience and emergency response capabilities, which depend on our ability to monitor and manage the subsurface**. Floods and other hazards have the potential to disrupt the vital services that our use of subsurface space enables.
5. **Future trends are set to make it more important to address these challenges**. These include the need to accommodate more people in cities, build net zero infrastructure and adapt to worse floods and heatwaves caused by climate change. Long-term solutions to cross-cutting subsurface challenges will need to be developed in a way that accounts for these trends.
6. **New technology offers potential solutions, but policy makers will need to be proactive to ensure the UK benefits from these changes**. New technologies that make it easier and cheaper to measure, monitor, excavate, tunnel, and maintain the subsurface are on the horizon, but may need new policy or regulation to enable their widespread use. Measures to promote wider adoption of existing technology should be considered alongside supporting new technological developments.

7. **Our analysis has identified 'low regret' areas** that policy makers should consider, which focus on data, building on the progress made through NUAR:
    - **Collecting more data and improving quality**: Progress has been made in collection of data on geology and subsurface infrastructure, but improving the quality and granularity of this data would make it more useful for informing decisions. This is also true for other subsurface features where data is not comprehensively collected, such as groundwater. Data collection systems should prioritise ongoing maintenance and interoperability of datasets.
    - **Making data more accessible**: Datasets that do exist are held in disparate places and are often not widely accessible, such as geothermal energy. Systems that improve access to datasets, standardise them, and bring them together for analysis would help provide the insight needed to make more effective decisions about the subsurface. Any move to do this would need to address the national security risks and commercial considerations of making data on critical national infrastructure more accessible.
    - **Investing in tools to help use data in decision making**: Once datasets are collected and assembled, policy makers should consider investing in tools that can further inform decision making, such as digital twins to simulate the impacts of subsurface interventions or changes in environmental conditions.
    - **Developing technological capability to solve subsurface challenges**: Policy makers should ensure that technology policy helps to develop capabilities that address the challenges set out above. Such capabilities include lower cost or higher performance measurement, excavation, and maintenance, which could be achieved through developments in technologies including quantum sensors, AI, and robotics.

8. **Addressing the other challenges identified will require policy makers to consider trade-offs**:
    - **How devolved?** Coordination could plausibly be improved through stronger national frameworks, by devolution of decision-making to a local or regional level, or a solution that sits somewhere between these extremes. Wherever coordination responsibilities sit, they will need to be supported by the data, tools, and skills required to inform decision making.
    - **How regulated and planned?** The market can bring investment and a state-of-the-art understanding of subsurface solutions, but without effective regulation and coordination is unlikely to optimise overall subsurface use for long-term public goods. Policy makers will need to consider how best to balance this trade-off.

These findings, alongside the other outputs including the systems maps and scenarios, provide tools to help policy makers develop more effective and resilient subsurface policies. GO-Science can advise policy makers on use of the report findings and other outputs.

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- Cleo Zhang, MA student at superFUTURES design studio at the Royal College of Art.

superFUTURES is a research-led design studio, where staff and students specialise in speculative spatial design and combine Futures Literacy with design criticality and action, to help prepare for today for the uncertainties of tomorrow.

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